PROCEEDINGS OF THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

SOLAR ENERGY, WIND POWER AND GEOTHERMAL ENERGY

Rome, 21-31 August 1961

VOLUME 7. WIND POWER

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ÉNERGIE SOLAIRE, ÉNERGIE ÉOLIENNE ET ÉNERGIE GÉOTHERMIQUE

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INTRODUCTION

The United Nations Conference on New Sources of Energy was held in Rome from 21 to 31 August 1961. A brief review of the proceedings, of the papers submitted to the Conference and of the related discussions has been printed in *New Sources of Energy and Energy Development : Report on the United Nations Conference on New Sources of Energy*.[1] That publication also contains the agenda and the lists of participants and conference officers, as well as lists of all the papers and reports.

The Proceedings of the Conference comprise seven volumes, as follows:

Volume 1. General sessions.
Volume 2. Geothermal energy: I.
Volume 3. Geothermal energy: II.
Volume 4. Solar energy: I.
Volume 5. Solar energy: II.
Volume 6. Solar energy: III.
Volume 7. Wind power.

The present volume, "Wind power", contains the papers and reports relating to the following agenda items: II.B.1. Studies of wind behaviour and investigation of suitable sites for wind-driven plants; II.B.2. The design and testing of wind power plants; II.B.3. Recent developments and potential improvements in wind power utilization.

The rapporteurs' general reports and their summations of the proceedings in connexion with each agenda item are given in full in both English and French, as are those individual papers that were submitted to the Conference in both languages. With a few exceptions, all the papers are summarized in both English and French.

Within each agenda item, the papers are printed in the alphabetical order of the authors' names. References supplied by the authors are listed after the text. As a rule, they are numbered consecutively throughout each paper and are indicated by arabic figures in parentheses.

The reports and papers are printed in the form in which they were presented to the Conference, and the affiliations of the participants are those in effect at that time. Corrections to the papers have been incorporated; some of the figures have been rearranged; and minor editorial changes have been made.

The views and opinions expressed are those of the individual authors and do not imply the expression of any opinion on the part of the Secretariat of the United Nations.

The symbols appearing after the titles of the papers and reports, and in references to them in the text, correspond to the symbols under which they were presented at the Conference. They have here been abbreviated by the elimination of the prefix "E/CONF.35/", which should be included in all full references.

[1] United Nations publication, Sales No.: 62.I.21.

INTRODUCTION

La Conférence des Nations Unies sur les sources nouvelles d'énergie s'est tenue à Rome du 21 au 31 août 1961. Le document intitulé *Sources nouvelles d'énergie et production d'énergie : rapport sur les travaux de la Conférence des Nations Unies sur les sources nouvelles d'énergie*[1] donne un aperçu des travaux, des mémoires soumis à la Conférence et des débats dont ceux-ci ont fait l'objet. Il contient en outre l'ordre du jour, la liste des membres du Bureau et des autres personnes ayant pris part à la Conférence, ainsi qu'une liste de tous les mémoires et rapports présentés.

Les Actes officiels de la Conférence comprennent les sept volumes suivants :

Volume 1. Sessions générales.
Volume 2. Énergie géothermique : I.
Volume 3. Énergie géothermique : II.
Volume 4. Énergie solaire : I.
Volume 5. Énergie solaire : II.
Volume 6. Énergie solaire : III.
Volume 7. Énergie éolienne.

Le présent volume, « Énergie éolienne », groupe les mémoires et rapports ayant trait aux points suivants de l'ordre du jour : II.B.1. Étude du comportement des vents et recherche de sites appropriés pour des installations éoliennes; II.B.2. Plans et essais d'installations éoliennes; II.B.3. Utilisation de l'énergie éolienne : progrès récents et améliorations possibles.

[1] Publication des Nations Unies, numéro de vente : 62.I.21.

Les rapports généraux des rapporteurs et le résumé des débats sur chaque point de l'ordre du jour qui a été établi par le rapporteur intéressé sont donnés intégralement, en anglais et en français, ainsi que les mémoires qui ont été soumis à la Conférence dans les deux langues. Sauf quelques exceptions, ils sont tous résumés en anglais et en français.

Pour chaque point de l'ordre du jour, les mémoires sont classés dans l'ordre alphabétique des noms d'auteurs. La liste des références fournies par les auteurs figure à la suite du texte. D'une façon générale, elles sont numérotées consécutivement pour chaque mémoire, et sont indiquées par des chiffres arabes entre parenthèses.

En règle générale, les rapports et mémoires sont publiés sous la forme dans laquelle ils ont été présentés à la Conférence, et les fonctions indiquées pour chaque participant sont celles qu'il occupait à cette époque. Toutefois, les corrections nécessaires ont été apportées et certaines figures ont été remaniées; des modifications de rédaction mineures ont de même été faites.

Les vues exprimées n'engagent que leur auteur et n'impliquent aucune prise de position de la part du Secrétariat de l'Organisation des Nations Unies.

Les cotes indiquées après les titres des mémoires et des rapports, ainsi que dans les renvois qui y sont faits dans le texte, correspondent aux cotes utilisées pour la Conférence. On les a cependant abrégées en éliminant « E/CONF.35 », qui doit être maintenu dans les cas où la référence complète est donnée.

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EXPLANATORY NOTE

The following symbols have been used in this volume:

A full stop (.) is used to indicate decimals; spaces are inserted to distinguish thousands and millions.

In most cases abbreviations used by the authors have been retained.

For conversion factors to be used in obtaining metric equivalents of British units, or British equivalents of metric units, see *World Weights and Measures*, prepared by the Statistical Office of the United Nations in collaboration with the Food and Agriculture Organization of the United Nations (Statistical Papers: Series M, No. 21; United Nations publication, Sales No.: 1955.XVII.2).

NOTE EXPLICATIVE

Les signes suivants ont été employés dans ce volume :

La virgule (,) indique les décimales; les espaces entre les chiffres distinguent les milliers et les millions.

Dans la plupart des cas, les abbréviations utilisées par les auteurs ont été retenues.

Pour la conversion des mesures métriques en mesures anglaises et pour l'opération inverse, consulter la brochure *World Weights and Measures*, que le Bureau de statistique des Nations Unies a établie avec le concours de l'Organisation des Nations Unies pour l'alimentation et l'agriculture (Études statistiques : série M, n° 21; publication de l'ONU, numéro de vente : 1955.XVII.2).

Agenda item II B.1

STUDIES OF WIND BEHAVIOUR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

Point II.B.1 de l'ordre du jour

ÉTUDE DU COMPORTEMENT DES VENTS ET RECHERCHE DE SITES APPROPRIÉS POUR DES INSTALLATIONS ÉOLIENNES

Chairman — Président

K. LANGLO

Rapporteur

Edward W. GOLDING

STUDIES OF WIND BEHAVIOUR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

Edward W. Golding *

When power is produced from conventional sources of energy—from solid, liquid or gaseous fuels, or from hydraulic energy—it is possible to predict with some certainty the performance of the driven machine because the power input is controllable and can be measured easily. With the exception of hydro-power, which frequently suffers from seasonal variations in the supply of water, it is also possible to predict what annual output of energy can be generated by a machine of given capacity. This output is governed almost entirely by the load demands: it is not limited by the availability of a source of energy for the input to the power plant.

Even for a solar power plant, the output in periods of bright sunshine can be accurately stated, while the annual output obtainable from a given piece of solar equipment, though somewhat variable, is also known within fairly narrow limits because it can be calculated from sunshine records collected by the nearest climatological station.

For wind power, the position is different. Neither the performance of a wind power plant—indicated by its efficiency as a power unit—nor its annual output of energy can easily be measured, or predicted in advance, for two reasons, both of which are subjects for discussion in this section of the Conference. The first is that the wind speed, and therefore the power input of the machine, is continually fluctuating, and the second is that the annual output of energy is influenced greatly by the precise location of the wind power installation in a given area for which, indeed, the general value of the annual mean wind speed may be known.

Variations in wind speed on time scales ranging from seconds to years are very important from different aspects of the problems involved in the design, testing and operation of wind power plants. Methods of wind measurement and the choice of instruments, suited to these time scales, must therefore receive most careful attention. Again, the influence of topography on the energy output from a windmill is so great that the selection of the site for its installation is a matter on which the economy of the whole project may depend.

It is fitting, therefore, that this section should deal with wind measurements and the selection of sites, and the fact that these two subjects are widely recognized as being of first importance is evidenced by the excellent group of papers covering the field in a well-balanced way. Thus, papers W/4, W/10, W/11, W/16 and W/19 deal with meteorological data for winds in various parts of the world and with the application of these data to wind energy calculations, while papers W/2, W/12, W/13 and W/35 discuss wind-measuring instruments and methods to be used in making wind surveys. In papers W/7, W/26, W/28 and W/33, we have valuable guidance on the principles to be followed in site selection, while paper W/14 describes methods of wind measurement associated especially with the performance of a particular wind-driven machine. Not only is the coverage of these papers wide, but the new information and ideas, some from contributors who have taken up wind power studies comparatively recently, will be refreshing to those of us who have been concerned with the subject for a lengthy period of years. Even in research work, there is a tendency to get into a rut, and one valuable function of such a conference as this is to broaden thoughts on the subject and so to encourage new methods of attacking the problems involved.

Wind measurements

Measurements to determine wind behaviour can best be classified according to the purposes which they are intended to serve. For wind power studies, as distinct from more general wind observations made by the national meteorological services, these purposes can be stated as follows:

(*a*) To provide data from which the probable energy output of a windmill of known characteristics, located at the site of the measuring station, can be predicted;

(*b*) To furnish information on the wind structure, under different weather conditions, at the site;

(*c*) To enable special studies, associated with the design and performance of wind power plant, to be made.

These three classes can be designated, according to the time scales appropriate to them, as (*a*) long-period measurements, (*b*) medium-period measurements, and (*c*) short-period measurements.

The measurements involve not only the choice of adequate instruments and their correct installation and operation, but also the subsequent analysis

* Electrical Research Association, London.

of the results obtained, to ensure that the data are presented in the form which is most useful. Let us consider the three classes individually.

Long-period measurements

The energy output of a wind-driven power unit, for any period of time T, during which the wind speed is varying—as it is always to a greater or less degree—is given by the expression

$$K \int_0^T v^3 \cdot dt$$

where v is the instantaneous wind speed and K is a factor which is a function of the efficiency of the machine, the area swept by its wind rotor and the density of the air. If the efficiency of the machine were the same for all wind speeds and, further, if a machine could be made to utilize the power in the wind over the complete range of speeds from the lowest to the highest values occurring, an integrating instrument with a driving torque proportional to (wind speed)^3 would give an accurate measurement of the total output of energy during any period of time. The French wind power specialists have used, in their surveys, an instrument of this type (as described by Argand in paper W/35), although its output is strictly proportional to v^3 only over a limited range of v. Unfortunately, it is not possible to take into account the actual, and varying, efficiency of a wind-driven generator which might be used to produce this measured energy. It must be clearly understood that such an instrument gives a measure of the energy available in the wind and not of that actually produced by a machine which must, in fact, have operating limits of wind speed, i.e., which can utilize only a part of the energy available.

This French instrument is, nevertheless, especially useful in making a comparison of the relative favourability of different sites without requiring frequent readings to be made: it can measure the total apparent energy for a long period of time. But it is important, when assessing the economy of a wind power project, to be able to determine, with some exactness, the fraction of this available energy that can be captured by a machine with specified operating characteristics. Again, it is usually necessary to subdivide the total energy into that obtainable in each month of the year or even in each day. Sometimes, indeed, it is useful to know the variations in output during a day, because any fairly regular diurnal pattern which might appear would have a bearing on the questions of utilization and energy storage. For these reasons, therefore, a measuring instrument of the "v^3" or "energy" type has limited applications: instruments which enable a more detailed examination of wind variations to be made are necessary.

The question of what types of anemometer should be chosen thus arises, and Sanuki (W/2), Tagg (W/12), Perlat (W/13) and Argand (W/35) have given helpful information on the alternative types of anemometer available and on their characteristics. One is pleased to note Sanuki's insistence on the importance of mounting anemometers correctly to avoid interference from near-by obstacles. This is a question to which, in general, insufficient attention is given by meteorologists.

The choice of instrument can be properly made only when it has been decided what is to be measured. In these long-period measurements, for the purpose of estimating the total energy which could be extracted by a windmill at a selected site, values of hourly mean wind speeds are probably the most useful. Tagg (W/12) has shown how these values, when cubed, can be used to estimate the energy output based on certain assumed operating limits of wind speed. And here, perhaps, the question of "energy pattern factor" should be briefly considered. This factor is the ratio

$$\left(\frac{\text{actual energy in the fluctuating wind}}{\text{energy calculated from the cube of the mean wind speed}}\right)$$

and it is somewhat greater than unity, because the sum of a series of cubes of numbers is greater than the cube of their mean value. It would appear, therefore, that the estimate of energy based on mean values of wind speed must err on the low side and this is, indeed, so, but it is probably wise to neglect any increase in the obtainable energy above that estimated for two main reasons: first, unless the wind-speed fluctuations, during the time over which the mean speed is measured, are wide, the energy pattern factor is not much greater than unity; and secondly, the wind-driven machine may not be able to follow these fluctuations due to the high inertia of its rotating system and to its control system which limits the power output in high wind speeds. Experience in testing such machines over a period of time has afforded no evidence that any serious under-estimation of output arises from the use of hourly mean values of wind speed in the way described by Tagg. The adoption of some period shorter than an hour might lead to a more exact estimate, but the labour involved for the analysis of the results would almost certainly not be justified.

If, then, we accept hourly mean values of wind speed, at a selected site, as the data to be obtained, the choice of suitable measuring equipment is greatly narrowed. There are several alternatives, of which the simplest is a cup anemometer, used with some form of recorder which will show the run-of-wind (in miles or kilometres) for each hour. Other instruments which may be used for the same purpose are the windmill anemometer, with a recorder, and the Dines pressure-tube anemometer. The method selected should be that which will give the most trouble-free service when installed at a remote site where little skilled maintenance is practicable,

which is cheap and which does not call for an excessive amount of analysis in converting the wind records to the form required for energy estimates.

The total cost of the measuring installations for a wind survey covering an area of country is often an important consideration. Fortunately, it does not seem to be essential that hourly wind speeds should be measured at all the sites being investigated. Unless the area is very extensive, or the topography varies greatly, the wind régimes at these sites (as exemplified by their velocity-duration and power-duration curves) are sufficiently similar for the annual mean wind speed to be used as a basis for estimations. The "specific output" (in kWh per annum per kilowatt) for a site, assuming reasonable wind speed limits in the operation of a windmill located there, can be given, accurately enough for most purposes, from a knowledge of the annual mean wind speed: a curve showing the relationship between these two figures can be prepared, for any survey area, provided that full wind data (i.e. hourly mean wind speeds for a period of a year) are available, for a few sites having different annual mean wind speeds. It may, indeed, be accurate enough to accept existing curves prepared for an area with a generally similar wind régime.

This leads to considerable simplification, and cost reduction, in wind surveys: the annual mean wind speed, only, need be measured at most of the selected sites, the remainder—perhaps one fifth or one sixth of the total—being equipped with more elaborate instruments for the more detailed measurement of hourly mean speeds. Cup anemometers, measuring simply the run-of-wind, then become usable for the former purpose. Their indications being given on a simple counter, or cyclometer, they can be attended by quite unskilled local observers who can take readings at weekly, or monthly, intervals. The annual mean wind speed is obtained by dividing the total run-of-wind by the number of hours in the year. Up to the present, it has been considered that "spot" readings taken from anemometers, such as those of the cup-generator or windmill type (which indicate the instantaneous wind speed), at certain selected hours each day do not form a reliable basis for a determination of the long-period (e.g. annual) mean speed. Soliman (W/4) has shown, however, from a comparison of the results of different methods of wind measurement at eight Egyptian meteorological stations, that this is not necessarily so and that the agreement between the annual mean speed as determined from hourly mean speeds and that based on twenty-four synoptic readings is surprisingly close when the annual mean exceeds about 7 knots. Indeed, the use of only four synoptic readings might not lead to a very serious error in the annual mean value.

A wind speed value of considerable importance is the maximum which is likely to occur at a given site. Clearly, this must involve a long-term study by means of some form of recording, or registering, instrument used in conjunction with an anemometer. The latter might be a cup-type or windmill-type of instrument coupled to a small electric generator giving an output—proportional to wind speed—which can be fed into a recorder. An alternative is a Dines pressure-tube type of anemometer which has its own recording mechanism.

The designer of a windmill obviously has an interest in this maximum wind speed because of its direct bearing on the stresses which have to be withstood by the machine. The difficulty in determining the maximum lies not so much in the measuring instrument to be used—although the more sensitive the instrument the higher will be the maximum speed recorded—but in choosing the time over which records should be taken, and in deciding the probability of a dangerously high speed occurring in any specified number of years.

Two interesting new instruments, developed especially for tests associated with the Danish 200 kW aerogenerator at Gedser but erected also at several other sites, are described by Jensen (W/14). These measure, respectively, the wind energy distribution between different ranges of wind speed and the maximum velocity pressures of the wind.

Medium-period measurements

These measurements differ from those discussed above not so much in instrumentation—in fact, the same types of anemometer may be used—but in their purpose and total duration. They include measurements for the determination of the vertical and horizontal distribution of wind speed at selected sites, including simultaneous measurement of wind direction. The direction of the wind, though not usually of first importance in wind power work, has a bearing on the stability of the wind (broken ground upwind of the site may induce turbulence) and, if sufficiently persistent wind directions are found, may lead to consideration of the possibility of omitting provision for orientation of the wind power plant, thus cheapening it.

Frenkiel (W/33), in his very comprehensive study of wind flow over hill sites, has described his measurements of wind speed, direction and temperature at different heights above ground in an endeavour to obtain the fullest possible information on the effects of topography on the mean wind vertical gradient. His results, showing that, for any particular wind direction, this gradient is independent of the strength of the wind, at least within the normal operating range of a wind power plant, are very important.

Another purpose of medium-period wind measurements is the study of diurnal variations in wind speed. The prospect of there being a usable wind at any particular time of the day is important from the point of view of utilization of the power produced and of energy storage to cater for calm spells. The daily charts of the Dines pressure-tube type of anemometer, commonly used by meteorological services, gives full information on these variations,

but such an instrument is expensive and is not very suitable for use at a remote site where skilled attention is not available.

Short-period measurements

Measurements of wind speed over periods of a few minutes, a few seconds, or even a fraction of a second, prove necessary in tests on the performance of wind-driven machines. They must employ instruments of sufficiently rapid response to enable gusts, which may rise very quickly and last for a very short time to be measured. This response time must, in practice, be related to the duration of gust likely to influence the machine. A high wind speed persisting for only a small fraction of a second may not contribute enough energy to have any measurable influence on the machine but, nevertheless, with only a little greater duration of the maximum gust speed, there may be effects which are important enough to measure.

These effects are of two kinds, electrical and mechanical: both the electrical power output and the stresses in the rotor blades, and other parts of the windmill structure, are affected by gusts.

In research and development work on a new type of wind-driven generator, an important series of tests are those to obtain the curve of power output for different wind speeds, and the question of how these two variables should be measured arises. Some investigators have used a wattmeter and a standard type of anemometer or, alternatively, have measured the energy output during a few minutes and the mean wind speed for the same period. The result of a number of measurements by such methods is usually a "cloud" of points, on the graph, through which some representative characteristic curve is drawn. An examination of the machine's performance in detail—which may be necessary to study the effects of small experimental changes in design—calls for quick-response instruments for measurement of both the electric power and the wind speed. The "moving-sphere" type of gust anemometer, developed by the Electrical Research Association for such a purpose, is mentioned by Tagg in his paper (W/12). By mounting the gust anemometer at the same height as the hub of the windmill rotor and locating it upwind of the machine at a distance of several rotor diameters, it has been found possible to get very good correlation between the high-speed fluctuations in wind speed and the corresponding variations in power output.

To study, by means of strain-gauges, the stresses set up in windmill blades when rotating in gusty winds, the same method of wind speed measurement has been used successfully.

Argand (W/35) describes an interesting new type of quick-response anemometer and recording equipment which can be used to measure rapid changes in both the speed and direction of the wind. No doubt this instrument will prove useful in testing the performance of a large aerogenerator. It is interesting to note that the photographic method of recording is used.

The use of meteorological data

In our consideration of the methods to be used in measuring wind, with the especial object of wind power generation in view, we must not, of course, overlook the fact that much valuable information on wind speeds and directions already exists in the records of national meteorological services. For obvious reasons, wind data obtained by these services have not been based on wind power requirements: they are related to the general wind régime for the districts surrounding the observation stations, not to particularly windy sites. Nevertheless, they are, in the main, reliable long-term records and should not be neglected merely because higher average wind speeds than those at the meteorological station can often be found at selected sites.

The papers by the World Meteorological Organization (W/11), Ramakrishnan and Venkiteshwaran (W/19), Barasoain and Fontán (W/16), Cambilargiu (W/10) and Soliman (W/4) all give valuable information on the winds in different parts of the world and relate this, as far as possible, to wind power potentialities in those areas.

How can meteorological data of this kind be put to the best advantage? One can list its uses as follows:

(*a*) As a basis for wind surveys indicating the areas where the highest wind speeds are to be found;

(*b*) As an indication of the direction of the prevailing wind—a knowledge of this is important when selecting wind power sites;

(*c*) As a measure of the constancy, or variability, of the annual mean wind speed from year to year;

(*d*) As an indication of the annual wind régime, for an area, from values of monthly mean wind speeds;

(*e*) As a measure of the diurnal variations in wind speed to be expected at different seasons of the year;

(*f*) As a guide to the maximum wind speeds, and to the durations of calm spells, which might occur.

The degree of usefulness of meteorological records naturally depends upon their detail and on the number of years for which they have been kept. Chart records of wind speed and direction, as produced, for example, by the Dines pressure-tube anemometer, will, if available for a number of years, fulfil all the uses mentioned above, while long-term records obtained even from simple cup-counter anemometers can serve purposes (*a*), (*c*) and (*d*)—and even (*e*) in the unlikely event of sufficiently frequent readings having been taken.

Much of this information is directly applicable to wind survey work because the general features of the wind régime for an area will hold also for

particular sites within it. The values which, for a selected site, may differ significantly from those at the nearest meteorological station are those of annual mean wind speed, of maximum wind speed and of the durations of calm spells. But, of course, these three values are all of the highest importance in estimating the energy output of a projected windmill, in designing it to withstand high stresses set up by the wind, and in determining the dependability of the power generated or the need for energy storage.

The best procedure to be followed, therefore, is to take full account of long-term meteorological records and to supplement them by the use of measuring installations, of the kinds discussed in the papers presented, to gain full information on the wind's behaviour at the sites which appear to be most favourable for wind power.

Site selection and wind surveys

Surveys for wind power sites have as their main object the discovery of especially windy points at which wind power plants might be installed. The first considerations, in making them, are topographical. Secondary, but still important, considerations are the existence of, or the possibilities of building, access roads or tracks, and the distances of the sites from centres of habitation where the wind-generated energy could be used.

The increase of wind speed with height above level ground is a well-recognized phenomenon, so that, if the installation of windmills in a flat area, completely devoid of hills, is projected, an enhanced output from a machine of a given design and diameter of wind rotor can be achieved only by increasing the height of its supporting tower. But this must add to the capital cost of the installation and therefore to the cost of the energy produced. Whether such an increased tower height is economically justifiable must be judged by comparing this higher capital cost with the increase in output which would be achieved.

If the area in which wind power installations are to be made includes hilly country, an obvious step is to choose sites on hill summits to take advantage of their altitude above that of the surrounding level ground and so to "tap" the faster moving stream of air at this altitude. It is not, however, merely a question of choosing any hill at random. Hills on a seacoast, particularly if the prevailing wind blows from the sea, are likely to give good results but, on the other hand, hills inland, if surrounded, at a short distance, by high ground of the same order of altitude as themselves, may have disappointingly low mean wind speeds and may also be subject to frequent turbulence—induced by broken ground upwind—in the wind stream flowing over them. A really significant increase in mean wind speed, as compared with that for the surrounding low ground, can be obtained by choosing a hill with good profiles so that, acting as an aerofoil, it causes an acceleration of the wind over its summit. This means that the wind speed may, in fact, be greater than that which would be found it if were possible to measure it at the altitude of the summit but over level ground. In other words, the mean wind speed may be greater than that due to altitude alone. There is what has been called a "speed-up" effect due to the shape of the hill.

That this effect might be expected was recognized by P. C. Putnam and his co-workers on the Grandpa's Knob windmill project in the United States some twenty years ago, and such experience as it has been possible to obtain since, in the British wind surveys and those, in other countries, following similar methods, tends towards confirmation. It is, however, very difficult to prove, positively, that this speed-up effect exists at a given site and this section of the Conference is fortunate in having papers (W/26 and W/28) on this subject prepared respectively by Petterssen and Lange, both of whom were associated with the Grandpa's Knob project. These papers give valuable guidance on site selection from the theoretical and practical aspects.

Hitherto, site selection has been an art rather than a science: good hill sites have been chosen by inspection, taking into account their apparently favourable shape—with fairly steep but smooth slopes—and the nature of their surroundings. Although much has been written, during the past few decades, on the subject of wind flow over hills, very little guidance has been forthcoming on the factors influencing wind speeds over summits of hills of different shapes, so that correct selection of sites has remained very much a matter of judgement, or "inspired guessing", on the part of the wind surveyor.

As time has passed, valuable experience, and some skill, has been acquired but, even so, there have been instances of unexpected failures. Some of these have been due, almost certainly, to the fact that, although the general shape of the hill has been good, its actual summit has been too flat, so that the air stream has passed over at a height greater than that of the measuring instrument which has, therefore, been situated in a stream of slower moving air.

Accompanying the acceleration due to "speed-up effect", there is undoubtedly a reduction in the vertical wind speed gradient at the summit: the wind speed does not increase, with height above the ground, as much as it does when flowing over level country. Frenkiel, in paper W/33, describes his experimental studies of this question on both ridge-shaped and conical hills and concludes that the vertical wind gradient at the summit should be used as a quantitative measure of the favourability of the site.

The three last-mentioned papers, together with that of Ballester (W/7), who presents a very useful discussion on the theory and practice of wind surveying, have undoubtedly made an important contribution to our knowledge of the subject.

Topics for discussion

The papers presented introduce a large number of points of detail which could be discussed, but it may be more profitable to confine the discussion to the following four major subjects:

(*a*) How far can existing long-period meteorological records of wind, and the current records from meteorological stations, be used for the estimation of wind power potentialities in any region?

(*b*) What forms of measuring installations, including both the instruments themselves and their mounting above ground, should be recommended for wind surveys?

(*c*) What degree of standardization of measuring methods, and of the analysis of results, is desirable to assist in the international exchange of information on wind behaviour?

(*d*) Are we now, as a result of the papers presented (particularly W/26, W/28 and W/33), in a position to specify criteria for the selection of good wind power sites?

ÉTUDE DU COMPORTEMENT DES VENTS ET RECHERCHE DE SITES APPROPRIÉS POUR DES INSTALLATIONS ÉOLIENNES

(Traduction du rapport précédent)

Edward W. Golding *

Pour les installations utilisant une source d'énergie classique — combustible solide, liquide ou gazeux, ou énergie hydraulique —, il est possible de connaître à l'avance le rendement avec une assez grande précision, car la quantité d'énergie utilisée dans l'installation peut être contrôlée et mesurée facilement. Sauf pour les machines hydrauliques dont l'alimentation en eau subit fréquemment des variations saisonnières, on peut également prévoir la production annuelle d'énergie d'une installation ayant une puissance donnée. Cette production est presque uniquement fonction des exigences de la charge et n'est pas limitée par l'énergie disponible pour alimenter la centrale.

Même pour une installation utilisant l'énergie solaire, la production peut être estimée assez exactement pour les périodes ensoleillées, et la production annuelle d'une installation, quoique variable dans une certaine mesure, est connue également d'une façon précise, car elle peut être calculée à partir des données recueillies par la station climatologique la plus proche.

Pour les installations éoliennes, la situation est différente. Ni le travail d'une installation — caractérisée par son rendement en tant que générateur d'énergie — ni sa production annuelle ne peuvent être mesurés ou estimés d'avance d'une façon précise, et ceci pour deux raisons qui précisément feront l'objet des discussions de cette section de la Conférence. La première raison, c'est que la vitesse du vent, et par conséquent l'alimentation en énergie de l'installation, varie continuellement; la seconde, c'est que la production annuelle d'énergie dépend dans une large mesure de la situation exacte de l'installation dans une zone pour laquelle, dans son ensemble, la valeur moyenne annuelle de la vitesse du vent est connue d'une façon assez précise.

Les variations de la vitesse du vent enregistrées pour des périodes allant de quelques secondes à quelques années présentent une grande importance pour la solution des problèmes de construction, d'essais et de fonctionnement des installations éoliennes. C'est pourquoi les méthodes de mesure du vent et le choix des instruments convenant à l'enregistrement des variations dans le temps pour des périodes différentes doivent être étudiés avec la plus grande attention. De plus, il faut souligner que l'influence de la topographie aux alentours du site d'implantation joue un rôle tellement important dans la production d'une installation éolienne que la rentabilité du projet dans son ensemble peut dépendre du choix de ce site.

Il est donc normal que cette section de la Conférence examine la question de la mesure des vents et du choix des sites favorables. Les excellents mémoires qui étudient l'ensemble de ce domaine, sous tous ses aspects, témoignent de l'importance que tous les spécialistes attachent à ces deux questions. C'est ainsi que les mémoires W/4, W/10, W/11, W/16 et W/19 donnent les relevés météorologiques des vents dans différentes parties du monde et traitent de l'application de ces données au calcul de la puissance éolienne disponible. Les mémoires W/2, W/12, W/13 et W/35 sont consacrés à l'étude des instruments de mesure du vent et des méthodes à employer pour les relevés de vitesse du vent. Dans les mémoires W/7, W/26, W/28 et W/33, nous trouvons des indications intéressantes sur les principes à appliquer dans le choix des sites d'implantation, et le mémoire W/14 présente une description des méthodes de mesure du vent convenant spécialement à l'estimation du rendement d'une installation éolienne d'un type déterminé. Le champ de ces mémoires est donc très vaste, mais ils contiennent des idées et des renseignements nouveaux, provenant parfois de collaborateurs qui viennent seulement d'entreprendre l'étude de la question des installations éoliennes. Ces éléments nouveaux ne peuvent qu'encourager ceux d'entre nous qui se sont consacrés à cette étude depuis de nombreuses années. Même dans les travaux de recherche, on peut suivre une ornière, et une Conférence comme la nôtre permet d'ouvrir de nouveaux horizons et de provoquer l'éclosion de nouvelles méthodes pour résoudre les problèmes qui font l'objet de nos débats.

Mesure des vents

Les mesures qui servent à déterminer le comportement du vent doivent être classées suivant le but qu'elles visent. En ce qui concerne l'étude de la puissance du vent, par opposition aux observations d'ordre général effectuées par les services météorolo-

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giques nationaux, le but visé peut se définir de la façon suivante :

a) Recueillir les données permettant d'estimer la production d'énergie probable d'une installation éolienne de caractéristiques connues qui serait placée à l'endroit de la station de mesure;

b) Recueillir des données sur le comportement du vent au site choisi dans différentes conditions météorologiques;

c) Recueillir des données servant à l'étude d'un problème particulier se rapportant à la construction et au rendement des appareils à installer.

Ces trois groupes de mesures peuvent être désignés, d'après la durée des observations, sous les titres suivants : *a*) mesures de longue durée, *b*) mesures de durée moyenne, et *c*) mesures de courte durée.

Ces mesures exigent non seulement un choix rationnel des appareils, leur installation et leur maniement corrects, mais également une analyse ultérieure des résultats obtenus permettant de présenter les renseignements recueillis sous la forme la plus profitable. Considérons maintenant ces trois groupes de mesures séparément.

Mesures de longue durée

L'énergie produite par une installation éolienne pendant un temps T, temps pendant lequel le vent souffle avec une vitesse variable — comme c'est toujours le cas dans une mesure plus ou moins grande —, est donnée par l'expression

$$K \int_0^T v^3 \, dt$$

dans laquelle v est la vitesse instantanée du vent et K une constante qui dépend du rendement de l'appareil, de la surface balayée par son rotor et de la densité de l'air. Si le rendement de l'appareil était le même pour toutes les vitesses du vent, et si de plus l'appareil était capable d'utiliser la puissance du vent pour tout le spectre des vitesses, de la vitesse la plus faible à la vitesse la plus grande à laquelle le vent peut souffler, un appareil intégrateur ayant un entraînement proportionnel au cube de la vitesse du vent donnerait une mesure exacte de la production totale d'énergie pour n'importe quel laps de temps. Les éoliens français ont utilisé dans leurs recherches un instrument de ce type (décrit par Argand dans le mémoire W/35; le rendement de cet appareil n'est cependant strictement proportionnel à v^3 que pour une gamme limitée de v). Malheureusement, il n'est pas possible de faire intervenir pour ce genre de mesure le rendement réel et variable d'un aéromoteur qui serait installé pour utiliser cette énergie. Il faut avoir présent à l'esprit le fait qu'un tel instrument donne une mesure de l'énergie disponible du vent et non pas de l'énergie qui serait réellement produite par un appareil travaillant nécessairement entre certaines limites de vitesses du vent, c'est-à-dire ne pouvant utiliser qu'une partie de l'énergie disponible.

Cet appareil français est cependant particulièrement utile pour faire la comparaison entre différents sites possibles sans exiger une lecture fréquente des appareils : il peut effectivement donner une mesure de l'énergie totale apparente pour un long laps de temps. Cependant, pour estimer la rentabilité d'un projet d'installation éolienne, il est nécessaire de pouvoir déterminer avec une certaine exactitude la partie de cette énergie disponible qui peut être captée par un appareil ayant certaines caractéristiques données. De plus, il est généralement nécessaire de connaître non seulement l'énergie totale annuelle, mais également celle qui peut être obtenue au cours de chaque mois ou même de chaque journée. Il est même utile parfois de connaître les variations de production au cours d'une journée, car une répartition journalière plus ou moins régulière présente une grande importance en ce qui concerne l'utilisation et l'accumulation de l'énergie produite. C'est pour cela qu'un instrument mesurant v^3 ou l'énergie n'est que d'application limitée; des instruments permettant un examen plus détaillé du comportement du vent sont indispensables.

Nous arrivons ainsi à la question du choix d'un anémomètre; Sanuki (mémoire W/2), Tagg (mémoire W/12), Perlat (mémoire W/13) et Argand (mémoire W/35) nous donnent des informations utiles sur les différents types d'anémomètres et sur leurs caractéristiques. Il faut souligner l'importance que Sanuki attache à un montage correct des anémomètres, qui les soustrait à l'influence perturbatrice des obstacles pouvant se trouver à proximité. C'est une question à laquelle, d'une façon générale, les météorologistes n'attachent pas une importance suffisante.

Un choix judicieux d'un instrument de mesure ne peut se faire que lorsqu'on a décidé ce que l'on veut mesurer. Pour les mesures de longue durée, dont le but est d'estimer l'énergie totale qui peut être produite par un appareil éolien en un endroit donné, le plus intéressant est probablement d'utiliser les valeurs moyennes horaires. Tagg (W/12) a montré comment ces valeurs à la troisième puissance peuvent servir à la détermination de l'énergie produite si l'on se fixe certaines limites pour les vitesses du vent utiles. Il est peut-être opportun ici d'examiner la question du « coefficient d'irrégularité ». Ce facteur est le rapport

$$\left(\frac{\text{énergie réelle du vent variable}}{\text{énergie calculée à partir du cube de la vitesse moyenne du vent}}\right)$$

Il est légèrement supérieur à un, car la somme des cubes d'une série de nombres est toujours plus grande que le cube de la valeur moyenne. Il semblerait donc qu'une estimation de l'énergie utilisant des valeurs moyennes de la vitesse du vent devrait présenter une erreur par défaut, et il en est effectivement ainsi. Mais il est raisonnable sans doute de ne pas forcer cette estimation de l'énergie utilisable pour deux raisons. Tout d'abord, si les variations de la vitesse du vent pendant le temps pour lequel

la valeur moyenne de la vitesse a été établie ne sont pas très grandes, le coefficient d'irrégularité n'est pas beaucoup plus grand que un et, de plus, l'installation éolienne peut ne pas être capable de suivre ces fluctuations de vitesse par suite de la forte inertie de son système rotatif et à cause de son système de contrôle, qui limite la production d'énergie pour les grandes vitesses du vent. Les essais des installations éoliennes pendant un temps assez long ont montré qu'il n'y a pas de raison de croire que l'utilisation des valeurs moyennes horaires de la vitesse du vent, comme le propose Tagg, entraîne une sous-estimation sensible de l'énergie produite. En prenant une période plus courte qu'une heure, on pourrait arriver à une estimation plus exacte, mais très probablement le travail nécessaire pour l'analyse des résultats ne serait pas justifié.

Si donc nous adoptons la valeur moyenne horaire de la vitesse du vent à un site donné comme variable à mesurer, le choix de l'appareillage de mesure se restreint sensiblement. Plusieurs appareillages sont possibles, mais le plus simple est l'anémomètre à coupelles relié à un enregistreur qui donnera le vent ayant traversé l'appareil en une heure (en milles ou en kilomètres). Les autres instruments qui peuvent être utilisés aux mêmes fins sont l'anémomètre à hélice, relié à un enregistreur, et l'anémomètre Dines à tube de Pitot. La méthode à choisir est celle qui, pour une installation en un site isolé, où l'entretien par un spécialiste est difficile, donnera le moins d'ennuis de fonctionnement, qui n'entraînera pas trop de frais, et qui ne demandera pas un trop grand travail de dépouillement pour donner aux enregistrements la forme permettant une estimation de l'énergie disponible.

Le coût total des installations de mesure indispensables pour faire le relevé éolien d'une zone d'une certaine étendue joue souvent un grand rôle. Il ne semble pas heureusement qu'il soit indispensable que les vitesses horaires du vent soient mesurées à tous les sites envisagés. A moins que la zone ne soit très vaste ou les conditions topographiques trop diverses, le régime des vents aux différents sites (caractérisé par les courbes vitesse-temps et puissance-temps) est suffisamment semblable pour que l'on puisse utiliser dans l'estimation de la puissance disponible la vitesse moyenne annuelle du vent. Le « rendement spécifique » (en kWh par an par kilowatt) pour un site donné peut être obtenu d'une façon suffisamment précise à partir de la vitesse moyenne annuelle du vent si l'aéromoteur travaille dans des limites raisonnables de la vitesse du vent : une courbe donnant le rapport entre ces deux variables peut être préparée pour une zone donnée si l'on dispose de renseignements complets sur la vitesse du vent (valeurs moyennes horaires de la vitesse du vent pour une année) pour un certain nombre de sites où la valeur moyenne annuelle du vent est différente. En fait, la précision peut même être suffisante si l'on utilise les courbes déjà préparées pour une zone ayant dans son ensemble un régime des vents semblable à celui de la zone étudiée.

Ceci permet de simplifier beaucoup et de réduire les coûts des relevés éoliens : pour la plupart des sites étudiés, il suffit de mesurer la vitesse moyenne annuelle, et une petite partie seulement des sites, un cinquième ou un sixième du total, doit être équipée des instruments plus complexes que nécessite la mesure des valeurs moyennes horaires. Des anémomètres à coupelles, donnant simplement le courant aérien, suffisent dans le premier cas. Leurs indications, visibles sur un simple compteur ou tambour, peuvent être relevées par des observateurs locaux non qualifiés, à des intervalles d'une semaine ou d'un mois. La vitesse moyenne annuelle du vent est obtenue en divisant le total annuel par le nombre d'heures de l'année. Jusqu'à présent, on a toujours considéré que les relevés journaliers « sur place » des anémomètres du type à coupelles ou à hélice (qui donnent la vitesse instantanée du vent) à certaines heures fixes ne forment pas une base sûre pour la détermination de la vitesse moyenne au cours d'une longue période (par exemple pour une année). Cependant, Soliman (W/4) a montré, en comparant les résultats des mesures du vent par huit stations météorologiques égyptiennes utilisant des méthodes différentes, qu'il n'en est pas nécessairement ainsi et que la valeur de la vitesse moyenne annuelle déterminée à partir des valeurs moyennes horaires et la valeur obtenue à partir de 24 relevés synoptiques sont extrêmement proches l'une de l'autre lorsque la vitesse moyenne annuelle dépasse sept nœuds environ. En fait, en n'utilisant que quatre relevés synoptiques, la valeur obtenue pour la moyenne annuelle ne serait pas entachée d'une trop grande erreur.

Une donnée présentant une importance considérable est la vitesse maximum du vent possible en un site donné. Il est évident que pour la connaître il faut une étude de longue durée utilisant un enregistreur relié à un anémomètre. Ce dernier peut être du type à coupelles ou à hélice relié à un petit générateur électrique donnant un courant (proportionnel à la vitesse du vent) qui sera envoyé à un enregistreur. Une autre possibilité est l'utilisation d'un anémomètre du type Dines à tube de Pitot, qui, lui, possède son propre mécanisme d'enregistrement.

Le constructeur d'un appareil éolien a besoin de connaître cette vitesse maximum du vent, car c'est elle qui détermine les efforts auxquels doit résister l'installation. La difficulté de déterminer la vitesse maximum ne consiste pas dans le choix de l'appareil à utiliser — bien que plus un instrument est sensible plus la vitesse maximum enregistrée sera grande —, mais dans le choix du temps pendant lequel l'enregistrement doit être fait et dans l'estimation de la probabilité qu'une vitesse maximum donnée se produise au cours d'un certain nombre d'années.

Deux nouveaux instruments créés spécialement à l'occasion des essais de l'aérogénérateur danois de Gedser de 200 kW, mais utilisés également sur plusieurs autres sites, sont décrits par Jensen (mémoire W/14). Ces instruments servent à mesurer respectivement la répartition de l'énergie du vent

par rapport à différentes vitesses et à la pression du vent produite par la vitesse maximum

Mesures de durée moyenne

Ces mesures diffèrent de celles décrites plus haut non pas tant au point de vue des appareils utilisés — en fait les mêmes types d'anémomètres peuvent servir — que par le but qu'elles visent et par la durée totale. Dans ce groupe entrent les mesures servant à la détermination de la distribution verticale et horizontale de la vitesse du vent aux sites étudiés, mesures qui donnent simultanément la direction des vents. La direction du vent, bien que n'étant pas en général de première importance pour les installations éoliennes, est intéressante à connaître en ce qui concerne la stabilité du vent — un relief tourmenté coupant le vent peut provoquer une turbulence au site choisi, et d'autre part, si la direction du vent est particulièrement constante, il peut se faire qu'il soit avantageux de supprimer le dispositif d'orientation de l'installation éolienne, diminuant ainsi son prix.

Frenkiel (mémoire W/33), dans son étude très complète sur les courants aériens au-dessus des collines, donne le résultat des mesures de la vitesse du vent, de la direction de celui-ci et des températures à différentes hauteurs au-dessus du sol en vue de présenter les données les plus complètes possibles sur l'effet des conditions topographiques sur le gradient moyen vertical du vent. Les résultats obtenus montrent que pour une direction de vent donnée, ce gradient est indépendant de la force du vent, du moins dans les limites d'utilisation normale des installations éoliennes. Cette constatation présente un très grand intérêt.

Les mesures du vent de durée moyenne servent également à l'étude des variations de la vitesse du vent au cours de la journée. L'existence d'un vent utilisable à un moment donné de la journée présente un grand intérêt au point de vue de l'utilisation de l'énergie produite et de l'accumulation nécessaire pour pallier les périodes sans vent. Les graphiques quotidiens obtenus à l'aide de l'anémomètre Dines à tube de Pitot, utilisé normalement par les services météorologiques, donnent des indications complètes sur ces variations; cependant cet instrument est cher et ne convient pas particulièrement bien pour les mesures à effectuer en un site isolé où l'on en dispose pas de personnel qualifié.

Mesures de courte durée

Des mesures de la variation de la vitesse du vent pour des périodes de quelques minutes, de quelques secondes ou même d'une fraction de seconde sont indispensables pour les essais de rendement des installations éoliennes. Pour ces mesures, il est nécessaire de disposer d'instruments à réponse suffisamment rapide pour qu'une augmentation soudaine et momentanée de la vitesse du vent, ne durant parfois qu'un temps très court, soit enregistrée. Ce temps de réponse doit correspondre, en fait, à la durée d'une rafale de vent pouvant agir sur l'appareil. Un vent violent pendant une fraction de seconde pourrait ne pas apporter assez d'énergie pour agir d'une façon sensible sur l'appareil, mais si la durée est un peu plus grande ce vent de vitesse maximum peut avoir des effets suffisamment importants pour qu'il soit utile de les mesurer.

Ces rafales de vent influencent l'installation tant au point de vue électrique qu'au point de vue mécanique : la production d'énergie électrique peut être augmentée tandis que les tensions dans les pales du rotor et dans d'autres éléments de l'installation sont accrues.

Dans les travaux de recherche et de mise au point d'un nouveau type de générateur éolien, les essais donnant la courbe de production d'énergie en fonction de la vitesse du vent sont essentielles, et la question se pose de savoir comment ces deux variables doivent être mesurées. Certains chercheurs emploient un wattmètre et un anémomètre du type normal, tandis que d'autres mesurent la production d'énergie pendant quelques minutes et la vitesse moyenne du vent pendant la même période.

Les résultats obtenus à l'aide de ces méthodes forment généralement sur le graphique un « nuage » de points à partir desquels on peut tracer la courbe caractéristique. L'étude poussée du rendement d'un générateur éolien, indispensable pour déceler l'effet de légères modifications expérimentales dans sa construction, nécessite des mesures effectuées à l'aide d'instruments à réponse rapide tant pour la puissance électrique produite qu'au point de vue de la vitesse du vent. L'anémomètre à sphère mobile pour vents turbulents mis au point à cet effet par l'Electrical Research Association de Grande-Bretagne est décrit par Tagg (W/12). En plaçant l'anémomètre de turbulence à la hauteur de l'axe du rotor du générateur éolien, à une distance égale à plusieurs diamètres du rotor face au vent, il est possible, comme l'expérience l'a montré, d'obtenir une très bonne corrélation entre les variations très rapides de la vitesse du vent et les variations correspondantes de la production d'énergie.

Pour étudier, à l'aide de jauges de tension, les tensions produites dans les pales du rotor par un vent d'intensité variable, on peut utiliser la même méthode de mesure de la vitesse du vent.

Argand (mémoire W/35) décrit un nouveau type d'anémomètre à réponse rapide et d'appareillage d'enregistrement servant à mesurer les variations rapides de la vitesse et de la direction du vent; ces appareils présentent un grand intérêt, et il est certain qu'ils seraient très utiles pour l'étude du rendement d'un grand générateur éolien. Il est intéressant de faire remarquer que pour l'enregistrement on utilise la méthode photographique.

Utilisation des données météorologiques

Lorsqu'on étudie les méthodes à utiliser pour l'étude du vent, spécialement quand il s'agit de la production d'énergie éolienne, il ne faut pas oublier

qu'un grand nombre de renseignements intéressants sur la vitesse et la direction du vent existent déjà dans les archives des services météorologiques nationaux. Il est évident que ces renseignements ne sont pas établis en fonction des besoins des éoliens : ils concernent le régime des vents pour l'ensemble de la zone entourant la station d'observation et non pas les sites particulièrement favorables du point de vue éolien. Cependant, d'une façon générale, ce sont des données sûres, se rapportant à une longue période, et il ne faut pas les négliger simplement parce qu'aux sites choisis la vitesse moyenne du vent est souvent plus grande qu'à la station météorologique.

Les mémoires présentés par l'Organisation Météorologique Mondiale (W/11), par Ramakrishnan et Venkiteshwaran (W/19), par Barasoain et Fontán (W/16), par Cambilargiu (W/10) et par Soliman (W/4) donnent tous des informations précieuses sur la vitesse du vent dans différentes parties du monde, du point de vue autant que possible des possibilités d'installations éoliennes dans ces régions.

Les données météorologiques que nous possédons ainsi peuvent servir aux fins suivantes :

a) Comme départ pour l'étude des vents, en montrant les zones où la vitesse du vent est la plus grande;

b) Comme indication sur la direction du vent dominant — question importante pour le choix des sites;

c) En indiquant dans quelle mesure la valeur moyenne annuelle de la vitesse du vent varie ou reste constante d'une année à l'autre;

d) Pour donner une idée du régime annuel des vents dans une région, par les valeurs moyennes mensuelles de la vitesse du vent;

e) Comme indication des variations de la vitesse du vent au cours de la journée aux différentes saisons;

f) Pour l'estimation des maximums de vitesse et de la durée des accalmies qui peuvent se produire.

L'utilité des données météorologiques dépend évidemment de leur précision et du nombre d'années sur lesquelles elles s'étendent. Les diagrammes de la vitesse et de la direction du vent enregistrés par exemple à l'aide de l'anémomètre Dines à tube de Pitot, s'ils couvrent un certain nombre d'années, pourront satisfaire aux exigences des six points indiqués ci-dessus, tandis que des enregistrements de longue durée à partir de simples anémomètres à coupelles ne peuvent servir qu'aux usages indiqués, aux points *a*, *c* et *d* — et éventuellement au point *e*, au cas peu probable où des relevés suffisamment fréquents ont été faits.

Une grande partie de ces renseignements est applicable directement à l'étude des vents du point de vue de l'énergie éolienne, car dans ses grandes lignes le régime des vents relevé pour une zone pourra s'appliquer pour les différents sites de cette zone. Les valeurs qui peuvent différer d'une façon sensible pour un site donné de celles relevées à la station météorologique la plus proche sont la vitesse moyenne annuelle du vent, le maximum de la vitesse du vent et la durée des accalmies. Évidemment ces trois valeurs sont de la plus grande importance pour estimer la production d'énergie d'une installation éolienne en projet, pour calculer la résistance aux tensions provoquées par le vent et pour estimer les périodes pendant lesquelles on peut compter sur une production d'énergie suffisante, c'est-à-dire pour estimer l'importance de l'accumulation nécessaire.

Le mieux est donc d'utiliser le plus largement possible les données météorologiques de longue durée et de les compléter par les renseignements obtenus grâce à des appareils de mesure comme ceux décrits dans les mémoires présentés. De cette façon, on obtient les renseignements les plus complets possible sur le comportement des vents pour les sites qui semblent le plus favorables à la production d'énergie éolienne.

Étude des vents et choix des sites

L'étude des vents en certains endroits particuliers a pour objet principal la recherche de sites où le vent est particulièrement fort et où l'installation de générateurs éoliens présente le plus d'intérêt. Dans cette recherche, il faut d'abord prendre en considération les données topographiques. L'existence de routes ou de chemins d'accès, ou la possibilité d'en construire, et la distance des sites aux centres d'habitation où l'énergie produite pourrait être utilisée sont des questions secondaires mais qui présentent encore de l'importance.

L'augmentation de la vitesse du vent à mesure que l'on s'élève au-dessus du sol est un phénomène bien connu, de sorte que si l'on envisage de construire des installations éoliennes en plaine, où aucune colline n'existe, la seule possibilité d'augmenter la production d'un appareil de type donné muni d'un rotor d'un diamètre déterminé est d'augmenter la hauteur de la tour qui le supporte. Ceci entraîne nécessairement une augmentation du coût de l'installation et par conséquent du prix de revient de l'énergie produite. Pour déterminer si une augmentation de la hauteur de la tour de support se justifie du point de vue économique, il faut comparer cette augmentation des investissements avec l'augmentation de production possible.

Si la région dans laquelle on désire installer des appareils éoliens est vallonnée, il faut évidemment choisir des sites au sommet des collines et profiter ainsi de leur altitude par rapport à celle du terrain environnant pour « capter » les courants aériens plus rapides qui règnent à cette altitude. Il ne suffit pas cependant de choisir une colline quelconque. Des collines près d'une côte, spécialement si le vent dominant souffle de la mer, sont en général favorables, tandis que les collines à l'intérieur des terres, si elles sont entourées à proximité d'autres collines de même altitude, peuvent n'avoir qu'une vitesse moyenne du vent relativement faible; de plus, le

courant aérien peut souvent être dans ce cas perturbé par le relief tourmenté environnant. Une augmentation vraiment sensible de la vitesse moyenne du vent par rapport à une plaine environnante peut être obtenue en choisissant une colline ayant un profil favorable qui, agissant comme entonnoir, provoque une accélération du courant aérien au-dessus du sommet. Ceci revient à dire que la vitesse du vent constatée peut être plus grande que celle du vent qui régnerait à la même altitude mais au-dessus d'un terrain plat, s'il était possible de la mesurer. Autrement dit, la vitesse moyenne du vent peut être plus grande que celle due à la seule altitude; il se produit, comme on l'a appelé, un « phénomène d'accélération » dû à la forme de la colline.

Qu'il faille s'attendre à un phénomène de ce genre avait déjà été reconnu, il y a quelque vingt ans, par P.C. Putnam et ses collaborateurs lors du projet éolien américain de Grandpa's Knob, et les observations qu'il a été possible de recueillir depuis par l'étude des vents en Grande-Bretagne et dans d'autres pays à l'aide de méthodes semblables tendent à confirmer cette théorie. Il est très difficile cependant de prouver de façon certaine que cet effet d'accélération se produit en un site donné, et notre section de la Conférence a la chance de disposer des mémoires (W/26) et (W/28) préparés sur cette question respectivement par Petterssen et Lange, qui tous deux ont participé au projet de Grandpa's Knob. Ces mémoires peuvent utilement orienter le choix des sites, tant du point de vue théorique que du point de vue pratique.

Jusqu'à présent, le choix des sites favorables a été plus un art qu'une science : les collines favorables pour l'installation d'appareils éoliens ont été choisies après inspection du terrain, compte tenu de leurs formes apparemment favorable — des pentes assez fortes mais régulières — et de la configuration des terrains environnants. Bien qu'on ait beaucoup écrit au cours des dernières décennies sur l'écoulement des masses d'air au-dessus des collines, nous disposons de peu de renseignements sur les facteurs qui influencent la vitesse du vent au-dessus des sommets de collines de formes différentes, de sorte que le choix des sites favorables est resté pour les éoliens une question de bon sens et de jugement, c'est-à-dire « d'intuition intelligente ».

Avec le temps, les éoliens ont acquis une expérience utile et un certain savoir-faire, et cependant des échecs inattendus se produisent encore. Quelques-uns de ces échecs sont dus en toute probabilité au fait que, malgré une forme générale favorable, la colline présente un sommet trop plat, de sorte que le courant aérien passe à une hauteur plus grande que celle où se trouve l'instrument de mesure, qui enregistre ainsi un courant aérien relativement lent.

En même temps que le phénomène d'accélération, on constate au-dessus du sommet une diminution du gradient vertical de la vitesse du vent : la vitesse du vent n'augmente pas en fonction de la hauteur autant que lorsque le courant aérien passe au-dessus d'un terrain plat. Frenkiel, dans son mémoire (W/33), donne les résultats de son étude expérimentale qui a porté sur les collines en falaises et sur les collines de forme conique; il propose dans dans sa conclusion d'utiliser le gradient vertical du vent au sommet de la colline comme mesure quantitative pour le choix des sites.

Ces trois derniers mémoires, de même que celui (W/7) présenté par Ballester, dans lequel on trouve une analyse extrêmement utile de la théorie et de la pratique des relevés éoliens, constituent indiscutablement un apport important à nos connaissances sur la question.

Sujets de discussion proposés

Dans les mémoires présentés, on trouve un grand nombre de points de détail qu'il serait intéressant de discuter, mais il semble préférable de se borner à examiner quatre questions principales :

a) Dans quelle mesure peut-on se fonder sur les données météorologiques de longue durée et les données fournies régulièrement par les stations météorologiques sur la vitesse du vent pour estimer les ressources éoliennes d'une région donnée?

b) Quels types d'appareils de mesure (instruments eux-mêmes et montage au-dessus du sol) faut-il recommander pour l'étude des vents?

c) Quel est le degré de normalisation des méthodes de mesure et d'analyse des résultats qu'il serait souhaitable d'adopter sur le plan international pour faciliter l'échange des données sur le comportement des vents?

d) Est-il possible actuellement, à partir des mémoires présentés (notamment W/26, W/28 et W/33), de préciser les critères à utiliser pour choisir les sites favorables à l'installation d'aéromoteurs?

STUDIES OF WIND BEHAVIOUR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

Rapporteur's summation

Session II.B.1, on wind measurements and the selection of wind power sites, provided us, through the remarks of many contributors to the discussion, with a very comprehensive review of the present state of the art, of the accomplishments and of the deficiencies. Because the whole subject of wind measurement for power purposes is basic, as a beginning for wind developments in any area, we should try to obtain a clear statement on it as a guide to those who are considering the possibilities of this form of power. The discussion ranged over all forms of wind-measuring installations, for different purposes, and their relationship to existing wind data from the meteorological services, as well as over many points concerning the selection of favourable sites and the testing of machines. It is important now to separate these questions and to place them in their proper perspective.

In the first place, we must distinguish between the measuring methods which should be followed by those undertaking a wind survey for the first time and those which are already being followed by investigators who have had considerable experience and who have in mind the installation of large wind-driven machines, the characteristics of which must be tested under operating conditions. Both the instruments used, and the methods of installing them and analysing the results of measurements, are quite different.

For a general wind survey, with selected wind power sites, we need simple and cheap instruments, easily installed and maintained and affording only basic information on the wind régimes at the different sites to enable comparisons of their relative favourability to be made. On the other hand, when wind data is needed for the study of the performance of an installed machine of large power capacity or even — at an experimental research station — to obtain detailed information for design purposes, we need a much more elaborate installation, perhaps with a number of wind-measuring instruments placed at different heights above ground and having different response times.

As a guide on survey methods, some straightforward recommendations can certainly be made and this might be considered to be the most important object of session II.B.1. of the Conference. The most elaborate wind-measuring instruments and methods, at present, are of interest to a limited number of research workers who have already developed their own methods which can be discussed, on a semi-private basis, between the groups in the few countries concerned.

Wind survey methods

The first procedure is to choose the areas which are most likely to be windy. The long-period records from the meteorological services can be used as a guide — but only as a guide — for this purpose. Records for meteorological stations not chosen because of their especially high wind régime cannot take the place of measurements at selected sites, which may be capable of giving two or three times the annual energy which would be indicated by the meteorological station records. Those contributors who have made estimates of available wind energy in their countries, using such records, have shown their inadequacy. Although the discussion showed that synoptic records of wind speed can be useful, it is very important that, in all data from the meteorological services, both the precise method of making the measurement (including the type of instrument and method of taking the reading) and the height above ground of the instrument should be clearly stated.

If, in the areas considered, there are hills of shapes which will give unusually high winds over their summits — and information on the choice of these hills has been given in several papers — they should be selected for studies. There can be no doubt that a simple counter-type of cup anemometer should be used in the preliminary measurements. It has all the advantages of simplicity, robustness, cheapness and ease of reading to afford results which need no analysis.

If we know the annual run-of-wind at the selected sites, we know the suitability of those sites for wind power. It is pointless to attempt to install anything more elaborate than this instrument when making an initial assessment of the wind power potentialities of an area.

As for the height above ground at which the instrument should be placed, this need be no more than 3 metres if the site is on a suitably shaped hill-top without obstructions, because then the wind speed increases only very slowly with height. If the ground is flat, on the other hand, a height of 10 metres should be used. It must be remembered, however, that at 3 metres, the instrument can be

read by a person standing on the ground, whereas at 10 metres it can be read only by climbing the mast.

For a second stage of a wind survey, when the wind régime at certain sites is to be measured because, as a result of measurements for a relatively short period (a few months), they have been found generally favourable, hourly mean wind speeds should be measured by a cup-contact anemometer and a chart, or tape, recorder. Analysis of the results gives the velocity-duration curve, from which annual energy estimates can be made, and indicates also diurnal variations of wind speed, as well as the duration of calm spells and the magnitudes of maximum hourly mean wind speeds.

Instruments, such as that made by the Compagnie des Compteurs de Montrouge, which measure an integrated total of wind energy within certain limits of accuracy are useful in giving a general indication of the relative windiness of sites if they are well located, in exposed positions without obstructions. They can be read at infrequent intervals, but they do not give the information which is needed for more precise estimates of annual energy obtainable, nor do they enable measurements to be made of the duration of calm spells, the diurnal variations of wind speed or maximum hourly wind speeds. These first two stages of a survey are concerned merely with wind régimes at sites.

A further stage of measurement is useful, and perhaps necessary, when it has been decided to consider a particular site in more detail in relation to a machine which might be installed there. Then, measurements of hourly mean wind speeds, or average wind speeds for shorter periods, together with wind directions, can be made at different heights above ground, particularly at that corresponding to the hub-height of the windmill to be installed. This is more important on hill-top sites than on flat ground. Measuring installations of this kind are expensive. Over level country, the rate of increase of mean wind speed with height above ground is well enough known for such measurements to be unnecessary.

The question of the height of the instrument above ground in relation to nearby obstructions can be answered by saying that such obstructions influence wind measurements in a way which cannot be stated with any precision. It is safest to measure as far as possible away from any obstructions. If measurements must be made close to, say, a group of trees or buildings, the higher the instrument above them the better. No general method of correcting for the effect of ground obstacles can be depended upon for accuracy.

One can summarize the position as follows.

(*a*) 1st-stage survey: Cup-counter anemometers should be used, mounted at 3 metres above ground on hill-tops or 10 metres above flat ground and used for a period of only a few months.

(*b*) 2nd-stage survey: Cup-contact anemometers, at the same heights as in (*a*) above, should be used with some form of simple recorder from which hourly mean wind speeds can be obtained easily.

(*c*) Wind behaviour at selected sites: Measurements of mean hourly (or shorter period) wind speeds and of wind directions can be made at various heights above ground up to at least the hub-height of the wind power machine to be installed. Such measurements are more important on hill-top sites than on level ground.

(*d*) Short-period measurements: These measurements, to determine the detailed structure of the wind, the maximum values of gust speeds and the wind distribution in both the vertical and horizontal planes, are made by means of quick-response instruments and recorders which differ with the investigator and with his purpose in making them. They are elaborate and costly and are, in the main, useful only at a wind research station where skilled staff, with full laboratory facilities, are available. Their object is to study design questions rather than the general performance of an installation.

In wind survey work, it must be borne continually in mind that, whilst the choice of good hill sites can increase the available energy by perhaps 200 or 300 per cent in relation to that obtainable on lower ground nearby, extreme accuracy is not necessary. Errors of, say, $\pm$ 5 to 10 per cent would not usually be serious and the elimination of such errors might be prohibitively costly in a widespread survey.

Site selection remains as a difficult question from the theoretical point of view, although several papers at the session gave very valuable guidance. It appears doubtful whether measurements based on such theory can, in practice, take the place of intelligent choice of sites, bearing in mind the requirements of good exposure and smoothly shaped hills with fairly steep slopes but without precipitous faces or ground obstacles.

Standardization of methods of measurement, as far as possible, is desirable for the interchange of information and the recommendations made above aim in this direction. Certainly the type of instrument used, the method of using it and of analysing the results and its height above ground should always be stated.

General requirements

Turning to more general questions, beyond the scope of session II.B.1, three points should be emphasized.

(*a*) The most important requirement in wind power development, at the present time, is to make the two participants in such developments, namely, the possible manufacturers of the plants and the potential users of these plants, much better aware of the possibilities. On the one hand, the manufacturer, busy with many good profit-earning products, is discouraged by apparent lack of demand for wind power plants, and, on the other hand, people who

badly need power in the developing countries are not aware of what could be done by its use if properly organized.

(*b*) In many areas in non-industrialized countries, the inhabitants are unaccustomed to the use of machines as an aid to their own labour and, also, they cannot at present afford to buy elaborate and costly machines. The possibilities of introducing to such areas simple, even crude, machines, easily operated and repaired, should be studied as an urgent question. Local materials and local labour — with proper instruction — could often be used. It is much more important to introduce some kind of machine, even if it is inefficient, provided that it is cheap, than to insist on a refined and efficient, though costly, power plant.

(*c*) Some kind of international organization — committee, working group or association — for the continual exchange of information on wind power developments is badly needed. Much of its work could be done by correspondence, but occasional meetings should be held. A really effective, though simple, newsletter, regularly issued, could keep all interested people and organizations informed on progress and requirements.

Although, in the past, some facilities have been given for the exchange of such information (e.g. by the World Power Conference and by UNESCO through its Arid Zone Research Advisory Committee), these are quite inadequate. Wind power is a sufficiently important subject, especially for the developing countries short of power, to merit the establishment of its own means of communication. It should not have to depend upon the very limited facilities which organizations with more general interests are occasionally prepared to afford — more out of good will than of real conviction that wind power is of true significance.

ÉTUDE DU COMPORTEMENT DES VENTS ET RECHERCHE DE SITES APPROPRIÉS POUR DES INSTALLATIONS ÉOLIENNES

Résumé du rapporteur

L'examen du point II.B.1 concernant l'anémométrie et le choix des emplacements pour les installations éoliennes a permis, grâce aux observations présentées par un grand nombre de participants, de se faire une idée très complète de la situation actuelle, des résultats obtenus, ainsi que des lacunes. Étant donné que la question de l'anémométrie en vue de la production d'énergie présente un intérêt capital lorsqu'on veut entreprendre l'utilisation de l'énergie éolienne, il faut essayer d'établir un exposé clair de la question, dont pourront s'inspirer ceux qui envisagent d'utiliser cette forme d'énergie. La discussion a porté sur tous les types d'installations anémométriques utilisés à des fins diverses et sur les rapports existants entre les renseignements obtenus au moyen de ces installations et les données anémométriques fournies par les services météorologiques; elle a porté également sur de nombreuses questions concernant le choix d'emplacements favorables et l'utilisation expérimentale des machines. Il y a lieu maintenant de sérier les questions et de les placer dans la perspective qui convient.

Il faut tout d'abord établir une distinction entre les méthodes de mesure que doivent adopter ceux qui entreprennent une enquête anémométrique pour la première fois et les méthodes déjà utilisées par des enquêteurs très expérimentés qui envisagent l'installation de grandes éoliennes dont les caractéristiques doivent être éprouvées dans des conditions normales d'exploitation. Les instruments utilisés, ainsi que les modes d'installation et les méthodes employées pour analyser les mesures obtenues sont très différents.

Une enquête anémométrique de caractère général, effectuée aux emplacements choisis en vue de l'installation éventuelle de centrales éoliennes, n'exige que des instruments simples et peu coûteux, faciles à installer et à entretenir, et permettant d'obtenir seulement des renseignements de base sur le régime des vents aux différents emplacements, de manière qu'on puisse comparer leurs avantages respectifs. En revanche, lorsqu'on a besoin de données anémométriques pour étudier le fonctionnement d'une machine installée de grande puissance, voire pour obtenir, dans une station de recherche expérimentale, des renseignements détaillés en vue de mettre au point le modèle à utiliser, il faut une installation beaucoup plus complexe comprenant, par exemple, plusieurs anémomètres placés à des hauteurs différentes au-dessus du sol et entrant en activité à des moments différents.

En ce qui concerne les méthodes d'enquête, on peut certainement formuler quelques recommandations simples, et c'est peut-être là l'objet le plus important de l'examen du point II.B.1 par la Conférence. A l'heure actuelle, les instruments et méthodes anémométriques n'intéressent qu'un petit nombre de chercheurs qui ont déjà mis au point leurs propres méthodes, lesquelles peuvent être étudiées, à titre semi-privé, par les groupes appartenant aux quelques pays intéressés.

Méthodes d'enquête anémométrique

Il faut tout d'abord déterminer les régions qui ont le plus de chance d'être venteuses. On peut recourir à cette fin aux observations recueillies par les stations météorologiques pendant une longue période de temps, mais seulement à titre d'indication. Les observations faites pour l'installation de stations météorologiques non retenues en raison du régime particulièrement élevé du vent ne peuvent remplacer les mesures effectuées en des emplacements choisis, qui peuvent permettre d'obtenir le double ou le triple de l'énergie annuelle que laisseraient prévoir les observations recueillies par les stations météorologiques. Les participants qui ont utilisé ces observations pour évaluer l'énergie éolienne disponible dans leur pays en ont indiqué l'insuffisance. La discussion a montré qu'il est peut-être utile de disposer d'un relevé synoptique des observations anémométriques, mais il est indispensable que, pour toutes les données fournies par les services météorologiques, on indique clairement la méthode précise utilisée pour effectuer les mesures (notamment le type d'instrument et le mode de lecture), ainsi que la hauteur de l'instrument au-dessus du sol.

S'il existe, dans les régions considérées, des élévations de terrain qui, par leur conformation, sont exposées à des vents exceptionnellement forts (plusieurs mémoires contiennent des renseignements sur le choix de ces élévations), celles-ci devraient faire l'objet d'une étude. Il est certain que, pour les mesures préliminaires, il faut utiliser un anémomètre simple à coupes et à compteur. Simple, robuste, peu coûteux et de lecture facile, il permet d'obtenir des résultats qui n'exigent aucune analyse.

Si l'on connaît le débit annuel du vent aux emplacements choisis, on sait si ceux-ci se prêtent à l'exploitation de l'énergie éolienne. Il est inutile d'installer un instrument plus compliqué que l'anémo-

mètre à coupes et à compteur pour obtenir une première évaluation du potentiel d'énergie éolienne d'une région donnée.

En ce qui concerne la hauteur, il suffit de placer l'instrument à trois mètres du sol s'il s'agit d'un emplacement situé au sommet d'une colline découverte de forme convenable, car, dans ce cas, la vitesse du vent n'augmente que très lentement avec la hauteur. En revanche, si le terrain est plat, il faut placer l'instrument à dix mètres du sol. Toutefois, il ne faut pas oublier qu'à trois mètres l'instrument peut être lu par une personne débout, tandis qu'à dix mètres il faut grimper au mât pour le lire.

Au second stade de l'enquête anémométrique, lorsqu'il devient nécessaire de mesurer le régime du vent à certains emplacements parce que, d'après les mesures effectuées pendant une période relativement courte (quelques mois), on les juge favorables dans l'ensemble, il faut mesurer la vitesse horaire moyenne du vent au moyen d'un anémomètre à coupes et à contact et d'enregistrements sur diagramme ou sur ruban. L'analyse des résultats obtenus permet de tracer la courbe des vitesses classées, d'après laquelle on peut évaluer l'énergie annuelle; elle indique également les variations diurnes de la vitesse du vent, ainsi que la durée des périodes de vent faible et l'ordre de grandeur des vitesses horaires maximales.

Des instruments comme ceux que fabrique la Compagnie des compteurs de Montrouge, qui permettent de mesurer l'énergie éolienne totale avec une certaine exactitude, peuvent donner des indications générales sur l'exposition relative des sites au vent, à condition d'être placés convenablement sur un terrain exposé au vent et dépourvu d'obstacles. Il n'est pas nécessaire de relever les mesures fréquemment, mais ces instruments ne fournissent pas les renseignements nécessaires à des estimations plus précises de l'énergie disponible annuellement, et ne permettent de calculer ni la durée des périodes de vent faible, ni les variations diurnes de la vitesse du vent, ni les vitesses horaires maximales. Ces deux premières phases de l'enquête ne portent que sur le régime des vents aux différents emplacements.

Des mesures plus détaillées sont utiles, et même nécessaires, lorsqu'on a décidé d'étudier d'une manière plus approfondie un emplacement particulier en vue d'y installer éventuellement une machine. Dans ce cas, on peut relever les vitesses horaires moyennes ou les vitesses moyennes pendant une période plus brève, ainsi que l'orientation des vents, à différentes hauteurs au-dessus du sol, notamment au niveau du moyeu de l'éolienne à installer. Ceci est plus important pour les emplacements situés sur des hauteurs qu'en terrain plat. Les installations anémométriques de ce type sont coûteuses. En terrain plat, le taux d'accroissement de la vitesse moyenne du vent en fonction de la hauteur au-dessus du sol est assez bien connu pour qu'il ne soit pas nécessaire d'effectuer ces mesures.

En ce qui concerne la question de la hauteur de l'instrument au-dessus du sol en relation avec des obstacles voisins, tout ce que l'on peut dire, c'est qu'il n'est pas possible de préciser jusqu'à quel point ces obstacles influent sur les mesures anémométriques. Le plus sûr est d'effectuer les mesures loin de tout obstacle. Si les mesures doivent être faites près d'un arbre ou d'un groupe de bâtiments, il est préférable de placer l'instrument le plus haut possible. Il n'existe aucune méthode générale permettant de compenser exactement l'effet des obstacles au sol.

La situation peut se résumer de la manière ci-après.

a) Première phase de l'enquête : il faut utiliser, pendant quelques mois seulement, des anémomètres à coupes et à compteur situés à 3 mètres au-dessus du sol sur les hauteurs ou à 10 mètres en terrain plat.

b) Deuxième phase de l'enquête : il faut utiliser des anémomètres à coupes et à contact situés aux hauteurs indiquées dans l'alinéa *a*) ci-dessus, ainsi qu'un type quelconque d'enregistreur simple permettant d'obtenir facilement les vitesses horaires moyennes du vent.

c) Comportement du vent aux emplacements choisis : on peut mesurer la vitesse moyenne du vent à l'heure (ou pendant des périodes plus brèves) et l'orientation des vents à diverses hauteurs au-dessus du sol, au moins jusqu'au niveau du moyeu de l'éolienne à installer. Ces mesures revêtent plus d'importance sur les hauteurs qu'en terrain plat.

d) Mesures pendant des périodes de brève durée : ces mesures, qui permettent de déterminer les caractéristiques précises du vent, la vitesse maximale pendant des rafales, ainsi que la répartition du vent sur les plans vertical et horizontal, sont effectuées au moyen d'instruments et d'enregistreurs très sensibles, qui varient selon l'enquêteur et l'objectif visé par celui-ci. Ces appareils complexes et coûteux ne sont utiles, dans l'ensemble, que dans des stations de recherche anémométrique qui disposent d'un personnel spécialisé et de laboratoires tout équipés. Ils servent à étudier les questions de modèles à adopter putôt que le fonctionnement général d'une installation.

Dans les enquêtes anémométriques, il ne faut jamais oublier que, si le choix de bons emplacements élevés peut accroître l'énergie disponible de quelque 200 ou 300 p. 100 par rapport à celle que l'on pourrait obtenir dans les terrains moins élevés situés à proximité, l'exactitude absolue n'est pas nécessaire. Des erreurs de l'ordre de 5 à 10 p. 100 en plus ou en moins ne seraient, en général, pas très graves et, dans une enquête de grande envergure, il serait extrêmement coûteux de vouloir les éliminer.

Le choix du site demeure, du point de vue théorique, une question difficile à régler, bien que plusieurs mémoires présentés au cours de son examen aient donné de précieuses indications. Il semble douteux que des mesures effectuées en fonction des théories puissent remplacer, dans la pratique, un choix judicieux des sites, c'est-à-dire d'emplacements

situés sur des hauteurs bien exposées, de conformation régulière et ayant des pentes assez abruptes, mais sans escarpements ni obstacles.

Une normalisation aussi complète que possible des méthodes de mesure faciliterait l'échange des renseignements; les recommandations présentées plus haut ont été conçues à cette fin. Il ne fait aucun doute que le type d'instrument utilisé, son mode d'emploi, la méthode d'analyse des résultats et sa hauteur au-dessus du sol devraient toujours être indiqués.

Conditions générales

Si l'on aborde des questions d'ordre plus général qui dépassent le cadre de l'examen du point II.B.1, il convient de souligner les trois points ci-après.

a) Si l'on veut assurer la mise en valeur de l'énergie éolienne, il faut avant tout obtenir, au stade actuel, que les deux parties intéressées — à savoir les fabricants et les utilisateurs éventuels des installations — soient beaucoup mieux renseignées sur les possibilités qui se présentent. Le fabricant, occupé à manufacturer de nombreux produits d'un bon rapport, est découragé par l'absence apparente de demande de centrales éoliennes; d'autre part, les populations des pays en voie de développement, qui ont le plus grand besoin d'énergie, ignorent les avantages qu'elles pourraient tirer d'une exploitation rationnelle de l'énergie éolienne.

b) Dans de nombreuses régions des pays non industrialisés, les habitants ne sont pas habitués à utiliser des machines pour alléger leur travail, et n'ont pas actuellement les moyens de se procurer des machines complexes et coûteuses. Il faudrait étudier d'urgence la possibilité de doter ces régions de machines simples, voire rustiques, faciles à faire fonctionner et à réparer. Dans bien des cas, on pourrait utiliser des matériaux locaux et faire appel à la main-d'œuvre que l'on trouve sur place, après lui avoir donné les instructions nécessaires. Il vaut beaucoup mieux installer une machine quelconque, même de faible rendement, à condition qu'elle soit peu coûteuse, que de vouloir installer une centrale perfectionnée et de rendement élevé, mais onéreuse.

c) Il est indispensable de créer un organisme international — qu'il s'agisse d'une commission, d'un groupe de travail ou d'une association — chargé d'assurer l'échange permanent de renseignements sur l'utilisation de l'énergie éolienne. Cette organisation pourrait effectuer la plupart de ses travaux par correspondance, mais des réunions devraient être convoquées de temps à autre. Un bulletin d'information, simple mais véritablement efficace et publié régulièrement, pourrait tenir toutes les personnes et organisations intéressées au courant des progrès et des besoins.

On a bien eu, jusqu'à présent, certaines occasions de procéder à des échanges de renseignements de ce genre (notamment grâce à la Conférence mondiale de l'énergie et au Comité consultatif de recherches sur la zone aride, de l'UNESCO), mais elles ont été tout à fait insuffisantes. La question de l'énergie éolienne revêt assez d'importance, notamment pour les pays en voie de développement où l'énergie fait défaut, pour qu'il soit justifié d'établir à cet égard un moyen d'échange spécialisé. Elle ne devrait pas dépendre des moyens très limités que des organisations s'occupant de problèmes plus généraux sont disposées à fournir de temps à autre — par bonne volonté plus que par une réelle conviction de l'importance effective de l'énergie éolienne.

MESURE DES PARAMÈTRES CARACTÉRISTIQUES DE L'ÉNERGIE ÉOLIENNE EN VUE DU CHOIX DES SITES FAVORABLES A L'INSTALLATION D'AÉROMOTEURS

André Argand *

La puissance contenue dans le vent est le produit d'une variable de tension par une variable de débit. La variable de tension est la différence des pressions instantanées du vent avant et après que celui-ci ait travaillé à renverser un édifice, à propulser un bateau à voiles ou à entretenir la vitesse de rotation des organes mobiles d'un aéromoteur. Elle est donc liée notamment à la masse spécifique de l'air ρ et au carré de la vitesse de cet air en avant de l'obstacle. Le débit, dans le cas particulier d'un aéromoteur, est proportionnel à la surface balayée S et à la vitesse de l'air qui traverse ladite surface.

On ne pourrait pas mesurer facilement ces vitesses que la présence de l'aéromoteur perturbe; aussi cherche-t-on plutôt à mesurer des vitesses du vent V représentatives, le moins inexactement possible, de la puissance éolienne.

S'il s'agit de la prospection des sites venteux d'une région, on mesurera par exemple la vitesse du vent au centre de la surface balayée par les organes en rotation d'un aéromoteur, « mais en l'absence de cet appareil » (1, page 2, nº 102).

S'il s'agit au contraire de déterminer le rendement de l'aéromoteur déjà érigé, on est souvent amené « à mesurer la demi-somme des vitesses dans le plan perpendiculaire au vent », passant par l'appareil, « à des distances suffisantes à droite et à gauche de celui-ci » (2, page 4, nº 6-1).

Rappelons d'ailleurs qu'un raisonnement simplifié, mais qui a jusqu'à ce jour semblé correspondre suffisamment à la réalité, permet de démontrer (3) que la puissance théoriquement récupérable par un aéromoteur à hélice éolienne d'axe horizontal est :

$$P_{\max} = \left(\frac{\rho}{2} \times V^2 \times \frac{8}{9}\right) \left(S \times V \times \frac{2}{3}\right)$$

Mesure des paramètres caractéristiques de la puissance du vent — Présentation des résultats

Masse spécifique de l'air

Tout au long de l'année 1956 à Saint-Cyr-l'École, Seine-et-Oise, en un point situé à 165 mètres d'altitude au-dessus du niveau de la mer (ce qui semble correspondre à une assez bonne moyenne tant des positions des divers aéromoteurs actuels et futurs en France et même autour du globe terrestre, que des températures ambiantes correspondantes), des calculs systématiques de la masse spécifique de l'air ont été effectués à l'aide des indications d'un baromètre à mercure, d'un thermomètre sec et d'un thermomètre mouillé. Le nombre total des lectures simultanées de ces trois appareils s'est élevé à 462. Les résultats moyens ont été les suivants : 1,231 kg-masse par mètre cube d'air le matin et 1,216 à la fin de l'après-midi.

La masse spécifique de l'air à Saint-Cyr-l'École s'est avérée être en moyenne plus élevée d'environ 5 p. 100 pendant les mois d'hiver que l'été, avec les valeurs extrêmales suivantes : 1,336 un matin de février 1956 et 1,146 un soir de juin et un soir de septembre, ce qui donne un rapport maximal hiver sur été de 1,16 environ.

Une valeur moyenne généralement adoptée en France est $\rho = 1{,}250$ kg-masse par mètre cube d'air (4, page 550; 5, page 5; 2, page 4, paragraphe 6-3). Putnam (6, page 33), à 600 mètres d'altitude (Grandpa's Knob, États-Unis), qui fit des mesures pendant cinq ans, trouva 1,201 kg, tandis que d'autres expérimentateurs du même pays (7, page 825-3) ont pris, par sécurité disaient-ils, 1,281. Les Britanniques (8, page 23) choisissent 1,290 kg et les Brésiliens (9, page 10) 0,116 (valeur calculée dans le système mètre, kg-force, sec). En Uruguay (10, page 1) et en URSS (11, page 127), il semble qu'on préfère 0,125 (dans ce même système d'unités).

C'est approximativement aussi cette dernière valeur $\frac{1}{8}$ qu'on emploie en Italie (12, page 137), tandis qu'au Danemark (13, page 321) on a adopté $\frac{1{,}22}{9{,}81}$ et en Suisse (14, page 81) 0,12. Voir ci-dessous « Normalisation souhaitable ».

Vitesses du vent

Parmi les principaux anémomètres actuellement employés, nous trouvons divers types.

Anémomètres adirectionnels, type Robinson, tournant à l'emballement autour d'un axe vertical et mesurant la vitesse du vent

Le plus employé en France et dans la Communauté, notamment par les météorologistes, est l'anémomètre à coupelles du Colonel Papillon. Un autre est l'anémomètre à gouttières (figure 1) construit depuis une

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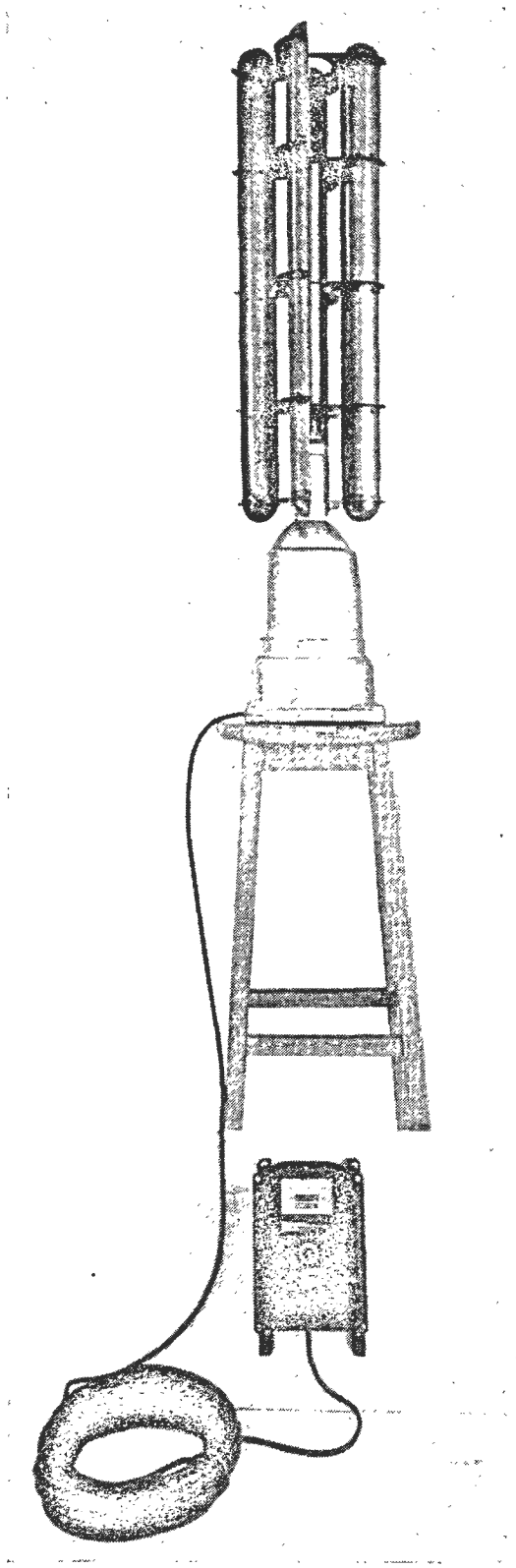


Figure 1. Anémomètre à compteur d'énergie éolienne

quinzaine d'années par la Compagnie des compteurs de Montrouge (15) à la demande de M. Ailleret, directeur général adjoint d'Électricité de France (5, page 6). Les constantes de temps de ces anémomètres vont de une à quelques secondes.

Par lectures directes ou photographiques, effectuées à des époques autant que possible préétablies, des indications d'un compteur spécial U_3X_1 placé au voisinage du sol et relié électriquement au petit alternateur entraîné par l'anémomètre Ailleret-C.d.C., on peut différencier directement les tranches correspondantes d'énergie éolienne théoriquement récupérable. Et ceci grâce au fonctionnement de certains organes du compteur qui élèvent au cube les indications qui lui parviennent et les multiplient par le coefficient voulu.

On peut remplacer le compteur U_3X_1 par un U_3X_2 qui plafonne les puissances théoriquement récupérables suivant une loi se rapprochant de celle imposée à telle ou telle espèce d'hélice éolienne (régulation par perte de vitesse des profils des pales, par variation du calage de celles-ci, par désorientation générale de l'hélice, etc.). On peut aussi adjoindre au compteur précédent un compteur type O'KNV comptabilisant les kilomètres de vent passés sur l'anémomètre.

Il semble qu'il eût été relativement facile de disposer sur le cadran des compteurs U_3X_1, U_3X_2 ou O'KNV une aiguille supplémentaire se déplaçant devant une graduation et donnant une indication sur la puissance ou la vitesse « instantanée » du vent au moment de la lecture, alors que ces appareils peuvent sembler avoir été conçus seulement pour faire apparaître des moyennes.

Anémomètres dont la traînée varie avec la pression dynamique

Des lames en se déformant agissent sur des jauges résistantes, des cordes vibrantes ou des potentiomètres qui interviennent dans des circuits électriques comportant des appareils enregistreurs ou comptabilisateurs et alimentés par accumulateurs ou par piles.

Les anémomètres Best-Romani de ce genre (figure 2) que nous avons eu l'occasion d'utiliser comportent un cylindre d'axe vertical dont la surface a été rugosifiée pour échapper aux nombres de Reynolds critiques (16, page 250). L'anémomètre peut être à une seule composante, et dans ce cas être ou non monté en girouette, ou encore à deux composantes orthogonales fixes de la force du vent, respectivement proportionnelle par exemple à

$$\frac{\rho}{2} V^2 \sin \psi \text{ et à } \frac{\rho}{2} V^2 \cos \psi$$

comme le montre la figure 3.

Par le calcul (ou directement à l'aide d'un mécanisme approprié), on peut en déduire la direction du vent et la pression dynamique $\frac{\rho}{2} V^2$. On peut obtenir la valeur de $\frac{\rho}{2} V^3$ en faisant le produit $\frac{\rho}{2} V^2 \times \sqrt[2]{\frac{\rho}{2} V^2}$ et en divisant par $\sqrt[2]{\frac{\rho}{2}}$, racine carrée de la demi-masse spécifique de l'air, mesurée par ailleurs (ou même

seulement estimée, du fait que l'erreur ne porte dans ce cas que sur une valeur sous radical).

Les anémomètres Best-Romani ont une constante de temps inférieure au dixième de seconde et permettent l'enregistrement de vitesses presque « instantanées », à des cadences photographiques rapides.

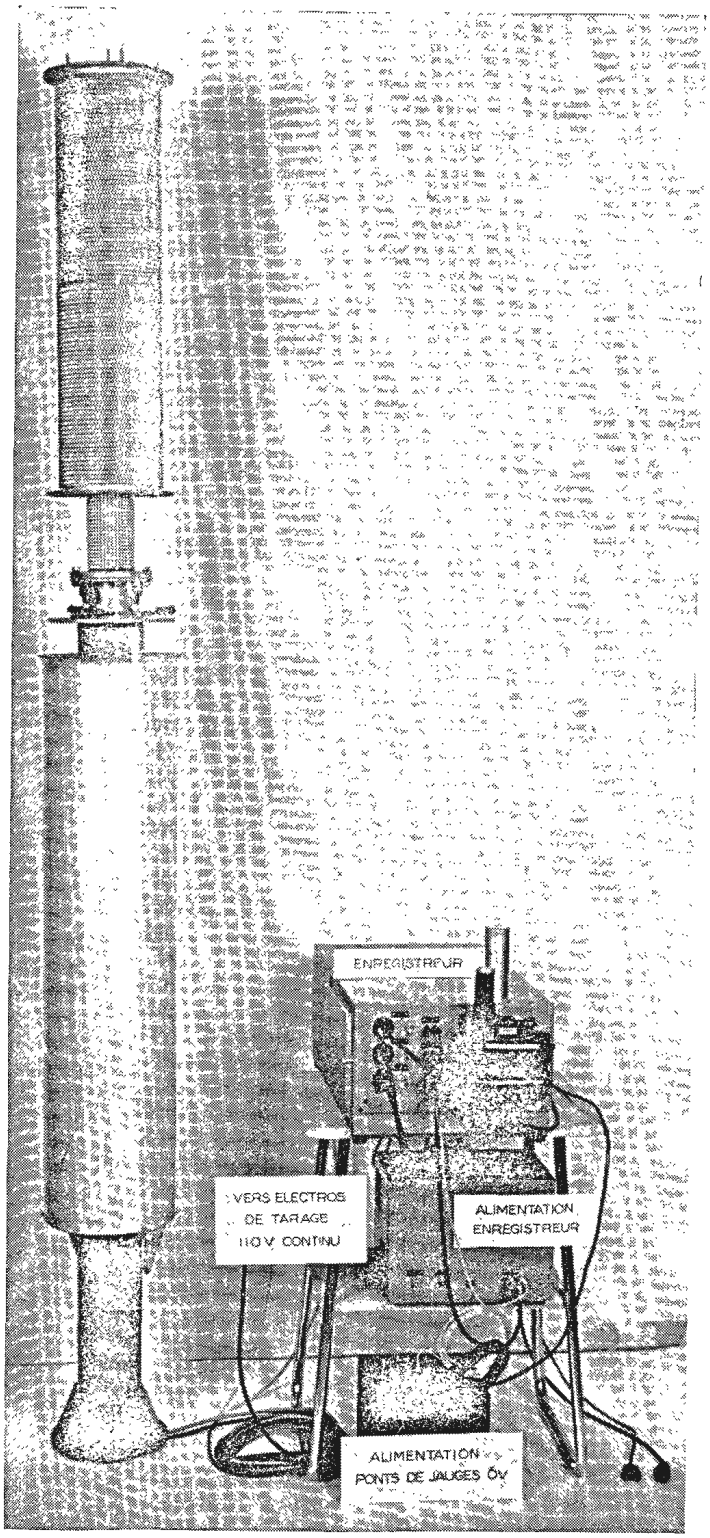
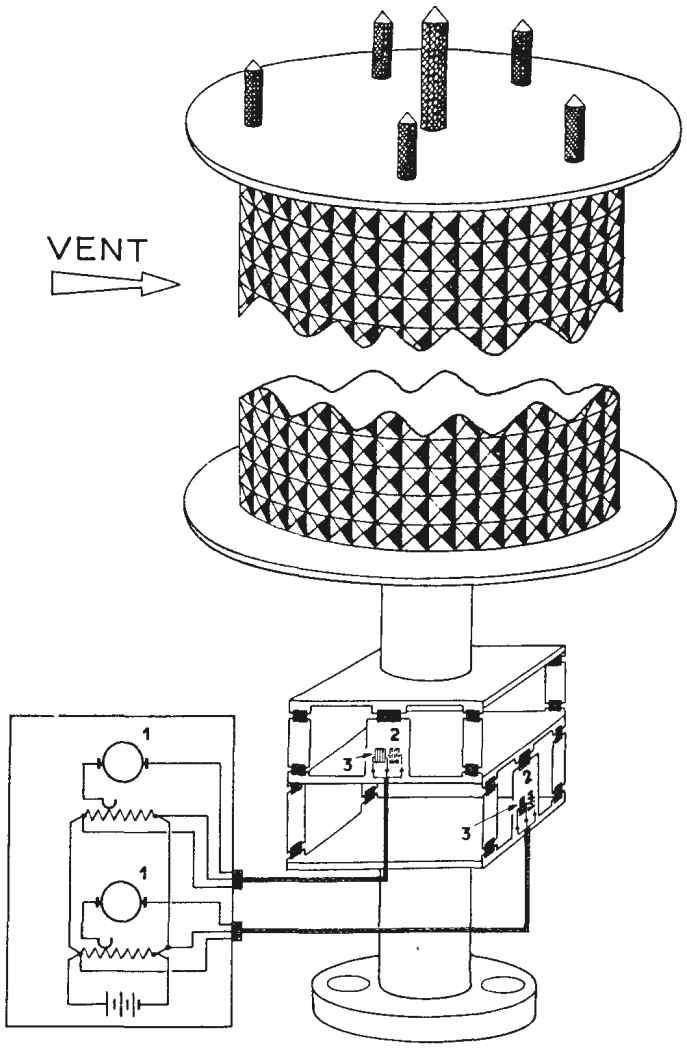


Figure 2. Anémomètre à cylindre rugueux



① Galvanomètre

② Lame flexible

③ Jauges de contrainte

Figure 3. Schéma d'un anémomètre à cylindre rugueux

Autres anémomètres

On a construit bien d'autres appareils permettant la mesure de la vitesse ou de la puissance du vent, et notamment des anémocinémographes, des anémomètres à tube de Pitot (14, page 75), des anémomètres spécialement conçus pour étudier les rafales (17, page 12; 18, page 438).

Comparaisons

On a souvent confronté les résultats donnés par les divers genres d'appareils (19, page 137). En France, une comparaison faite à Saint-Cyr-l'École à 42 mètres de hauteur au-dessus du sol entre deux anémomètres français, l'un à compteur d'énergie éolienne, l'autre à cylindre rugueux, et un troisième anémomètre

d'origine britannique, enregistrant les milles de vent ayant traversé l'appareil, a été très satisfaisant (figure 4).

Courbes des vitesses classées du vent

On présente souvent les mesures des vitesses du vent faites en un lieu du globe, sous la forme condensée de courbes dites des vitesses classées, dont les abscisses sont graduées en unités de temps, ou mieux en pourcentages de la durée totale des observations : $V = f(\theta)$.

Il est indispensable de préciser alors non seulement cette durée totale (une heure, une quatorzaine de jours, une ou plusieurs années par exemple), mais encore si les vitesses ont été « moyennées » sur une minute, une heure, une journée, une semaine, une quatorzaine de jours par exemple, ou si, ce qui est mieux, elles correspondent à des lectures de vitesses suffisamment « instantanées ». Dans ce cas on ne peut espérer en connaître un nombre immense, mais la loi des grands nombres peut jouer et des courbes annuelles de vitesses classées déjà extrêmement exactes peuvent être obtenues à l'aide de 2 000 à 3 000 mesures (une lecture au vol ou une photographie de la vitesse « instantanée » toutes les trois ou quatre heures, par exemple).

Puissances classées — Fréquences classées compte tenu des cubes des vitesses du vent

On peut aussi tracer des courbes $V^3 = f(\theta)$ ou des courbes de même allure dont les ordonnées sont directement graduées en puissances éoliennes théoriquement récupérables $\left(\frac{16}{27}\frac{\rho}{2}S\right) V^3 = f(\theta)$.

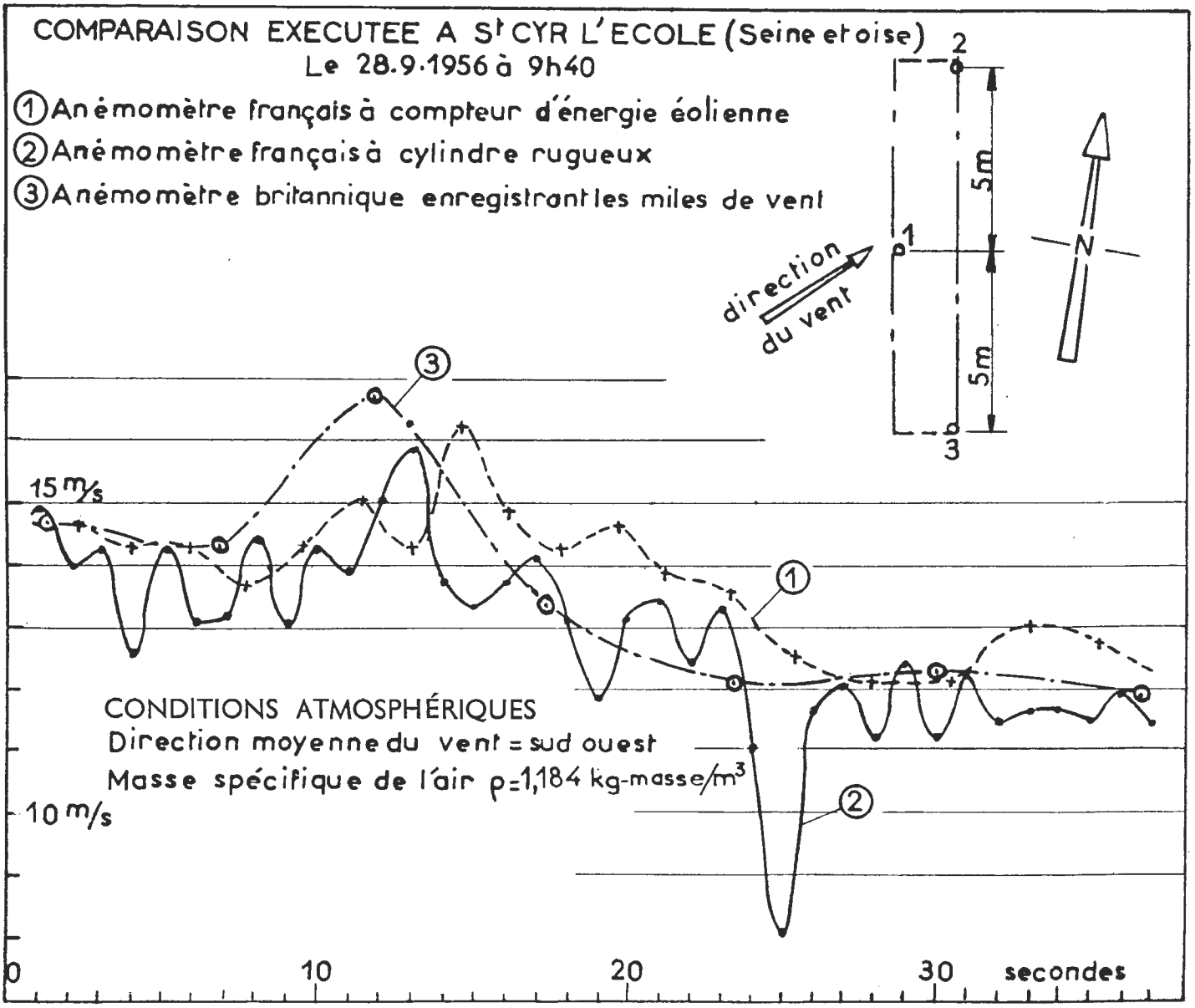


Figure 4. Comparaison entre trois anémomètres

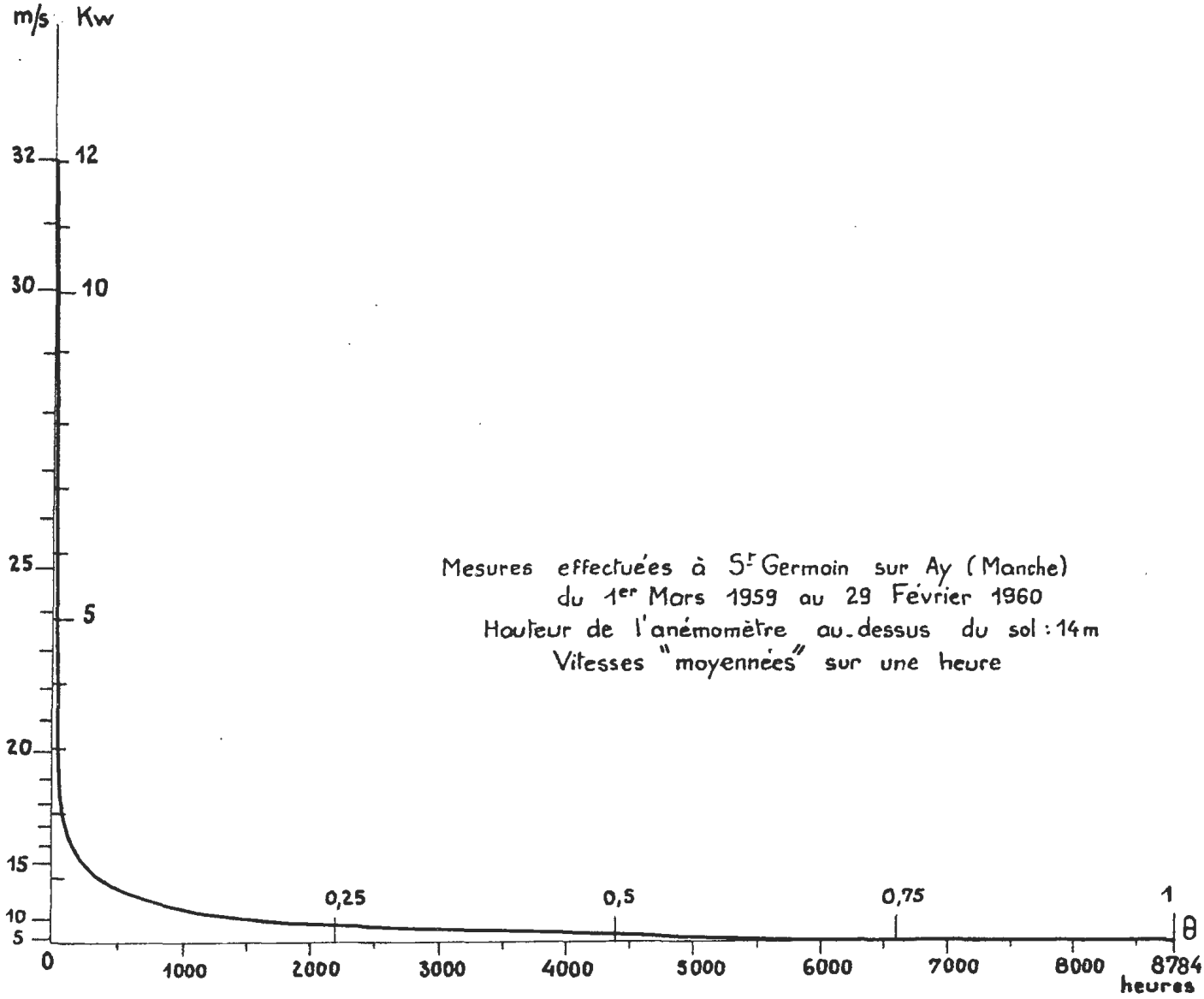


Figure 5. Courbe des puissances éoliennes classées

On peut encore tracer des courbes de fréquences classées dont les abscisses sont graduées en vitesse du vent et dont les ordonnées sont égales ou proportionnelles à $V^3 \frac{d\theta}{dV}$, c'est-à-dire :

$$V^3 \frac{d\theta}{dV} = f(V) \text{ ou } \left(\frac{16}{27}\frac{\rho}{2} S\right) V^3 \frac{d\theta}{dV} = f(V)$$

Dans un cas comme dans l'autre, les surfaces limitées par les courbes sont proportionnelles ou égales à des énergies, puisqu'elles comportent des termes du genre $\int V^3 \, d\theta$ ou $\int V^3 \frac{d\theta}{dV} \, dV$. Il est donc facile d'en déduire la valeur de la vitesse cubique moyenne dans le temps :

$$\overline{V_3} = \sqrt[3]{\frac{\int V^3 \, d\theta}{\int d\theta}}$$

Les figures 5 et 6 ont été établies à l'aide de mesures effectuées à Saint-Germain-sur-Ay (Manche). Les puissances y ont été « moyennées » sur une heure. La vitesse du vent le plus productif correspond à l'ordonnée maximale de la courbe de la figure 6.

Fréquences classées proprement dites

Il est possible de présenter de bien d'autres manières les valeurs des vitesses des vents ou des énergies éoliennes correspondantes mesurées dans un site. Sur la figure 7 relative aux relevés exécutés à Saint-Germain-sur-Ay, pendant la même période que ci-dessus, on a porté en abscisses les vitesses du vent et en ordonnées les fréquences classées proprement dites :

$$\frac{d\theta}{dV} = f(V)$$

A l'ordonnée maximale de cette courbe correspond la vitesse du vent le plus fréquent dans le site, tandis que le vent le plus productif y coïncide alors avec le point dont la tangente possède un coefficient angulaire égal et opposé au triple du rapport :

$$\frac{\text{valeur de l'ordonnée correspondante}}{\text{valeur de l'abscisse correspondante}}, \text{ c'est-à-dire } -\left(\frac{3\,\frac{d\theta}{dV}}{V}\right)$$

On voit qu'entre ces deux valeurs de la vitesse du vent il y a une différence très importante.

Fréquences classées compte tenu de la vitesse ou du carré de la vitesse du vent

On peut de même tracer des courbes des fréquences classées compte tenu de la vitesse du vent, $V\,\frac{d\theta}{dV} = f\,(V)$; à l'usage des architectes, des constructeurs ou des éoliens, notamment lorsque ceux-ci s'intéressent aux traînées du vent sur les supports des aéromoteurs, on peut tracer des courbes des fréquences classées, compte tenu du carré de la vitesse du vent $V^2\,\frac{d\theta}{dV} = f\,(V)$.

Aux ordonnées maximales de chacune de ces deux courbes correspondraient des vitesses de vent comprises entre le vent le plus fréquent et le vent

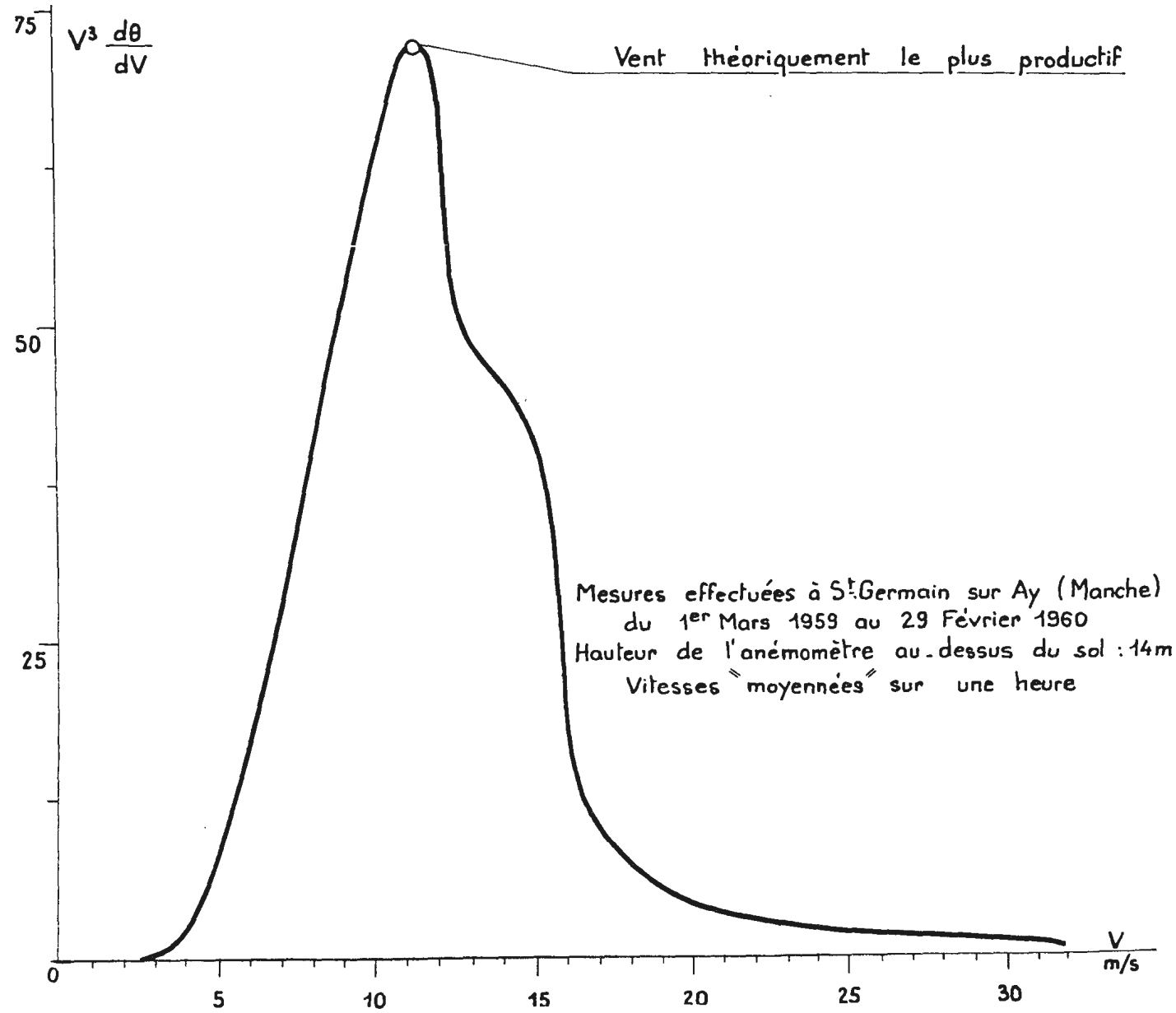


Figure 6. Courbe des fréquences classées compte tenu des cubes des vitesses du vent

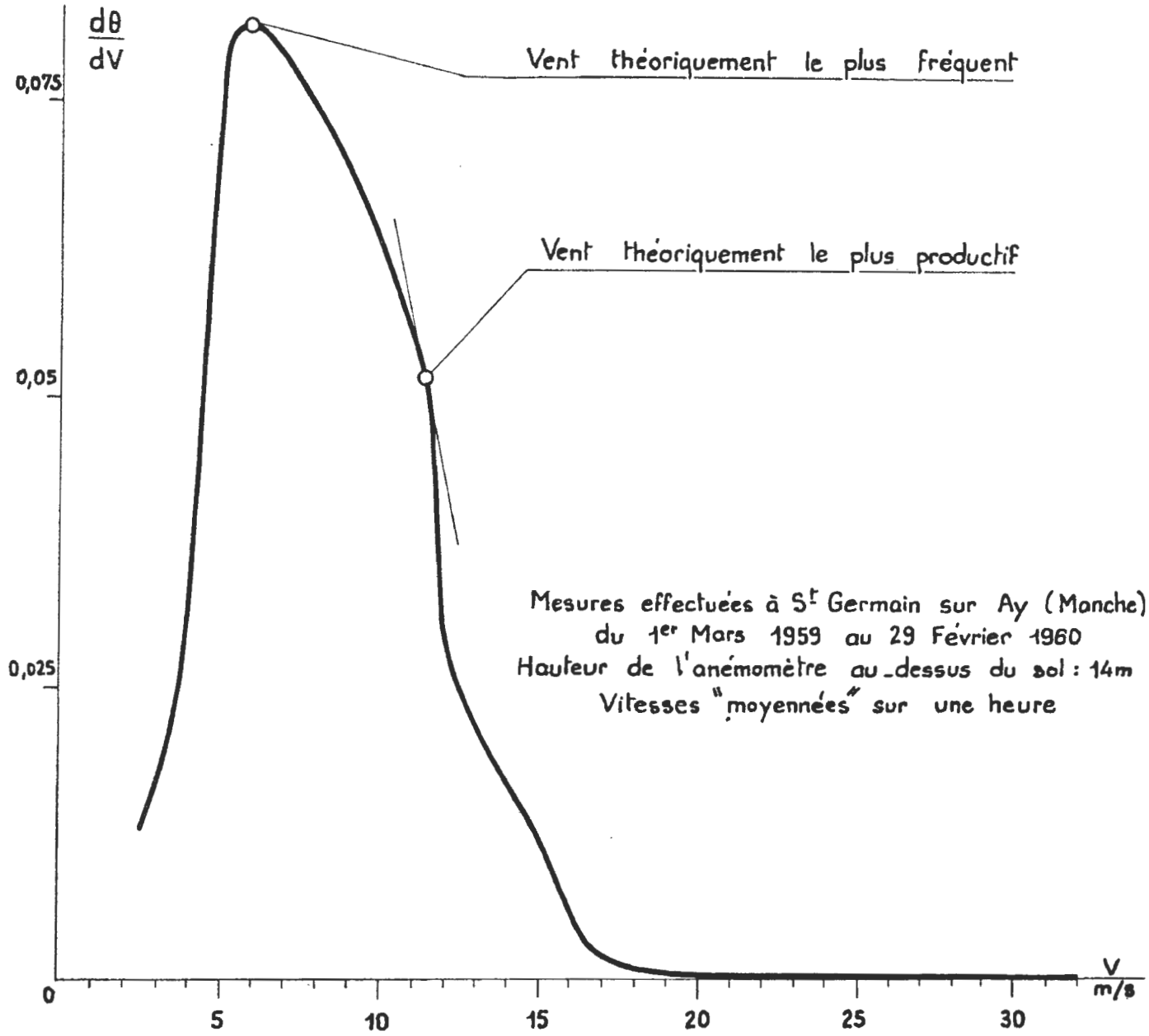


Figure 7. Courbe des fréquences classées du vent

le plus productif, et les surfaces comprises entre ces courbes et les axes des abscisses permettraient de calculer les valeurs moyennes respectives de la vitesse linéaire $\overline{V}_1 = \frac{\int V\, d\theta}{\int d\theta}$, et de la vitesse quadratique $\overline{V}_2 = \sqrt[2]{\frac{\int V^2\, d\theta}{\int d\theta}}$ du vent pour le site.

Paramètres caractérisant l'irrégularité du vent

Plusieurs paramètres permettent de juger dans quelle mesure les vitesses successives du vent en un point s'écartent de leur moyenne linéaire dans le temps.

M. Petry, directeur de l'Administration française des phares et balises, a insisté sur l'intérêt du « coefficient d'irrégularité » (13) qui se trouve être égal au cube du rapport de la vitesse cubique moyenne à la vitesse linéaire moyenne : $\left(\frac{\overline{V}_3}{\overline{V}_1}\right)^3$.

On a pu aussi bien chercher à connaître les valeurs maximale, moyenne ou minimale de ce coefficient pendant un intervalle de temps d'une seconde, d'une ou de plusieurs minutes (8, page 32) que pendant une heure, une journée, un mois (20, page 10 et figure 4), et même une ou plusieurs années (21, figure 11).

En France, sur les côtes de Bretagne ou de Normandie, ce coefficient mesuré sur une année semble devoir être de l'ordre de 2,2. Ceci revient à dire que le rapport $\frac{\overline{V}_3}{\overline{V}_1}$ y égale 1,3 environ. Il est vraisemblable que dans

les Pyrénées orientales françaises ou espagnoles il est compris entre 2,5 et 3 $\left(\frac{\overline{V}_3}{\overline{V}_1} = 1{,}4 \text{ environ}\right)$.

Un autre paramètre caractéristique de l'irrégularité du vent en un point a été proposé par un météorologiste anglais, R. Frith (22, page 689). Des mesures de vitesses moyennes du vent ayant été faites à intervalles réguliers, on note la différence entre la plus haute et la plus basse dans chaque groupe de cinq successives. La valeur moyenne de ces différences divisée par la moyenne de la vitesse du vent pendant toute la période est considérée comme le critère de la variabilité des moyennes dans ces intervalles. De nombreux auteurs ont proposé des définitions de « facteurs de rafales », « coefficient de turbulence »

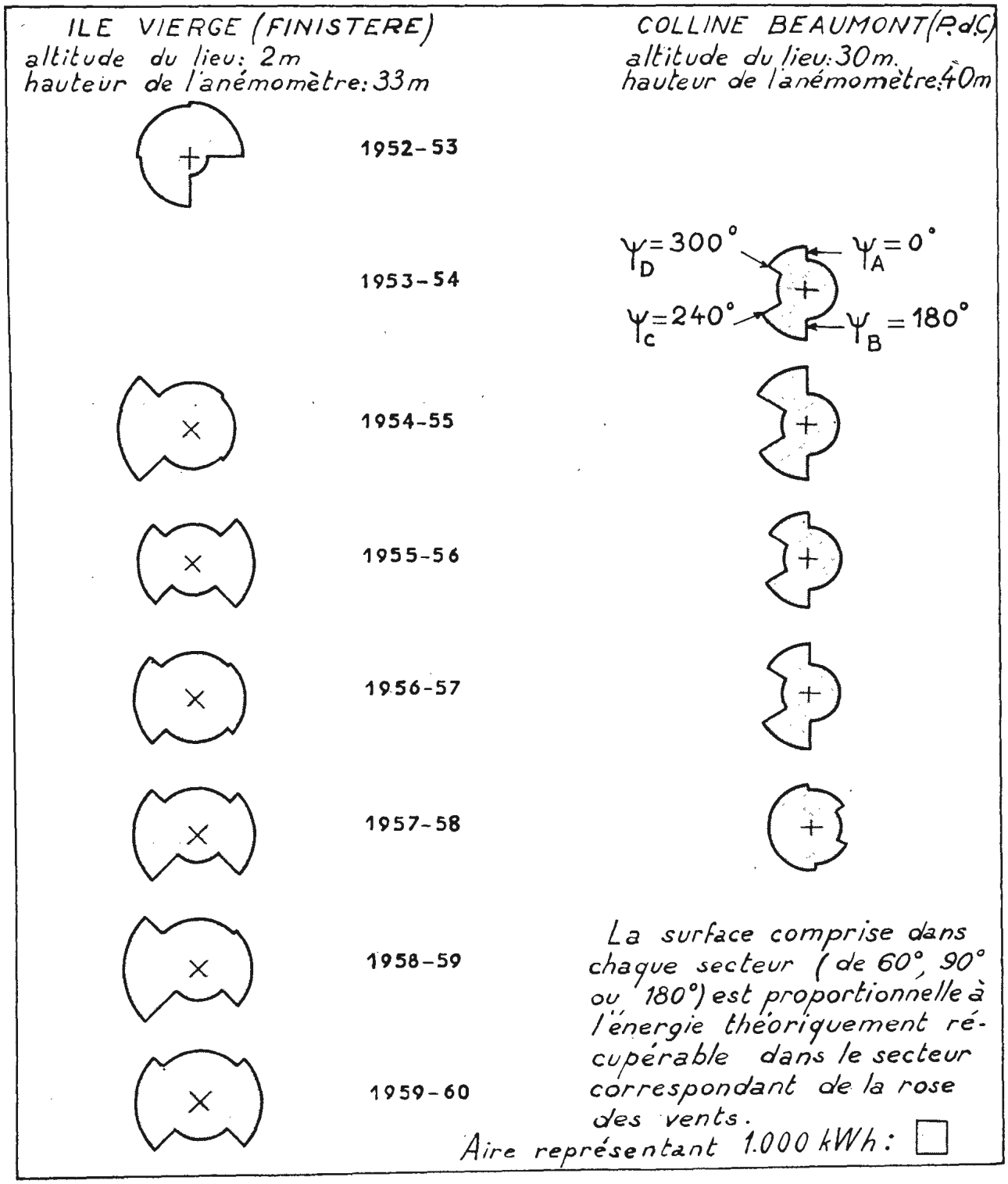


Figure 8. Directions des vents « Roses cubiques »

et « variances de la vitesse ». Leurs travaux notamment sur les « spectres de fréquence » sont en général d'un grand intérêt (7, page 825-11, fig. 3; 23, page 207; 24, page 162; 25, page 180; 26, page 25; 27; 28; etc.).

Directions des vents

Ainsi que nous l'avons exposé ci-dessus, on a pu tracer, en fonction des vitesses du vent, quatre sortes de courbes des fréquences classées, d'ordonnées respectives :

$$V^0 \times \frac{d\theta}{dV} \qquad V^1 \times \frac{d\theta}{dV} \qquad V^2 \times \frac{d\theta}{dV} \qquad \text{et} \qquad V^3 \times \frac{d\theta}{dV}$$

Il est de même nécessaire de bien définir, lorsqu'on dessine une rose des vents, si chacun des rayons vecteurs qui s'épanouissent autour du point de mesure ou si chacune des surfaces des secteurs que ceux-ci limitent est seulement proportionnel au pourcentage du temps θ pendant lequel le vent a soufflé d'une direction vers ce point, ou est au contraire proportionnel au produit de ce pourcentage par la vitesse correspondante du vent, par le carré ou par le cube de cette vitesse du vent. Autrement dit, les longueurs des rayons vecteurs, ou mieux les surfaces des secteurs d'une rose des vents, peuvent être proportionnelles à :

$$\int_{\psi_A}^{\psi_B} V^0\, d\theta \qquad \int_{\psi_A}^{\psi_B} V^1\, d\theta \qquad \int_{\psi_A}^{\psi_B} V^2\, d\theta \qquad \int_{\psi_A}^{\psi_B} V^3\, d\theta$$

Cette dernière représentation « cubique » est celle que nous avons adoptée sur la figure 8, où les indications de nos anémomètres adirectionnels, sélectionnées grâce à une girouette placée au voisinage, avaient été envoyées sur un premier compteur, un second, un troisième ou un quatrième, chacun de ceux-ci correspondant à un secteur d'angle au sommet limité par deux directions arbitrairement définies, par exemple pour Colline-Beaumont en 1953-1954 :

$\psi_A = 0°$ et $\psi_B = 180°$, $\psi_B = 180°$ et $\psi_C = 240°$, etc.

Nous avons souvent été surpris par le fait que les silhouettes des graphiques ainsi délimités ne fussent pas plus nettement décentrées par rapport au point de mesure, les vents d'est-sud-est, par exemple ($\psi = 110°$ à $125°$ environ), paraissant à la foie très rares et très faibles en Europe occidentals, notamment dans le nord du Finistère.

La plupart des moulins à vent sont orientables; aussi les roses des vents ont peut-être moins d'intérêt pour les éoliens que celles généralement en usage à des fins météorologiques, roses des vents seulement directionnelles, ou roses des vents « linéaires ».

Cependant, les roses des vents « quadratiques » ou « cubiques » donnent une représentation plus correcte des vents dominants, en direction desquels les sites doivent être dégagés au maximum pour des raisons respectivement constructives ou énergétiques.

Normalisation souhaitable des méthodes de mesures

La normalisation internationale d'une « classification des documents » et d'une « terminologie » relatives à l'énergie éolienne avait été esquissée il y a une dizaine d'années (13, pap. nos 43 et 44).

Plus récemment, des règles concernant les « symboles relatifs aux aéromoteurs » et les « aérogénérateurs de petite puissance » ont été définies par l'Association française de normalisation (1 et 2). Elles pourraient servir de base à une future normalisation internationale en ces domaines, car nous avons eu soin de ne les considérer que comme « provisoires ».

Dans les quatre documents précités, certaines précisions sur les paramètres à adopter en aérologie et sur les difficultés rencontrées dans les mesures correctes de ceux-ci ont été consignées, mais seulement à titre accessoire. Bien d'autres auteurs ont regretté l'absence d'une meilleure coordination internationale en la matière. Il n'est peut-être pas trop tard pour s'y employer, en commençant par faire l'inventaire des questions à étudier.

Ainsi il semblerait utile de définir dès maintenant, à l'usage des éoliens de tous pays, les mêmes début et fin de périodes de mesures (demi-journées, quatorzaines de jours, années, décennies, etc.), une présentation aussi uniformisée que possible des courbes de vitesses, puissances et fréquences classées ou des roses des vents et de proposer deux à trois paramètres caractéristiques de l'irrégularité du vent au maximum.

Il y aurait peut-être intérêt à suggérer l'emploi d'un seul type d'appareillage, ou au moins d'une méthode et d'une formule uniques pour la mesure de la masse spécifique de l'air et d'une valeur unique de celle-ci à employer internationalement dans le cas où une constante en paraît suffisante.

Quant aux anémomètres (cinq ou six modèles au maximum à normaliser), il faudrait, dans le cas de prospection des sites venteux, les installer, sauf exceptions, à des hauteurs au-dessus du sol qui ne soient pas inférieures à 25 mètres, par exemple. Et il faudrait toujours les dégager de leurs supports, de manières comparables dans le monde entier.

Modeste programme de début, à compléter largement par la suite.

Inventaire des éléments favorables ou non à l'installation d'aéromoteurs

Variations temporelles des vitesses du vent

Variations cycliques

Variations des vitesses du vent au cours de l'année

L'énergie éolienne, dont l'intégrale annuelle semble relativement assez constante d'une année à l'autre, est bien plus abondante l'hiver que l'été en Europe occidentale.

La figure 9 donne, pour l'ensemble de 38 stations de mesures situées en France métropolitaine (en dehors du sud-est du pays), les valeurs relatives de l'énergie éolienne théoriquement récupérable pour

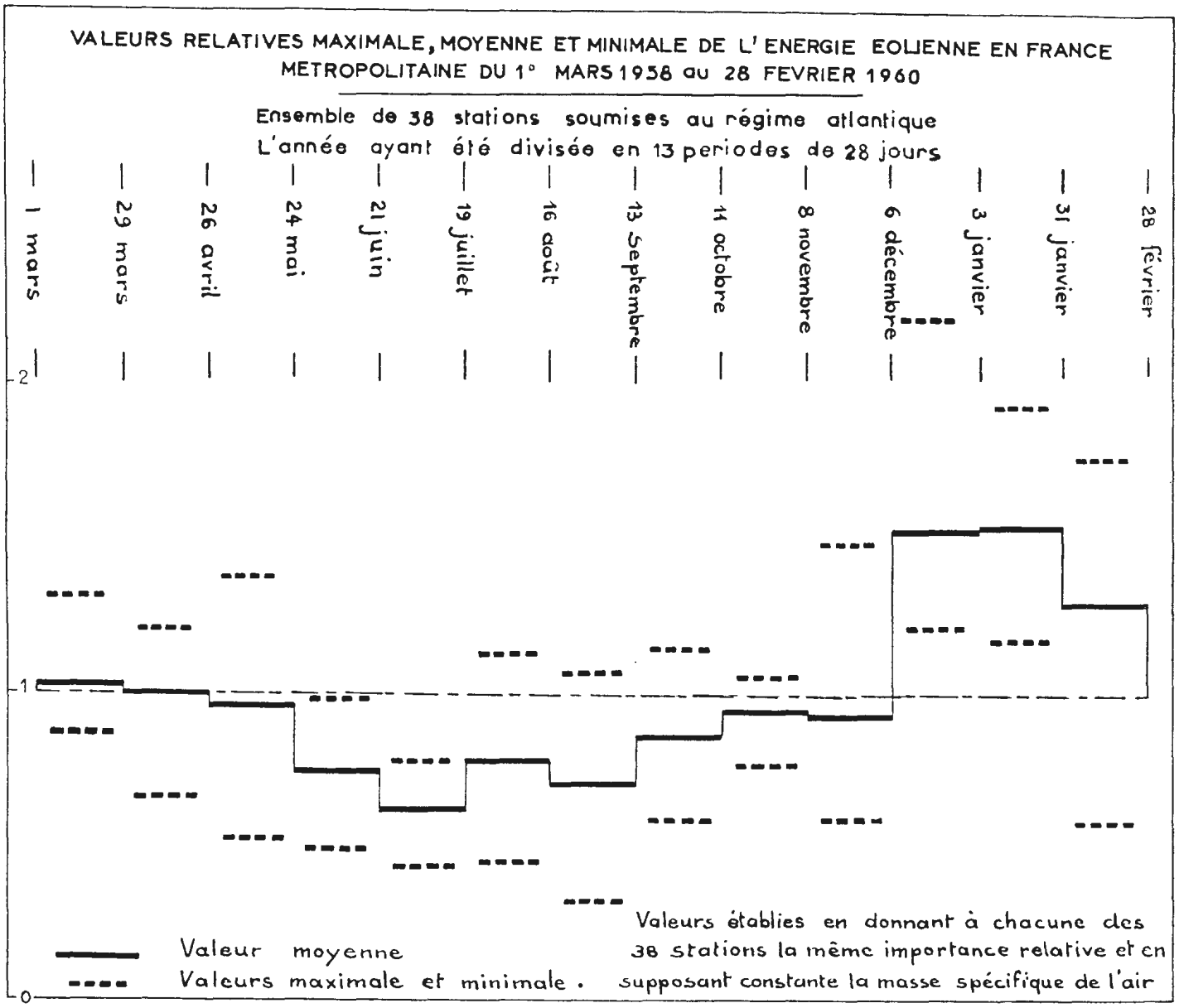


Figure 9. Valeurs relatives de l'énergie éolienne en France

chaque période de 28 jours, arbitrairement adoptée. Le fait que la masse spécifique de l'air soit un peu plus élevée en moyenne l'hiver que l'été renforce les écarts que souligne cette figure et qui s'accentuent d'ailleurs dans les meilleurs sites.

« La variation de la vitesse du vent est extrêmement nette », écrivait déjà Angot (29, page 91) en 1911 à propos des mesures faites de 1890 à 1910 au sommet de la Tour Eiffel. « Elle présente un maximum en janvier et un minimum en juillet; la seule irrégularité porte sur le mois de novembre, dont la moyenne est plus faible que celle des deux mois entre lesquels il est compris. » Du fait de son élévation au-dessus du sol, les indications d'un anémomètre placé en cet endroit sont en très bonnes corrélations avec celles de l'ensemble des trente-sept autres; nous avons pu le vérifier.

Variations des vitesses du vent au cours des 24 heures d'horloge

Comme on pouvait s'y attendre, les vents subissent des variations journalières, de même que des variations annuelles.

Cependant, entre 30 et 70 mètres de hauteur au-dessus du sol, il semble qu'il y ait en général égalité approximative d'énergie éolienne disponible de jour et de nuit. A partir de 70 mètres, il y aurait un peu plus de vent la nuit que le jour; nous l'avons aussi vérifié pour le sommet de la Tour Eiffel. A moins de 30 m, c'est l'inverse.

Au Brookhaven National Laboratory (30, figure 6), on a constaté vers 45 mètres de hauteur un minimum de la vitesse du vent le matin vers 10 h ou 11 h et un maximum vers 14 h ou 15 h. Vers minuit

il y a peut-être une tendance au renforcement, mais légère et peu durable.

Il semble que ceci soit exact aussi pour le Japon (31, page 106, figure 3). Mais il est possible qu'au-dessus de la mer ou d'îles de faibles superficies les hauteurs d'inversion soient très différentes.

Autres variations de la vitesse du vent

Variations de courtes durées

La figure 10 représente les variations en grandeur (et en direction) de la vitesse instantanée du vent enregistrée à Nogent-le-Roi (Eure-et-Loir) à 33 mètres

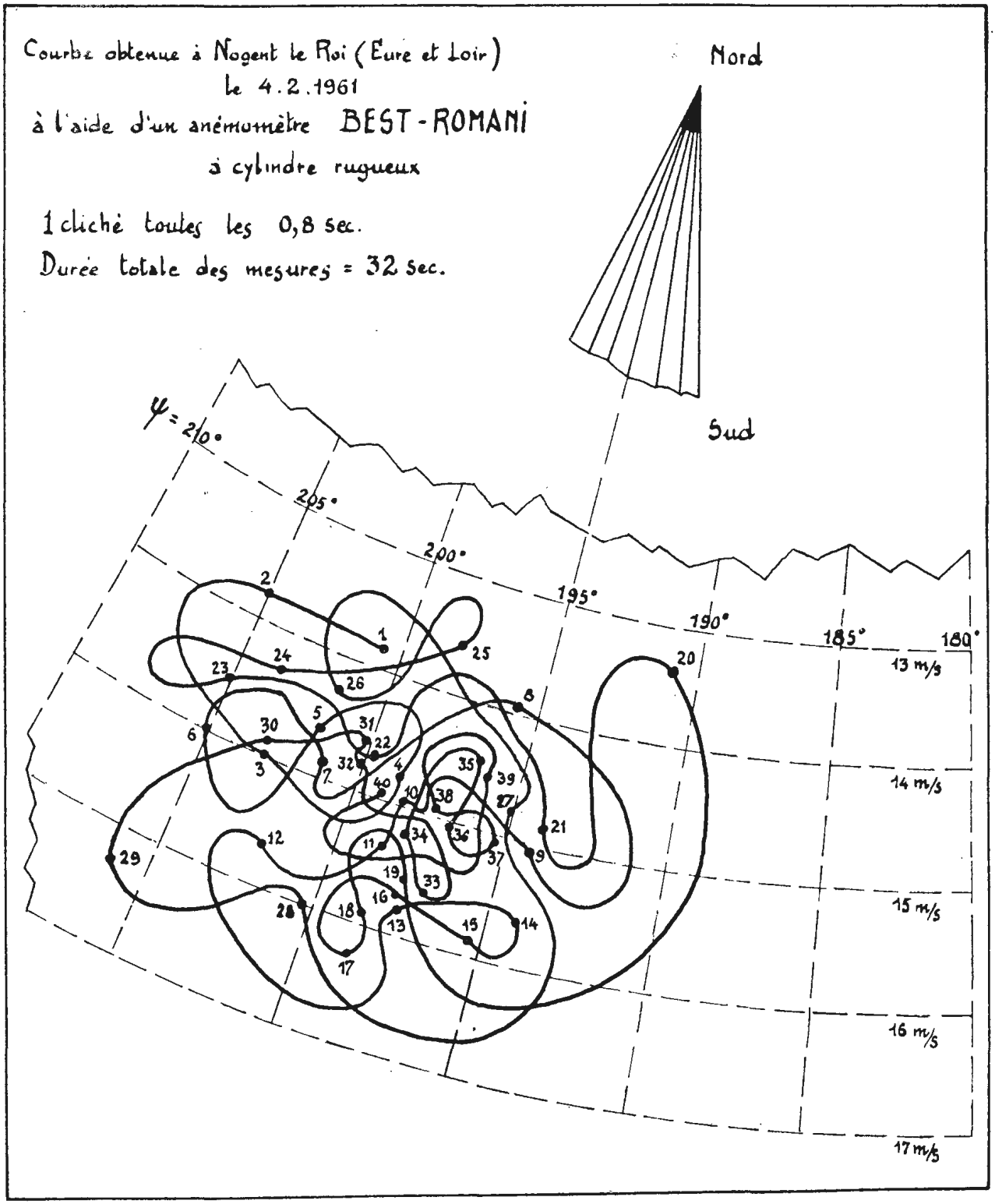


Figure 10. Variation de la vitesse du vent en grandeur et direction

de hauteur au-dessus du sol, toutes les 0,8 secondes, et pendant une durée totale de 32 secondes, à l'aide de l'un des anémomètres décrits ci-dessus. C'est un exemple pris au hasard parmi un grand nombre d'enregistrements analogues.

Il ne semble pas s'y confirmer que les vitesses du vent se modifieraient par sauts brusques comme certaines expériences avaient pu le faire croire (32, page 373) et il faudrait donc revenir au schéma antérieurement admis, indiqué par cet auteur : « Représenter la turbulence comme la superposition de tourbillons à mouvement circulaire uniforme à un courant permanent de vent moyen ».

Variations du vent dans le temps à l'échelle de plusieurs jours

On peut rapprocher cette dernière remarque d'une autre relative à une échelle des temps bien différente.

Après avoir mis sous formes de diagrammes log. probabilités (33, page 469) des courbes de fréquences classées, certains ont pu écrire (34, page 1171) : « Les vents faibles, très fréquents, sont gouvernés par des causes locales (vent du gradient); ils correspondent à un champ de pression continu non perturbé. Au contraire, les vents forts, plus rares, sont engendrés principalement par des perturbations cycloniques dont les causes, d'origine lointaine, sont tout à fait indépendantes de celles des vents faibles. Ils correspondent à des tourbillons d'axes verticaux se déplaçant à grande vitesse. »

Vitesses maximales

C'est souvent aussi en utilisant cette loi de l'effet proportionnel qu'on a étudié les risques qu'une fois par décennie, par siècle ou par millénaire le vent atteigne en un point telle ou telle vitesse maximale (7, pages 825-9, figure 1).

En France, bien que même au sommet de la Tour Eiffel on n'ait observé jusqu'à ce jour aucune vitesse « instantanée » du vent supérieure à 45 m/s, on prévoit en général dans les projets de grands aérogénérateurs que ceux-ci devront pouvoir résister en pointe peu durable à 60 m/s (hélice éolienne arrêtée si nécessaire).

Certains (35, page 42) estiment cependant que ce ne sont pas les vitesses maximales « instantanées » qui doivent être considérées mais bien les vitesses « moyennées » sur une minute, voire sur une heure. D'autres (36, page 471) comparent les moyennes horaires maximales du vent avec les pointes maximales des rafales.

Le choix de cette base de temps n'est pas sans importance, s'il est vrai, comme l'écrit Van der Hoven (24, page 160), qu'il y a dans le spectre deux principaux maximums d'énergie fluctuante, l'un se produisant à une période d'environ 4 jours, le second à une période d'environ 1 minute. Entre ces deux maximums se centre une large dépression spectrale d'une fréquence allant de 1 à 10 cycles par heure.

Variations dans l'espace

Zones venteuses

Les vitesses moyennes du vent autour du globe terrestre varient, d'un site à un autre pareillement dégagé, du simple au double, au quadruple, parfois même de 1 à 6. Et corrélativement, l'énergie disponible varie de 1 à 200 au moins en première approximation.

La nécessité de prospecter méthodiquement de nombreuses régions a conduit plusieurs pays à installer des stations de recherches composées d'anémomètres et d'enregistreurs ou de compteurs (8, page 66; 37, page 70; 10, page 7). Les résultats sont transformés en courbes $V^3 = f(\theta)$, $V^3 \frac{d\theta}{dV} = f(V)$, en courbes des débits véhiculés par une éolienne de pompage de caractéristique donnée (38, page 507) ou plus simplement obtenus directement en kWh par mètre carré théoriquement disponible (5, page 5).

Ainsi, plus de 350 sites dispersés sous toutes les latitudes (du Groenland aux îles Kerguelen en attendant la terre Adélie) et sous toutes les longitudes d'Europe, d'Asie, d'Afrique, d'Océanie et des deux Amériques ont été équipés des anémomètres à compteurs d'énergie éolienne dont on a parlé ci-dessus. Et les relevés exécutés par les soins de particuliers ou de personnes appartenant à divers organismes (administrations françaises et britanniques des phares et balises, expéditions polaires françaises, météorologie nationale française et belge, SEAS danoise, Société nationale des chemins de fer français, Administration des ponts et chaussées, Direction de l'hydraulique et de l'équipement rural d'Algérie (39), Commission nationale des énergies spéciales d'Espagne, Ministère des travaux publics du Viet-Nam, etc.) ont été assez régulièrement communiqués, parfois depuis plus de dix ans, à la Division énergie du vent d'Électricité de France, 6, Quai Watier, à Chatou (Seine-et-Oise), pour collationnements et comparaisons.

La carte figure 11 pour la France métropolitaine et, pour le monde entier, le tableau figurant en annexe 1 résument les résultats obtenus.

En France métropolitaine, on le voit, et pour ne parler que des sites peu sujets au givrage, plusieurs régions maritimes accusent en moyenne et en d'assez nombreux points, à une cinquantaine de mètres au-dessus du sol, des énergies annuelles théoriquement récupérables de l'ordre de 4 000 kWh par mètre carré de surface offerte au vent (et par conséquent pratiquement récupérables à l'aide de grands aérogénérateurs modernes de l'ordre de 2 000 kWh par mètre carré et par an). Il y correspond une vitesse linéaire moyenne de 8 à 8,5 m/s.

On peut remarquer qu'un site est sans doute d'autant meilleur aux yeux d'un éolien que $\overline{V}_3$ y est plus élevé mais aussi que $\frac{\overline{V}^3}{\overline{V}_1}$ y est plus faible. Si l'on donnait autant d'importance à ces deux facteurs, cela revien-

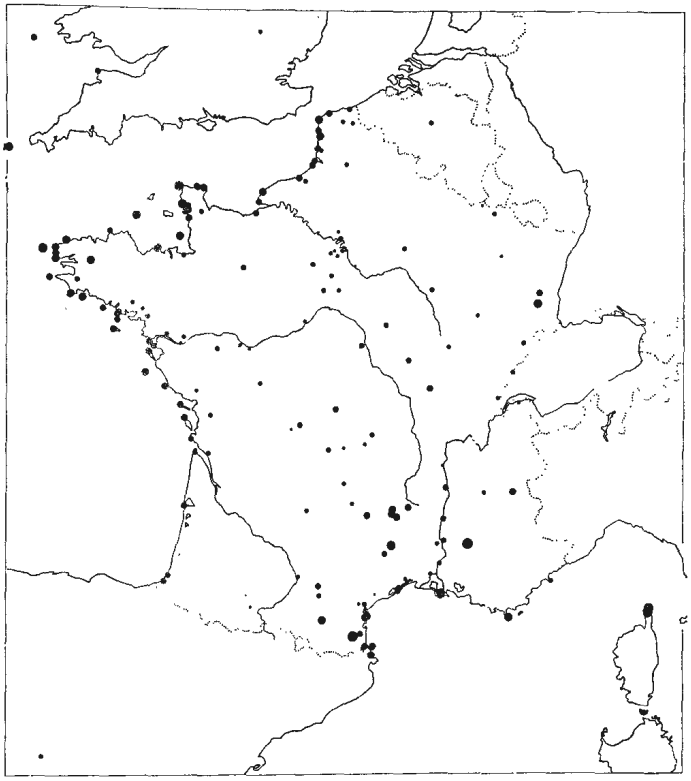


Figure 11. Stations de jaugeage de l'énergie éolienne théoriquement récupérable annuellement à 40 m au-dessus du sol

Pour chaque station, la surface du cercle est telle que l'énergie correspond à 100 fois le carré du diamètre *(Exemple :* ● ⌀5 *correspond à* 2 500 *kWh/m²)*

drait à dire que $\overline{V}_3 \times \frac{\overline{V}_1}{\overline{V}_3} = \overline{V}_1$ doit être maximal et serait cohérent avec l'opinion de certains auteurs (8, page 116; 40, chapitre VIII), qui ont critiqué les méthodes de recherches des sites venteux préconisées par les français.

Si l'on estimait au contraire que le premier des deux facteurs l'emporte assez nettement, il faudrait chercher par exemple à rendre maximal le produit $(\overline{V}_3)^2 \times \frac{\overline{V}_1}{\overline{V}_3} = \overline{V}_3 \times \overline{V}_1$, ou, en continuant un raisonnement aussi approximatif, à rendre maximal $(\overline{V}_2)^2$, dont la valeur doit être du même ordre de grandeur que $(\overline{V}_3 \times \overline{V}_1)$.

Ainsi, dans le cas d'une prospection des sites venteux, les différents points du globe devraient être classés non d'après les énergies théoriquement disponibles ni d'après les « isovents », mais d'après les pressions dynamiques $\frac{\rho}{2} V^2$ que les anémomètres du genre de celui décrit plus haut délivrent directement, donc sans approximation sur ρ.

Les courbes de fréquences classées, compte tenu du carré des vitesses de vent, et les roses des vents « quadratiques » dont il a été question plus haut y correspondent. Elles intéressent aussi les constructeurs et les architectes.

Choix du terrain sur lequel un aéromoteur doit être implanté

Généralités

Le Comité technique français de l'énergie des vents a diffusé en 1950 des conseils (41) à ce sujet, qui n'ont rien perdu de leur intérêt et figurent en annexes 2 et 3.

Influence éventuelle de la forme du terrain sur l'énergie éolienne disponible

Reprenons la valeur de la puissance théoriquement contenue dans le vent, non pas sous la forme habituelle rappelée ci-dessus, mais sous celle plus fouillée qu'on peut déduire du raisonnement de son auteur, le professeur allemand Betz :

$$P_{\max} = \left(\frac{\rho}{2} \times V_0^2 \times \frac{8}{9}\right) \left(S \times V_{\text{loc}} \times \frac{2}{3}\right)$$

dans laquelle V_O est la vitesse du vent à une grande distance vers l'amont, tandis que V_{loc} est la vitesse locale prise sur le même filet d'air en l'absence de l'aéromoteur, mais à proximité peut-être d'obstacles environnants (sol constitué par une colline, par exemple).

Le problème se complique encore du fait que les dimensions respectives de la surface balayée par l'hélice éolienne et de la courbure de la colline doivent intervenir, et aussi parce que les filets d'air ralentis pour céder leur puissance à l'hélice éolienne sont sans doute quelque peu entraînés par les filets extérieurs (viscosité bénéfique?), de sorte qu'en pratique la puissance est peut-être proportionnelle à $V_O^{1,5} \times V_{\text{loc}}^{1,5}$ ou même à $V_O \times V^2_{\text{loc}}$.

Nous avons essayé de vérifier cela il y a quelques années à la soufflerie aérodynamique à veine rectangulaire de Saint-Cyr-l'École, avec un modèle de ligne de crête donnant un écoulement plan parallèle et une éolienne maquette de petites dimensions. Mais les résultats n'ont évidemment pas valu ceux qu'on aurait obtenu dans la nature en montant deux grands aérogénérateurs aussi identiques que possible (sauf peut-être par le calage optimal des pales de leurs hélices), l'un très haut au milieu d'une plaine et l'autre assez bas au-dessus d'une colline bien arrondie et dénudée, les deux machines se trouvant par exemple à la même altitude au-dessus du niveau de la mer.

Tout ceci n'est pas seulement théorique, car, contrairement aux aéromoteurs petits ou grands qui ralentissent des quantités d'air importantes, les anémomètres perturbent peu le courant d'air. Ceux du type Robinson tournant à l'emballement semblent uniquement sensibles à la vitesse V_{loc}; quant aux anémomètres utilisant les traînées d'obstacles, ils mettent en jeu des différences de pressions statiques, lesquelles sont influencées par les courbures des lignes de courant, et le fonctionnement en est complexe.

Lorsque des anémomètres du type Robinson ont été placés au proche voisinage d'une coupole de phares, nous savons bien que leurs indications se sont trouvées être erronées presque toujours par excès, allant jusqu'à 20 p. 100 en vitesses ou 70 p. 100 en puissances éoliennes. Il serait grave qu'il en soit partiellement de même lorsqu'ils sont installés sur un support de trop faible hauteur, placé au sommet d'une colline ou d'une ligne de crête perpendiculaire aux vents dominants.

A l'inverse, il n'est pas impossible que deux hélices éoliennes contrarotatives autour d'axes parallèles, et dont les cercles balayés soient presque tangents, aient des rendements meilleurs que l'une d'entre elles, isolée de l'autre. Et il en serait peut-être de même d'une hélice éolienne dont la garde serait minimale, si l'effet n'était contrebattu par une diminution importante de la vitesse du vent au voisinage du sol, par suite du frottement.

Hauteurs au-dessus du sol — Couche limite Gradients

Sans aller chercher très au-dessus d'une couche limite qui doit atteindre, pensons-nous, 500 mètres environ au-dessus des mers et 1 000 m au-dessus des terres (42, page 44) des vents extrêmement violents appelés « jets », dont l'existence a été récemment mise en évidence, nous nous sommes demandés s'il n'y aurait pas intérêt à élever les axes des hélices éoliennes à des hauteurs au-dessus du sol de l'ordre d'une centaine de mètres, par exemple.

Sans doute fallait-il proscrire sévèrement le fait d'installer plusieurs anémomètres à diverses hauteurs le long d'un pylône très élevé, car seul l'anémomètre situé au sommet ne risque alors pas d'être gravement perturbé, à condition encore que la plateforme terminale ne soit pas trop encombrante. Or le nombre des endroits où il était possible de disposer à la fois de pylônes distincts à faible, à moyenne et à grande hauteur (Sainte-Assise, Pontoise) était très limité.

Aussi, pour minimiser les frais d'installations, des anémomètres ont été placés de préférence sur toutes sortes de supports naturels existants (pylônes de lignes à haute tension, tours, clochers, phares, antennes de T.S.F. isolées). Cependant, en maints endroits où ces supports faisaient défaut ou pour éviter des interactions aérodynamiques qui auraient gravement faussé les résultats (comme il arrive souvent par exemple à 10 ou 15 mètres seulement de hauteur au-dessus du sol), on a dû ériger des pylônes légers et haubannés, mais cependant relativement coûteux, de hauteur atteignant jusqu'à 65 mètres.

Systématisant alors une idée déjà proposée (43, pages 279 et 280), nous avons cherché à comparer les indications annuelles moyennes d'anémomètres à compteur d'énergie éolienne répartis en de nombreux sites d'une même région appartenant à la France métropolitaine ou aux pays limitrophes, en négligeant volontairement en première approximation les altitudes des lieux pour ne retenir que les hauteurs au-dessus du sol.

Les énergies annuellement récupérables en kWh par mètre carré ont été portées en abscisses et les hauteurs en mètres au-dessus du sol en ordonnées, en utilisant dans un cas comme dans l'autre des graduations logarithmiques. Il est apparu qu'aux exposants n de la formule bien connue :

$$\frac{E_1}{E_0} = \left(\frac{h_1}{h_0}\right)^n$$

$$\frac{E_2}{E_0} = \left(\frac{h_2}{h_0}\right)^n$$

correspondait un système de droites concourant approximativement en un point théorique unique d'abscisse environ 15 000 kWh et d'ordonnée environ 1 500 mètres. D'où la formule :

$$n \# \frac{\log \dfrac{E_0}{15\,000}}{\log \dfrac{h_0}{1\,500}} \# \frac{\log \dfrac{E}{15\,000}}{\log \dfrac{h}{1\,500}}$$

permettant de connaître approximativement l'énergie récupérable à une hauteur désirée au-dessus d'un lieu d'Europe occidentale, lorsqu'on connaît l'énergie récupérable E_0 à une hauteur quelconque h_0. Voir annexe 4.

On a trouvé des valeurs d'exposants qui, directement liées à celles des gradients de l'énergie éolienne en fonction de la hauteur, sont de l'ordre de 0,2 pour les meilleurs sites et 1,2 pour les plus mauvais. Sauf peut-être dans les très bons sites, il n'est donc pas du tout certain qu'on ait intérêt à faire « frotter par terre les ailes des moulins à vent ». Cela mérite en tout cas une vérification.

Il va sans dire que les gradients ainsi obtenus sont des moyennes qui peuvent à certains moments, notamment pour les sites en bordure de mer vers l'ouest et lorsque les vents y viennent du nord-est ou de l'est, être multipliées par 2 ou 3, et à d'autres, notamment en cas de tempêtes violentes, s'annuler ou presque (44, page 3).

Nous avons hésité pendant plusieurs années à publier un abaque aussi simple dont nous n'avions jamais pu vérifier la valeur, mais nous y avons été récemment incités par la lecture de l'article déjà cité de Davenport.

Partant d'autres considérations, cet auteur serait arrivé à des conclusions analogues s'il avait prolongé vers le haut les droites qui apparaissent sur certaines des figures qu'il a publiées (35, figures 3 et 4, pages 50 et 56). La hauteur au-dessus du sol de leur point de rencontre serait non de 1 500 mètres, mais d'environ la moitié, différence relativement faible en coordonnées logarithmiques La vérité est-elle entre les deux? Des différences de latitudes interviendraient-elles?

Bien entendu, si l'on voulait remplacer dans la formule ci-dessus les énergies par des vitesses cubiques moyennes annuelles, il suffirait de diviser par un

coefficient constant les valeurs des abscisses et par trois les exposants trouvés.

La question des variations de l'énergie éolienne avec la hauteur au-dessus du sol a été étudiée par de très nombreux expérimentateurs (45, chapitre VIII, page 148, 46, page 25; 47, page 11; 48, page 126; etc.).

Coût du transport éventuel de l'énergie

Mais on ne dispose pas toujours d'un bon site en tel ou tel lieu du monde où l'on a besoin de consommer de l'énergie, électrique par exemple. A quelle distance maximale dans ce cas doit-on placer un aérogénérateur, compte tenu d'une meilleure qualité éventuelle du site sur lequel il serait possible d'en envisager l'érection, pour que le coût du transport (installation de la ligne électrique, frais d'entretien, pertes en ligne, etc.) ne soit pas prohibitif?

Il est impossible de répondre simplement à un tel problème, qui méritait cependant d'être énoncé. La solution sera évidemment très différente s'il s'agit d'un aérogénérateur de petite puissance utilisé par un agriculteur isolé ou d'un grand aérogénérateur dont la fourniture irrégulière débiterait sur un réseau préexistant et interconnecté. Entre ces deux extrêmes, combien de cas intermédiaires devraient être étudiés.

Disons seulement qu'en France, si l'on avait à décider dès aujourd'hui entre les Pyrénées-Orientales, région très venteuse mais assez riche en énergies d'autres origines déjà captées, et la Bretagne ou la Normandie, un peu moins venteuses et actuellement dépourvues de sources locales, pour y installer des batteries de grands aérogénérateurs, à supposer que celles-ci fussent au point, le coût du transport du courant serait relativement faible, et ce sont d'autres considérations qui imposeraient sans doute les décisions à prendre.

Conclusions

Ainsi donc est née depuis quelques dizaines d'années une nouvelle branche de l'aérologie, à laquelle s'est posé le problème suivant :

De combien d'énergie éolienne peut-on disposer en tous endroits du monde, entre 25 mètres environ et 100 ou 125, hauteurs qui n'avaient intéressé qu'assez médiocrement jusqu'alors, on le conçoit, les marins, meuniers, agriculteurs ou architectes, d'une part, les aéronautes et météorologistes, de l'autre?

Sans doute existe-t-il une relative incertitude quant à la valeur absolue des renseignements donnés par des petits appareils souvent fragiles et capricieux, qui en outre ne fonctionnent pas tout à fait dans les mêmes conditions que les aéromoteurs, puisque les anémomètres tournent à l'emballement ou enregistrent des pressions, alors que les aéromoteurs travaillent en modifiant considérablement l'écoulement du vent.

Mais enfin, les indications des anémomètres sont déjà pleines d'enseignements, et il semble absolument indispensable, dans chacune des régions sous-développées, de procéder à des recherches anémométriques soigneuses du genre de celles que nous avons décrites, avant de prendre tout autre décision d'ensemble.

Car s'il n'y a, comme c'est à craindre, que relativement peu d'énergie éolienne à récupérer par mètre carré de surface balayée par les pales d'une hélice éolienne dans la plupart des régions équatoriales ou même tropicales, ainsi que nous l'avons déjà fait remarquer (49, page 691), il est bien inutile de vouloir y échafauder dans l'état actuel de la technique des grands aérogénérateurs, des installations multiples ou gigantesques assez mal interconnectées.

Pour l'érection d'un aéromoteur de pompage à faible profondeur ou d'un aérogénérateur de petite puissance, destiné par exemple à recevoir ou transmettre des informations ou à aider un agriculteur isolé, le problème s'y pose différemment, car on peut espérer alors pouvoir doubler ou tripler si nécessaire, sans dépenses prohibitives, les surfaces travaillantes. Mais sauf en cas d'abaissement imprévisiblement important du prix de ces machines ou sauf en cas d'absence totale de tout autre source possible, ce qui ne semble pas être le cas habituel, puisque ces régions sont très riches au contraire en énergie solaire, il ne faut guère espérer, semble-t-il, qu'on soit jamais amené à les y implanter par millions.

Dans les zones tempérées ou froides qui s'étendent sur la moitié environ des terres émergées, bien des parties ne restent-elles pas à prospecter d'urgence et à équiper peut-être ensuite par les éoliens?

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ANNEXE 1

Stations de jaugeage d'énergie éolienne

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
		I. France		
Alpreck I	46	12	2 000	Depuis 1947
Alpreck II	46	40	3 200	1951 à 1958
Amphion	374	14	300	1947
Antifer	94	26	3 000	Depuis 1947
Arzal	81	17	900	Depuis 1951
Aubrac I	1 405	15	2 100	1949 à 1954
Aubrac II	1 330	15	2 000	Depuis 1955
Ault	78	23	2 600	Depuis 1950
Bagnols	71	20	850	1948 à 1949
Baupte	3	10	650	Depuis 1957
Belle-Ile	40	52	3 400	Depuis 1950
Berck	10	46	2 750	Depuis 1952
Besneville	117	8,5	1 100	1951
Béziers	18	19	120	1948
Bidart	79	24	1 900	Depuis 1949
Calais I	7	52	2 800	Depuis 1947
Calais II	1	13	1 300	1948 à 1950
Cap-Bear	60	23	3 550	Depuis 1947
Cap-Ferret	6	33	1 900	1949 à 1951
Cap-Fréhel I	56	17	2 600	Depuis 1947
Cap-Fréhel II	56	31	3 200	Depuis 1952
Cap Gris-Nez	45	22	4 000	Depuis 1947
Cap de la Hague	4	33	3 600	Depuis 1954
Cap de la Hève	104	14	1 500	1948
Cap-Lévy	12	32	3 500	Depuis 1953
Carteret	65	19	4 000	Depuis 1950
Castelnaudary	156	13	750	1947
Cayeux	1	32	2 000	Depuis 1951
Chasseneuil	130	24	650	1948-1949
Château-Chinon	609	8	900	1947 à 1951
Chavanay	147	23	300	1947-1948
Clamart	165	35	850	Depuis 1949
Col de Babourade	615	12	2 900	Depuis 1947
Col des Goules	997	10	650	1948-1950
Colline Beaumont	30	40	1 900	1952-1958
Crêt du Vourbey	1 244	25	800	1948-1949
Distré	48	24	600	1948-1949
Dunkerque	5	27	1 700	Depuis 1948
Eckmühl	1	64	3 700	1948-1951
Enval	860	26	600	1948
Envermeu	149	18	1 000	Depuis 1952
Épi Dellon	2	22	2 000	Depuis 1957
Escalgrain	110	8,5	3 100	Depuis 1952
Eygurande	720	10	150	1947-1948
Faraman I	3	43	4 600	Depuis 1948
Faraman II	3	10	2 250	1948-1951
Fayl Billot	354	30	750	1947-1949
Força Réal	490	15	6 800	Depuis 1947
Gatteville I	1	75	3 900	Depuis 1947
Gatteville II	1	32	3 100	1947-1951
Grand Ballon	1 424	13,5	3 200	1948
Grand Champ	137	20	750	1948
Grattechat	45	18	950	1947-1950
Ile Chausey	20	20	2 700	Depuis 1950
Ile de Groix	65	29	2 900	Depuis 1950
Ile aux Moutons	3	16	2 700	Depuis 1950

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
Ile d'Oléron	7	49	3 500	Depuis 1953
Ile d'Ouessant	57	31	4 800	Depuis 1950
Ile de Ré	5	54	3 200	Depuis 1949
Ile de Sein I Est	1,5	43,5	3 000	Depuis 1949
Ile de Sein II Ouest	1,5	42,5	3 000	Depuis 1955
Ile de Sein III Phare	1,5	51	4 000	Depuis 1955
Ile Vierge I	2	33	3 700	Depuis 1947
Ile Vierge II	2	83	5 300	Depuis 1947
Ile d'Yeu	21	35	3 300	Depuis 1952
Jobourg	184	12	2 100	Depuis 1954
La Barre	15	20	1 450	Depuis 1949
La Bastide-Murat	442	12	550	1948
Lac Blanc	1 280	17	2 200	Depuis 1948
La Canche	179	6	2 000	Depuis 1952
La Coubre	6	65	2 600	Depuis 1948
La Garoupe	99	27	1 200	Depuis 1955
La Giraglia	63	27	5 000	Depuis 1950
La Grande-Ruine	3 765	4	3 500	1949
La Mure	1 583	34	1 050	1947 et 1949
La Narce	1 360	10	1 700	Depuis 1949
La Nouvelle (Colline)	78	12	2 850	1947 à 1950
La Nouvelle (Phare)	2	18	3 800	Depuis 1947
Lannemezan	613	24	250	1948
Larzac	756	22	1 500	1948
Laubert	1 265	6	1 500	1948-1949
Le Charpentier	2	28	3 000	Depuis 1956
Le Pilier	3	34	3 250	Depuis 1954
Les Avalloirs	417	10	800	1948 à 1950
Les Barges	5	27	2 700	Depuis 1954
Les Gardes	210	60	1 800	1949
Les Gribouzy	105	17	450	1947 à 1948
Les Rousses	1 110	12	350	1947 à 1948
Longpré-le-Sec	270	32,5	1 100	1947 à 1948
Longwy	360	119	1 550	1948 à 1949
Louvres	120	39,5	1 050	1954 à 1957
Luçon	20	21	600	1947
Millevaches	950	27	1 400	1948
Mondragon	48	13,5	1 050	Depuis 1956
Mont-Afrique	584	40	1 150	1948 à 1949
Mont-Aigoual	1 567	10	4 000	1948 à 1952
Mont-Canisy	112	9	1 400	Depuis 1953
Mont-Cassel	160	40	1 050	1948 à 1949
Mont-Saint-Clair	73	24	1 950	1956 (8 mois)
Mont-Saint-Vincent	603	16	1 450	Depuis 1950
Mont-Ventoux	1 912	11	5 100	1947-1948
Montélimar	73	16	1 300	Depuis 1948
Montpellier	21	47	1 150	1948 à 1949
Montpezat	300	27	100	1948
Montsoreau	32	45	650	1947 à 1948
Nancy	300	30	500	1948
Nantes-Chantenay	9	91	1 550	1947 à 1951
Narbonne	18	12	850	1948 à 1950
Néac	29	120	800	1948
Nevian	25	23	400	1949
Neuville-lès-Dieppe I	70	25		1948 à 1951
Neuville-lès-Dieppe II	70	40	2 900	1950 à 1957
Nieul	337	160	1 600	1948 à 1950
Nogent-le-Roi I	138	34	1 100	Depuis 1954
Nogent-le-Roi II	138	60	1 600	
Penmarc'h	1	40	3 500	Depuis 1948
Perpignan	43	11,5	1 350	1947 à 1951
Pertusato	83	20	4 800	Depuis 1950
Peseux	780	20	1 050	1948 à 1950

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
Petit-Mars	26	6	300	1949
Pic de Lagrange I	239	8	6 000	Depuis 1948
Pic de Lagrange II	237	40	6 500	Depuis 1952
Pithiviers	120	40	1 200	1947 à 1950
Plonéis	141	110	3 100	Depuis 1952
Plougonvelin I	60	103	4 000	Depuis 1956
Plougonvelin II	60	40	2 150	Depuis 1958
Plouharnel I Bego	10	28	2 000	Depuis 1951
Plouharnel II Plage	4	16	1 800	Depuis 1956
Pont-d'Aramon	19	33	1 400	Depuis 1959
Pont-Saint-Gilles	9	16	600	1948 à 1950
Pontoise I	85	100	1 500	Depuis 1948
Pontoise II	85	75	1 100	Depuis 1948
Pontoise III	85	40	700	1948 à 1956
Porquerolles	63	20	3 300	Depuis 1950
Porspoder I	31	34	3 800	Depuis 1954
Porspoder II	27,5	10,5	2 300	Depuis 1957
Quiberon	15	16	2 000	Depuis 1956
Roches Douvres	1	11	3 100	Depuis 1955
Rueyres	780	35	950	1947 à 1948
Sainte-Assise I	76	250	3 100	Depuis 1948
Sainte-Assise II	75	75	900	1948 à 1958
Sainte-Assise III	76	39	425	Depuis 1948
Sainte-Broladre	83	11	500	1947 à 1950
Saint-Chamant	926	30,5	1 000	1947 à 1950
Saint-Cyr-l'École	165	42,5	850	Depuis 1953
Saint-Félix-du-Lauragais	330	10	1 300	Depuis 1947
Saint-Germain-sur-Ay	4	14	2 050	Depuis 1954
Saint-Gildas (Préfailles)	11	18	1 750	Depuis 1951
Saint-Léger-la-Montagne	670	25,5	1 500	Depuis 1948
Saint-Mathieu	22	27	3 000	1947 à 1950
Saint-Michel	404	40	1 650	1948 à 1950
Saint-Michel-de-Brasparts	391	17	3 300	1952 à 1956
Saint-Nicolas-de-Pierrepont	121	8,5	1 450	Depuis 1952
Saint-Rémy-des-Landes	4	21	2 350	Depuis 1957
Saclay	154	28	700	Depuis 1954
Salin-de-Giraud	10	18	2 050	Depuis 1948
Sancerre I	369	17	1 300	1947 à 1949
Sancerre II	378	18,5	1 050	Depuis 1954
Sannois	167	23	1 100	Depuis 1950
Santilly	138	28	1 300	Depuis 1947
Savenay	80	10	750	1948 à 1950
Sept-Iles	40	15	3 600	Depuis 1954
Soulac	5	10	750	1947 à 1950
Surgères	75	18	800	1947 à 1948
Taingy	388	10,5	1 000	1948 à 1950
Thionville	143	17	700	1948 à 1950
Toulon-la-Montagne	239	20	900	1947
Toulouse	161	12	500	1947 à 1949
Toulx-Sainte-Croix	670	22	1 800	Depuis 1947
Tour Eiffel I	31	305	3 100	1947 à 1957
Tour Eiffel II	31	316	3 200	Depuis 1958
Tournon	250	15	1 400	Depuis 1947
Trappes	168	18	550	1947 à 1948
Tréfléan	126	20	600	1947 à 1948
Trévignon	9	10	1 250	1955
Trézien	49	39	2 900	Depuis 1952
Trois-Moulins	369	10	4 100	Depuis 1950
Truc-de-Fortunio	1 554	10	2 100	Depuis 1950
Truc-de-Randon	1 554	6	2 200	1952 à 1955
Vert Galant (Doullens)	170	35	1 300	Depuis 1948
Vitry	25	24	250	Depuis 1948
Watten	4	27	700	1948 à 1949

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
	II. Europe			
Royaume-Uni				
Barnsness	8	5	1 200	1954 à 1955
Bull Point	49,5	4,5	2 800	1954 à 1956
Butt of Lewis	26	15	900	1955
Costa Hill				un mois
Cranfield	112	11	375	1955 à 1956
Round Island	38,5	24	5 000	1954
Smalls	3	40,5	5 100	1955 à 1956
Danemark				
Gedser		25	2 000	Depuis 1956
Vester Egesborg	12	32	1 750	1954 à 1955
Belgique				
Melsbroek	35	13	700	1954 à 1955
Espagne				
Las Rozas	742	10	550	Depuis 1955
Port Bou	320	12,5	5 750	Depuis 1955
Tarifa	8	32,5	7 000	Depuis 1955
Manso Seco	173	10	1 000	Depuis 1959
	III. Afrique			
Algérie et Sahara				
Abd-el-Moulah	1 097	15	750	1956
Adrar I	270	13	950	Depuis 1956
Adrar II	270	30	1 150	Depuis 1956
Ain-el-Hadjel	539	15	750	Depuis 1956
Ain-Skrouna	1 000	18	800	Depuis 1951
Barika	456	15	475	Depuis 1956
Ben Mored	30	22	1 200	1951 à 1955
Bidon V		15	750	Depuis 1956
Birine	814	15	800	Depuis 1956
Burdeau	900	15	700	Depuis 1956
Cap-Bougarouni	80	15	3 500	Depuis 1958
Cap-Caxine	27	47	2 000	Depuis 1951
Cap-de-Fer	17,5	51	1 900	Depuis 1958
Cap-Matifou	65	37	2 100	Depuis 1952
Châteaudun	770	15	180	Depuis 1956
Chrea	1 550	20	1 750	1952 à 1953
Djebel Oroussc	630	15	2 000	Depuis 1956
El Arfianc	25	15	300	Depuis 1957
El Bordj	932	15	1 800	Depuis 1956
El Golea	380	15	400	Depuis 1956
Er Rahel	230	16	1 300	1954
Fetzara	20	15	400	Depuis 1956
Fort Flatters	380	15	700	Depuis 1956
Ghardaia	530	15	650	Depuis 1957
Grand-Vent I	265	22	2 100	Depuis 1951
Grand-Vent II	262	30,5	2 500	Depuis 1957
Guergeur I	917	20	750	1954 à 1955
Guergeur II	845	20	800	1954 à 1956
Guergeur III	791	20	925	1954 à 1955
Hamadenas	49	15	450	Depuis 1957
Haraouas	57	22	875	1951 à 1955
Igli	510	15	375	Depuis 1955
In-Salah	275	13,5	1 250	1953 — Depuis 1956
Kerrata I	712	22	750	1952 à 1956
Kerrata II	620	22	1 100	Depuis 1952
Kerrata III	563	22	2 150	Depuis 1951

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
Kerzaz	387	15	300	Depuis 1956
Ouargla	138	15	450	Depuis 1957
Oued Nini	875	15	575	Depuis 1955
Ouled Djellal (Mahismer)	240	15	800	Depuis 1956
Sidi-Bel-Abbes I	480	15	250	Depuis 1956
Sidi-Bel-Abbes II	480	30	450	Depuis 1957
Cap-de-Garde	155	15	2 800	Depuis juin 1959
Sidi-Naimi	1 100	15	600	Depuis 1956
Taguine	890	15	1 100	Depuis 1956
Tessala	1 061	15	2 000	Depuis 1956
Tilremt I	740	30	575	Depuis 1956
Tilremt II	740	15	850	Depuis 1956
Timimoun	277	15	800	Depuis 1956
Zouzouria	38	22	1 150	1951 à 1955
Tunisie (République de)				
Ben Métir	528	10	550	1952
Cap-Bon	393	28	8 000 ?	Depuis 1949
Cap-Serrat	186	28	6 500	Depuis 1949
Gabès	2	5	475	Depuis 1954
Gafsa	313	11	950	Depuis 1954
Ile Cani	18	24	3 500	1952 à 1955
Ile du Galiton	155	17	3 300	1954-1955
Ile Plane	8	16	2 900	Depuis 1952
Kairouan	60	13	300	Depuis 1952
Kasserine	674	21	800	Depuis 1953
Kebili	55	17	?	1954 (4 mois)
Kuriat	4	29	2 800	Depuis 1952
Remada	301	12	750	Depuis 1954
Souk-el-Arba	143	12	500	Depuis 1952
Thyna Sfax	11	46	1 950	Depuis 1950
Tunis-el-Aouina	5	12	700	Depuis 1951
Tunis Manoubia	66	13	400	Depuis 1953
Maroc (Royaume du)				
Cap Ghir	38	20	1 850	Depuis 1954
Col du Touahar	502	23	2 900	Depuis 1952
El Hank	63	47	875	1951-1952
Ghercif	383	21	1 000	1953-1956-1957
Midelt	1 509	20	900	1955
Mogador Azelf	130	19	2 200	Depuis 1948
Mogador Usine	5	19	1 950	1948-1952-1953
Piste des Crêtes	110	21	1 200	1953
Tagounit	600	20	800	1955
Taza	629	21	1 000	1954
Tazenaght	1 400	20	650	1955-1956
Zaouïa N'Ourbaz	1 160	20	800	1955-1957
Rio de Oro				
Villa Cisneros	10	10	3 200	Depuis 1957
Iles Canaries				
Fuerteventura	3,5	9,5	1 300	Depuis 1957
Gran Canaria	95	11	6 200	Depuis 1957
Hierro	1 501	9	1 950	Depuis 1957
Lanzarote	16	10,5	1 300	Depuis 1957
Tenerife	23	10	3 000	Depuis 1957
Mauritanie (République Islamique de)				
Atar	226	11	400	1949-1950
Atomaï	320	12	1 400	1956
Cap-Blanc	21	22	2 500	Depuis 1956
F'Derick Gisement	530	3	3 500 ?	1957

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
F'Derick Puits	410	3,5	2 400 ?	1957
Nema	267	11	1 700	1948 à 1950
Port-Étienne	7	10	2 000	1949 à 1953
Sénégal (République du)				
Dakar-Terme-Sud	32		500	1951
Dakar-Ville	48	15	250	1948
Tambacounda	44	30	20	1949 à 1951
Ziguinchor	10		60	1949 à 1951
Debi			600	1957-1958
Guinée (République de)				
Dalaba	1 200	6	100	1949 à 1950
Konakry	50	10	175	1950 à 1951
Mamou	785		100	1950 à 1951
Soudanaise (République) [Mali]				
Kayes	56	10	15	1949
Koulouba	480	20	100	1949
Mopti	276	10	300	1949 à 1951
République Voltaïque				
Bobo Dioulasso	438		400	1949
Côte d'Ivoire (République de)				
Abidjan	16	33	40	1949/1950
Bouaké	338		15	1951
Dahomey (République du)				
Cotonou	5,5	13,5	75	1949 à 1951
Tchaourou	326	16	50	1948 à 1950
Niger (République du)				
Agadès	520	5	200	1949 à 1951
Niamey	222	5	90	1949
Zinder	490	5	100	1949 à 1951
Tchad (République du)				
Fort-Lamy	297	9	100	1950-1951
Cameroun (État du)				
Batouri	660	13	20	1948
Douala	31	18	60	1948
Yaoundé	781	18	20	1948
République Centre-Africaine				
Bangui	403	8	30	1949/1950
Port-Archambault	367	9,5	40	1950-1951
Gabon (République du)				
Libreville	10	10	30	1950
Port-Gentil	1	10	60	1950
République du Congo				
Brazzaville	331	17	40	1949-1950
Franceville	380	5	5	1949-1950
Pointe-Noire	15	10	90	1950
Côte des Somalis				
Ali Sabieh	730		1 000	1948 à 1950
As Ela	350		400	1948-1949
Djibouti	3,5	21	500	1948 à 1950

Stations	*Altitude du sol au-dessus du niveau de la mer en mètres*	*Hauteur de l'anémomètre au-dessus du sol en mètres*	*Énergie théoriquement récupérable en moyenne en kWh/m² par an*	*Observations*
Dorra	400		550	1948-1949
Obock	20		550	1948-1950
Tadjourah	10		450	1948-1950
IV. Océan indien				
Madagascar (République de)				
Diégo Suarez	19	5	1 375	1952
Flacourt	27	10	1 700	Depuis 1955
Ilot des Aigrettes	5,5	32	3 800	Depuis 1955
Ile aux Prunes	3,5	55	1 550	Depuis 1955
Majunga	38	15	300	1951
Tamatave	28	13	650	1949 (9 mois)
Tananarive	1 460	20	425	1949-1952
La Réunion				
Pointe des Galets I	5	27	1 300	1952 à 1954
Pointe des Galets II	14	25	1 000	Depuis 1955
Pointe du Bel Air	25	25	1 150	Depuis 1952
Saint-Pierre	4	21	750	Depuis 1952
Iles Kerguelen				
Port-aux-Français		12	4 800	1951/1952/1954
V. Extreme-orient				
Viet-Nam (État du)				
Ban Me Thuot	482	16	150	Depuis 1954
Nha Trang	45	5	200	Depuis 1952
Phan Rhang	24,5	20	625	Depuis 1952
VI. Océan pacifique				
Nouvelle-Calédonie				
Ile Pott	?	?	300	1949/1950
Nouméa I	89	7	900	1949 à 1951
Nouméa II	78	2	550	Depuis 1953
VII. Groenland				
Station Dumont	320	1,50	1 400	Installation courant 1959
VIII. Amérique				
Saint-Pierre-et-Miquelon				
Cap Blanc	88	12	6 550	Depuis 1950
Galantry	71	24	5 100	Depuis 1950
Guadeloupe				
La Désirade I	46	16	900	1952-1953
La Désirade II	60	27	2 300	Depuis 1955
Martinique				
Fort-de-France	144	19	900	1951-1953
Ilet Cabri	17	27	3 300	Depuis 1955
La Caravelle	119	14	1 900	Depuis 1955
Guyane				
Ile Royale	73	30	550	Depuis 1952
Brésil				
Cabo Frio	0	15	?	Depuis 1956
Juazeiro	300	15	?	Depuis 1956

ANNEXE 2

Fiche descriptive d'un site favorable à l'installation d'aérogénérateurs

A. *Situation générale*

Nom du cap, ou de l'oasis, ou de la chaîne de montagnes, ou du couloir favorable. (Joindre une carte débordant très largement la zone choisie.)
Nom de la localité la plus proche et de la grande ville la plus proche (directions et distances).
Moyens d'accès (chemin, route, voie ferrée, aérodrome).
Implantation du réseau de transport d'énergie électrique le plus proche.
Nature et puissance de la centrale ou des centrales de production.

B. *Caractéristiques topographiques détaillées*

Longueur et largeur de la zone présumée utilisable.
Altitude moyenne (au-dessus du niveau de la mer, et s'il y a lieu au-dessus de la vallée ou de la plaine que le site domine).
Nature du sol (terrain dénudé, ou lande, ou forêt).
Obstacles voisins, arbres (hauteur moyenne), constructions diverses.

C. *Renseignements sur le vent*

Direction d'où vient le vent, en distinguant si possible les directions des vents par saisons.
Exemple : en automne, vent venant le plus souvent du nord-ouest; en hiver, vent venant le plus souvent du nord; etc.
Pourcentage estimé de la vitesse du vent.
Exemple : en automne, pendant 70 p. 100 du temps, vent dépassant 8 m/s,
Source des renseignements sur le vent (observatoire, sémaphore, aérodrome).
Durée des observations.
Divers (existence d'anciens moulins, d'éoliennes de pompage, d'aérogénérateurs modernes, noms locaux du vent, dictons populaires, etc.).

ANNEXE 3

Fiche de renseignements sur une station d'appareils de mesure du vent

A. *Nom de la station*

B. *Situation*

Emplacement de la station (joindre une carte d'ensemble).
Emplacement du site présumé favorable à l'installation d'aérogénérateurs. (Marquer ce site sur la carte.)
Moyens d'accès (chemin, route, voie ferrée, aérodrome).

C. *Caractéristiques détaillées*

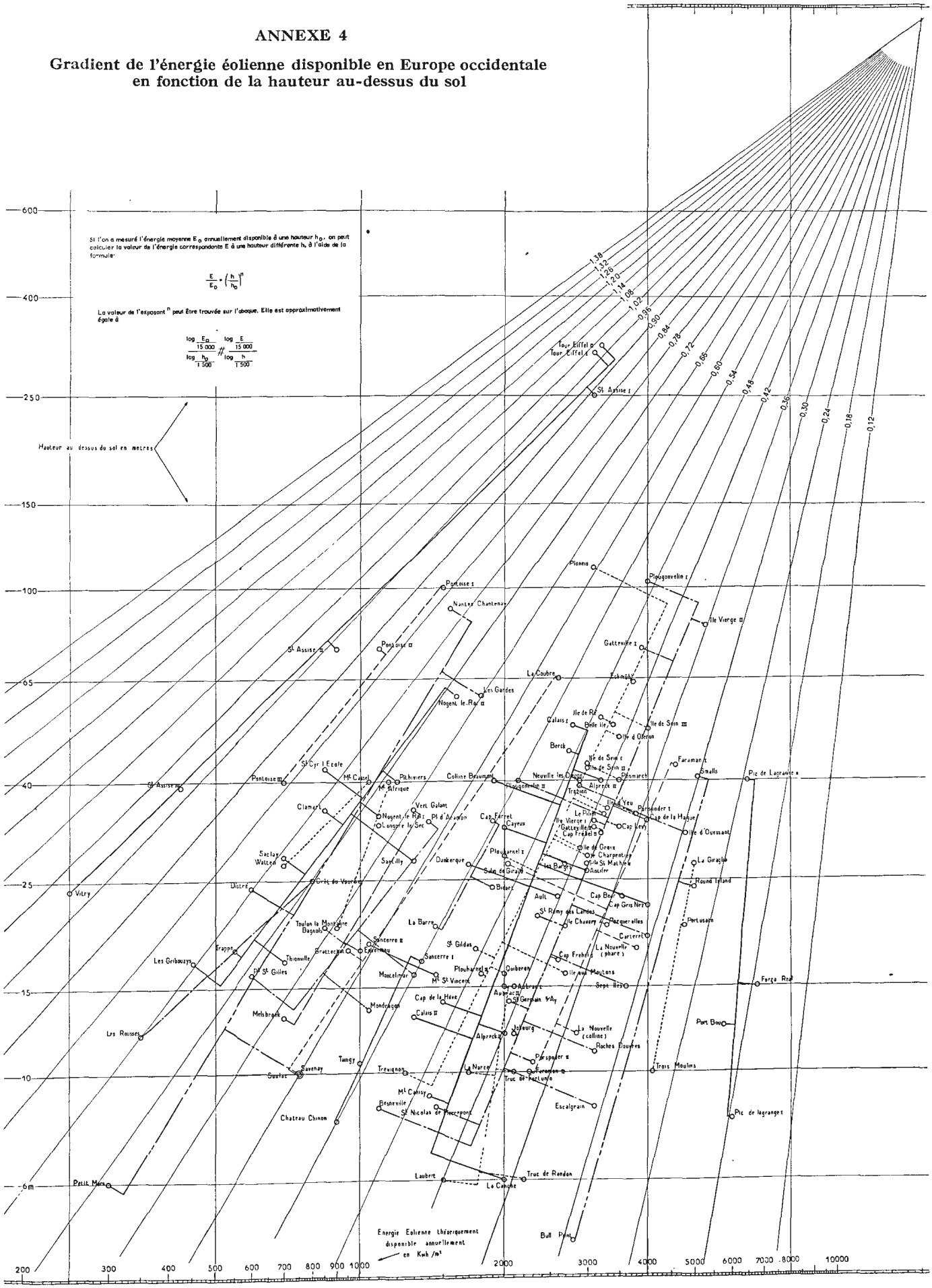
Position exacte du support des appareils de mesure : indiquer sur une carte à grande échelle la position précise du support par rapport aux accidents naturels du terrain, aux arbres, aux constructions, etc.
Altitude du sol au-dessus des plus hautes mers.
Hauteur du support au-dessus du sol.
Types d'appareils de mesure existants et projetés (appareil de jaugeage de l'énergie éolienne, anémomètre enregistreur, etc.).
Croquis coté de la partie haute du support et des appareils de mesure existants et projetés.
Description du local pouvant abriter les enregistreurs des appareils.
Longueur du câble nécessaire pour relier un appareil exposé au vent à son enregistreur.

D. *Relevés des observations*

Début des relevés d'observations et périodicité de ces relevés.
Nom, fonction et adresse de l'observateur. Distance de son habitation aux appareils.
Adresse où sont envoyés les relevés d'observations.
Remarques diverses concernant le fonctionnement des appareils (graissages, vérifications, avaries, etc.).

ANNEXE 4

Gradient de l'énergie éolienne disponible en Europe occidentale en fonction de la hauteur au-dessus du sol



Résumé

Les deux principaux paramètres permettant la mesure de la puissance P_{max} du vent théoriquement récupérable à travers la surface balayée S par les organes en rotation d'un aéromoteur sont la masse spécifique de l'air ρ et la vitesse du vent V, puisque :

$$P_{max} = \frac{16}{27} \times \frac{\rho}{2} \times V^3 \times S$$

Parmi les anémomètres utilisés jusqu'à maintenant en France et dans la Communauté, on trouve :

1. Des anémomètres Robinson adirectionnels, tournant à l'emballement autour d'un axe vertical : anémomètres à coupelles du Colonel Papillon, très employés notamment par les services météorologiques, et anémomètres à gouttières comptabilisant l'énergie éolienne théoriquement récupérable (type Ailleret, fabriqués par la Compagnie des compteurs). Les constantes de temps de ces deux sortes d'appareils vont de une à quelques secondes.

2. Des anémomètres dont la traînée, variant avec la pression dynamique du vent, modifie des circuits électriques alimentés par accumulateurs ou par piles et qui comportent des enregistreurs ou des compteurs. La constante de temps des appareils Best-Romani de ce genre (à cylindre vertical rugueux) est de moins d'un dizième de seconde.

Des mesures comparatives, effectuées dans le vent naturel entre un anémomètre à compteur d'énergie éolienne, un anémomètre à cylindre rugueux et un anémomètre Robinson d'origine britannique enregistrant les miles de vent franchissant le site ont été satisfaisantes.

On présente souvent les résultats des jaugeages effectués à l'aide des uns ou des autres, sous forme de courbes des vitesses ou des puissances classées du vent dans un site. Il importe alors de préciser non seulement la durée totale des observations (une ou plusieurs heures, une quatorzaine de jours, une ou plusieurs années), mais encore si les mesures nécessairement nombreuses de ces vitesses ou de ces puissances ont été « instantanées » ou « moyennées » sur une minute, une heure, une journée, par exemple.

On les présente aussi en fonction des vitesses du vent, sous forme de courbes des fréquences classées proprement dites des vitesses du vent dans le site, ainsi que des fréquences classées multipliées respectivement par les vitesses, par les carrés de celles-ci ou encore par les cubes de ces vitesses. Au maximum des ordonnées de la quatrième de ces courbes correspond la vitesse du vent théoriquement le plus productif, dont la valeur est considérablement plus élevée que celle du vent le plus fréquent (maximum des ordonnées de la première).

Une remarque analogue s'applique aux roses des vents qu'il est possible de tracer et dont les plus utiles pour les éoliens soulignent l'importance des pressions dynamiques du vent ou des puissances éoliennes disponibles et non pas seulement la direction des vents dominants, compte tenu ou non de la vitesse de ceux-ci.

Il semblerait nécessaire d'unifier internationalement, alors qu'il en est encore temps, les trop divers coefficients, symboles, appellations, règles, présentations des résultats obtenus, formules et constantes utilisés un peu partout et de normaliser si possible quelques modèles seulement d'appareils de mesure et quelques hauteurs au-dessus du sol où, de préférence, placer ceux-ci.

Ainsi, plusieurs paramètres permettent de juger dans quelle mesure les vitesses successives du vent en un point s'écartent de leur moyenne linéaire dans le temps. L'un des « coefficients d'irrégularité » proposés, le cube du rapport de la vitesse cubique moyenne à cette vitesse linéaire moyenne, est celui que les éoliens français ont principalement utilisé jusqu'ici. Sa valeur annuelle sur les côtes de Bretagne ou de Normandie exposées aux vents d'ouest paraît être d'environ 2,2.

Les vitesses moyennes annuelles du vent autour du globe terrestre, et à même hauteur au-dessus du sol, varient d'un site à un autre pareillement dégagé du simple au double, au quadruple, parfois même de 1 à 6. Et corrélativement l'énergie disponible varie de 1 à 200 environ.

Plus de 350 sites dispersés dans le monde entier ont été depuis une quinzaine d'années équipés d'anémomètres à compteurs d'énergie éolienne. En plusieurs régions tempérées ou froides et à environ cinquante mètres de hauteur au-dessus du sol, on a comptabilisé des énergies moyennes annuelles théoriquement récupérables de 4 000 kWh par mètre carré de surface offerte au vent (et par conséquent éventuellement récupérables en pratique à l'aide de grands aérogénérateurs modernes, de l'ordre de 2 000 kWh par mètre carré et par an). Des vitesses linéaires moyennes annuelles de 8 à 8,5 mètres par seconde environ devaient y correspondre.

L'énergie éolienne semble statistiquement assez constante d'une année à l'autre et, circonstance favorable en Europe occidentale, bien plus élevée l'hiver que l'été.

Il faut se méfier des indications d'anémomètres placés dans des zones de survitesses localisées dues à la trop grande proximité d'obstacles arrondis de dimensions diverses (coupoles de phares, sommets de collines dénudées). Les aéromoteurs petits ou grands, contrairement aux anémomètres, ralentissent en effet des quantités d'air importantes et paraîtraient sans doute y donner de bien mauvais rendements. Il faut souvent d'ailleurs se méfier des résultats obtenus à partir d'anémomètres placés à moins de 20 mètres de hauteur au-dessus du sol et surtout le long de pylônes supports élevés (dont seul le sommet, sans plateforme exagérément encombrante, doit être utilisé).

Un abaque expérimental, qui peut n'être valable qu'en Europe occidentale, nous permet de prévoir pour un site l'énergie éolienne annuellement disponible en moyenne à une hauteur désirée, lorsqu'on en connaît la valeur à une autre hauteur quelconque au-dessus du sol.

On pourrait se demander aussi à quelle distance horizontale il serait admissible de transporter, sans dépenses excessives, l'énergie obtenue (électrique par exemple), compte tenu de la meilleure qualité éolienne d'un site éloigné. Mais il semble impossible dans l'état actuel de la technique d'y donner une réponse générale.

Ainsi donc est née depuis quelques dizaines d'années une nouvelle branche de l'aérologie, afin de répondre à la question suivante : de combien d'énergie éolienne peut-on disposer en tous endroits du monde à des hauteurs au-dessus du sol variant de 25 mètres environ à 100 ou 125, hauteurs qui n'avaient intéressé qu'assez rarement jusque-là les marins, meuniers, agriculteurs ou architectes, d'une part, les aéronautes et météorologistes, de l'autre?

Dans chacune des régions sous-développées, il semble absolument indispensable de procéder à des recherches soigneuses du genre de celles que nous venons de décrire, avant de prendre aucune autre décision d'ensemble. Car s'il n'y a, comme c'est à craindre, que relativement peu d'énergie éolienne disponible dans la plupart des zones équatoriales ou même tropicales, les plus riches au contraire en énergie solaire, il est inutile de vouloir y échafauder des installations gigantesques ou même y installer par millions des aéromoteurs de petite puissance (sauf évidemment en l'absence de toute autre source pratiquement utilisable et sauf encore pour des usages spéciaux, tels que pompages et relais pour recevoir ou transmettre des informations, car ceux-ci ne demandent souvent qu'assez peu d'énergie).

Il restera heureusement aux éoliens bien des régions tempérées ou froides à prospecter, puis à équiper.

MEASUREMENT OF THE CHARACTERISTIC PARAMETERS OF WIND POWER FOR THE SELECTION OF FAVOURABLE SITES FOR WIND-DRIVEN GENERATORS

Summary

The two principal parameters involved in the measurement of P_{max}, the wind power theoretically recoverable over the swept surface S by the rotating elements of a wind-driven generator, are the specific mass ρ of the air and the wind speed V, since

$$P_{max} = \frac{16}{27}\frac{\rho}{2} V^3 S$$

The anemometers used up to now in France and the French Community include the following models:

(1) Robinson non-directional anemometers, rotating on ball-bearings about a vertical axis: Papillon cup anemometers, extensively used, especially by the meteorological services, and counter-type anemometers measuring the total wind energy theoretically recoverable (Ailleret type, manufactured by the Compagnie des compteurs). The time constants of these two types range from one to several seconds.

(2) Anemometers running at speeds varying with the dynamic pressure of the wind and thus affecting electric circuits fed by storage batteries or dry cells, including recorders or meters. The time constant of Best-Romani instruments of this type (with a roughened vertical cylinder) is less than a tenth of a second.

Comparative measurements taken in natural wind on an anemometer with a wind-energy recorder, a roughened-cylinder anemometer, and a Robinson anemometer of British make recording the wind speed in miles per hour, showed satisfactory agreement.

The results of measurements made with one instrument or another are often presented in the form of velocity or power frequency distribution curves. In such cases it is important to state not only the total duration of the observations (one or several hours, a fortnight, one or several years) but also whether the wind speed or wind power measurements — necessarily numerous — were "instantaneous" or "averaged", for instance over a minute, an hour, or a day.

Such results are also presented as a function of the wind speed, in the form of frequency distribution curves, in the strict sense of the word, of the wind speed at the site, or of weighted frequency distributions, in which each frequency is multiplied by the first power, square or cube of the wind speed. The theoretically most productive wind speed corresponds to the maximum ordinate of the fourth of these curves (V^3). It is considerably higher than the most frequent wind speed (the maximum ordinate of the unweighted frequency distribution).

There is a remarkable analogy that applies to the wind roses that can be drawn. The forms of these diagrams that are most useful to windpower engineers emphasize the importance of the dynamic wind pressure or of the available wind power, and not only the direction of the prevailing winds, whether or not the speed of such winds is reflected.

It would seem to be essential to achieve international standardization, while there is still time to do so, of the very varied coefficients, symbols, nomenclature, rules, presentation of results, formulae and constants used more or less everywhere, and to standardize, if possible, a few measuring instruments and a few preferred altitudes for siting them.

Thus various parameters permit us to judge the extent to which the successive wind speeds at a given point deviate from their arithmetic average with time. One of these "energy-pattern factors" proposed, the cube of the ratio of the cubic root mean wind speed to mean speed itself, is what French windpower engineers have used up to now as their primary indicator. Its annual value on the coast of Brittany or Normandy, exposed to the west winds, appears to be about 2.2.

The mean annual wind speeds at the same altitudes above the ground vary from point to point on the earth, by a factor of two, of four, and sometimes even of six. Accordingly, the available energy varies from 1 to about 200.

Over 350 sites, scattered over the whole world, have been equipped with energy-recording anemometers during the last fifteen years. In several temperate or frigid regions, the mean annual energy theoretically available at an altitude of about fifty metres has been found to be 4 000 kWh per square metre of swept surface (and consequently the energy that could in practice be recovered using large modern wind-driven generators is of the order of 2 000 kWh per square metre per annum). Mean annual wind speeds of about 8 to 8.5 m/s should correspond to this level.

Statistically, wind power appears to be fairly constant from year to year, and to be considerably higher in winter than in summer, which is a favourable circumstance in western Europe.

One should not rely on the readings of anemometers sited in zones of exceptional localized wind speeds owing to the excessive proximity of rounded obstacles of various size (lighthouse domes, bare hilltops). In contrast to anemometers, large or small wind-driven generators do slow down significant quantities of air and would seem without doubt to possess rather low efficiencies. Mistrust is likewise often in order as regards results obtained from anemometers less than 20 m above the ground, especially those placed on elevated supporting towers (of which only the top, without an excessively bulky platform, should be utilized).

An experimental abacus, whose area of application may perhaps be confined to western Europe, enables us to predict the mean annual wind energy available at any desired altitude at a given site, if the value at any other altitude above the ground is known.

One might also inquire into the horizontal distance over which transmission of the energy generated (electric energy, for instance) would be allowable without involving excessive transmission costs, taking account of the better windpower characteristics of a distant site. But any general answer, in the present state of the art, seems impossible.

So, during the last few decades, a new branch of aerology has arisen. Its object is to answer the question how much wind power is available in all parts of the world at altitudes of 25 to about 100 or 125 m above the ground. Such altitudes had previously but seldom concerned mariners, millers, farmers or architects on the one hand, and aviators and meteorologists on the other.

In each under-developed region it seems absolutely indispensable to undertake careful studies of the type just described, before taking any over-all decision. For if, as there is reason to fear, there is only relatively little wind power available in most equatorial or even tropical zones, which are, on the contrary, the richest in solar energy, then there is no sense in trying to erect huge plants, or even to install millions of low-power wind-driven generators (unless — obviously — there is no other practical source of energy, and unless, further, such generators are to be used only for specialized purposes, such as pumping or communications relays, for such uses often require only very little power).

But fortunately the windpower engineers still have plenty of temperate or frigid regions to prospect, and then to equip.

SPECULATIVE METHODS IN WIND SURVEYING

Miguel Ballester *

The fundamental object of a wind survey is to give a practical answer to a question that is simpler to pose than to answer — the location of the preferred site for harnessing wind power. When a more or less extensive windy area has once been designated (and in this preliminary step, economic, technical and industrial factors may combine with purely meteorological ones), we next proceed to the selection of the sites that are optimum by comparison with other neighbouring sites. Within this area, there will be points theoretically superior, in this sense, to the others. Are we then to try to discover them by subjective exploration alone, or is it worth-while to deploy a whole system of instruments for long-term observations? If we choose the latter, the question is equivalent to deciding on a definite network of stations, but the root of the matter lies in asking ourselves whether this network really should "exhaust" the field, in which case its density might be prohibitive. On the other hand, too sparse a network might not be representative.

Every problem stated in terms of mutually contradictory extreme propositions is customarily attacked by means of compromise solutions, the consistency of which is greater, the more the criteria applied in solving the problem allow the definition of recommended "threshold" regions. The compromise attempts to reconcile economy of means, time and investment with the fidelity and representativeness of the investigation. Here, however, the study no longer claims to cover a scientifically coherent objective, but is bound instead by a certain pragmatism. If the site selection problem is stated as a compromise between (*a*) subjective, visual exploration, giving full attention to the contours of the terrain, estimating the friction for the given surface conditions, the local modifications of the airflow, the ecology, the assumed structure of the wind, etc.; and (*b*) extremely dense coverage of the field, array of instruments, objective discernment of the superiority of some places over others from the instrumental data, etc., then we can conceive of the possibility of working out an intermediate solution of reasonable practical utility.

Confined to a zone with relatively uniform conditions, the employment of a certain number of anemometers will indicate several particular conditions of behaviour after a more or less prolonged experimental stage. The optimum locations still remain unknown, but can be found by shorter field surveys than required for fixed places. If there is not much difference between the various local conditions, and according to the distance between the stations, these stations, which react peculiarly to the general airflow or circulation, will show affinities with each other. Let us distinguish: it makes no difference if the mean wind speeds of each place differ among themselves. In that case, the supplementary exploration indicated will reveal the superiority of some places over others. What is important to us now is this relationship, manifested in parallel behaviour, and appearing in the form of a similarity or correlation between the data. Starting out from this premise, we approach the question: What are the acceptable values of these coefficients of correlation that can be associated with the compromise solution?

First, however, we must emphasize a few points. Two sources or types of discrepancy can be distinguished:

(*a*) The residual discrepancy between the total mean wind speeds at two places, which is still compatible with parallel behaviour;

(*b*) The discrepancy observed between simultaneous values of the time-series, which is due fundamentally to differences in the intrinsic nature of each locality.

Expressed in statistical terms, the former will give good correlations, while the latter will not.

Physically speaking, what causes can result in differences of wind between two places? Without exhausting all the possibilities, and confining ourselves to the specific object of our study, we have, on the one hand, the friction between airflow and ground, accidental geographical features, and highly localized factors. Each of these may make for peculiarities. Then there is the well-marked condition of the airflow, which reflects, on a surface, the situation or field of isolines (trajectories or flow lines — isobars or isohypses) giving the distribution of the velocity vectors under various conditions. Theoretically, in the extreme case of constant conditions, with neither friction nor viscosity, the correlation between two places should be perfect under such constant conditions, without those places necessarily having the same wind speeds. That is, such stations need not necessarily be on the same isotach. It would be sufficient if the stationary character of the airflow obtained in both places, for this would be equivalent to saying that the relationship between the data, which would then be purely functional, would consist

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in a physical law: the hydrodynamic equation of motion connecting the velocities with the gradient.

The nonfunctional component, which may be termed stochastic, is consequently due to the random action of geographical factors and friction, in conjunction with the accidental existence and development of various equiscalar configurations.

There can be no doubt that the task of site selection must take into account, in its programme, the stage of subjective, visual exploration mentioned above, which we consider not only the point of departure of the complementary development work, but also the lower limit of a wind-survey theory whose upper limit — extremely dense coverage of the field — although practically unattainable, would yield an objective answer beyond all discussion.

Elsewhere [1] we have suggested the possibility of a criterion formulated from analytical-statistical considerations, to find a "threshold region" for use as a pattern and derivation of a geographic "radius" of correlation, within which the instrumental observations might have a certain degree of conventional interdependence, so that the results could be extrapolated on application of a coefficient to reflect the difference in local wind speeds between one place and another. We have applied this idea of ours to actual cases, which we present in this paper, perhaps as an example, a debatable attempt, for this paper attempts only to make some contribution to the problem of planning site-selection surveys. It does not exhaust this theme, however. Even less does it pretend to give any definitive answer to the problem so formulated, but it does aim to point out a direction which may perhaps be useful, based on an experiment and on certain initial results.

Series of wind-speed observations, recorded by rotation anemometers installed at places aligned, in a certain way, have been studied for three different zones of the Iberian Peninsula, namely, La Mancha, Galicia, and the South zone. We had 54-month series for the five stations of La Mancha (Consuegra, Puerto Lápice, Campo Criptana, El Toboso and Mota del Cuervo); 50-month series for the four stations of the South zone (Tarifa, Casilla Mulata, Buenavista and San Fernando); and 54-month series for the three stations of Galicia (Estaca de Vares, La Coruña, and Malpica de Bergantiños).

The geographic arrangement will be seen in figures 1, 2 and 3 (scale 1 : 500 000), and the original

[1] World Power Conference, Sectional Meeting, Madrid, June 1960.

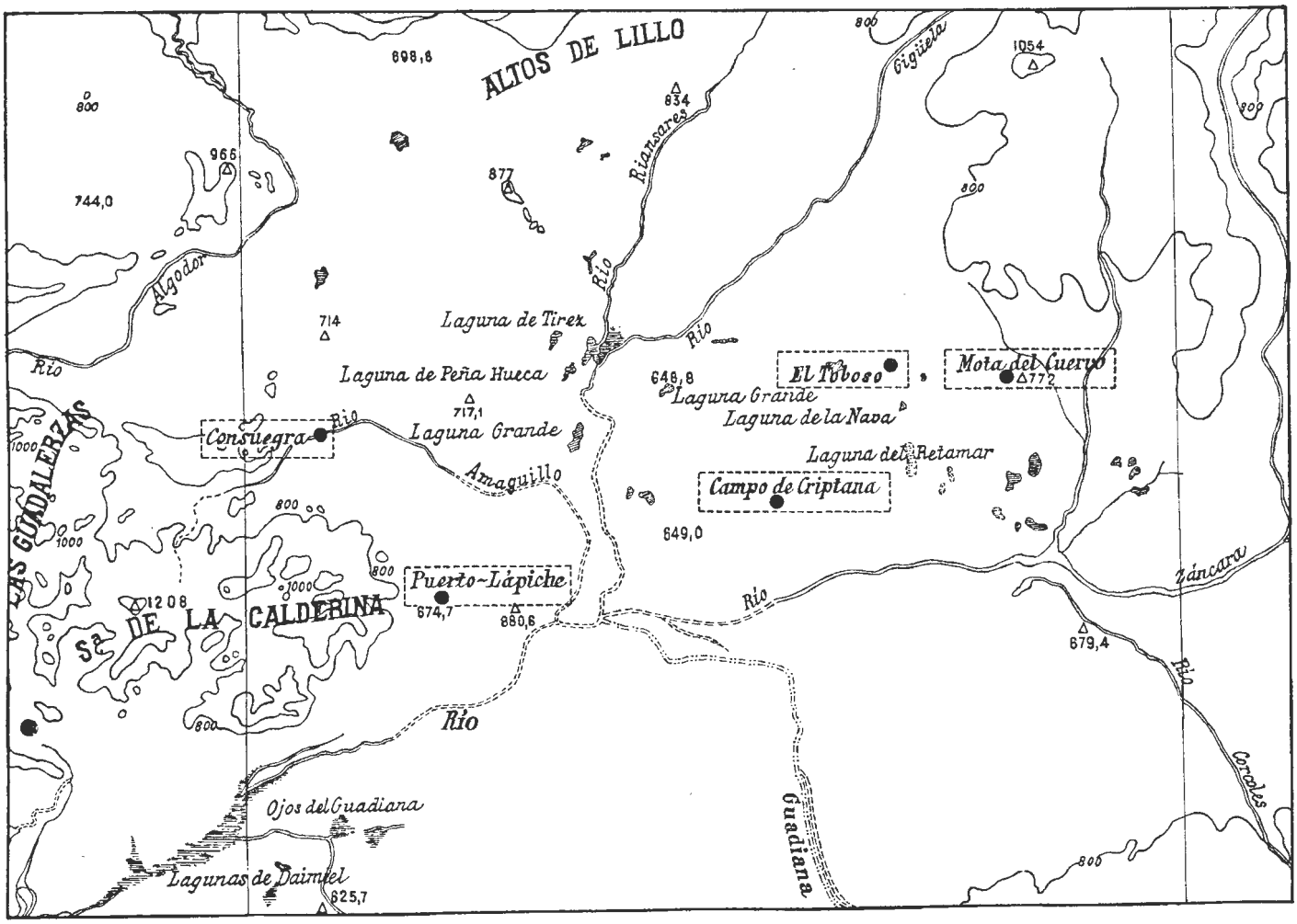

Figure 1. La Mancha

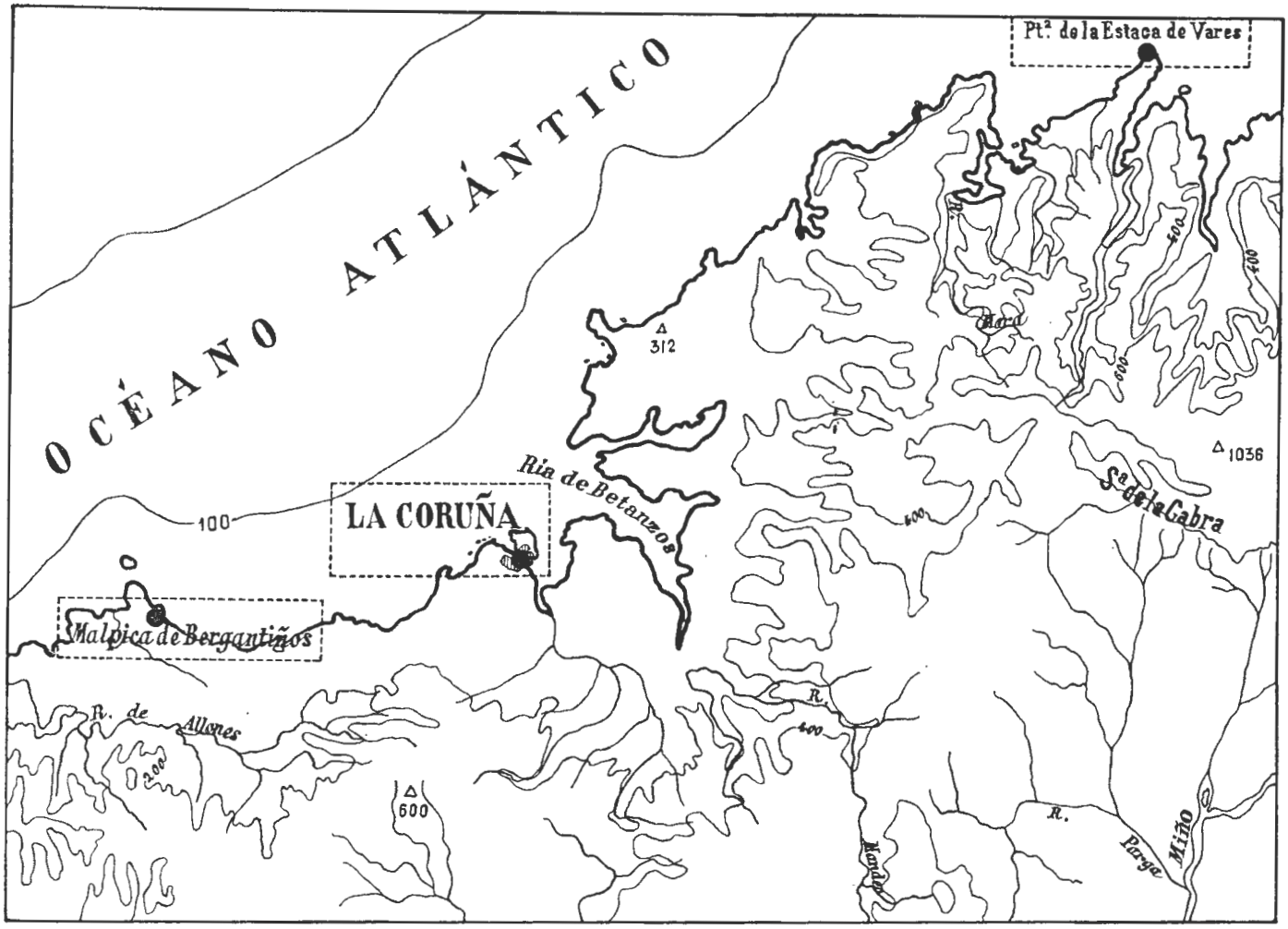

Figure 2. Galicia

series of mean monthly values are given in annex A, B and C at the end of this paper.

The series could have been longer, but only at the expense of homogeneity and comparability. We believe the period of about five years to have been sufficient on climatological grounds, confirmed by the convergence with time given by several precedents.[2]

For the La Mancha zone, the coefficients of correlation have been calculated between Consuegra and the other stations; for the Galicia zone, between Estaca de Vares and the others; and for the South zone, between Tarifa and the others. The values of the separate statistical-climatological indices, both local and with reference to the respective three control stations, may be seen from tables 1 and 2, which also give the distance from each station to its control station.

All these stations, except two, were established by the National Commission on Special Sources of Energy. The two exceptions, La Coruña and San Fernando, belong to the Meteorological Service. In spite of this disparity, the coefficients of correlation fortunately fitted well onto a linear regression. This will be discussed later.

The regression was found by the method of least squares. Taking the distance X between the station and its control station as the variable, and the coefficients of correlation between the series of these stations and that of the corresponding control station as the variable function, we attempted to fit the representative points to the straight line:

$$Y = aX + b$$

by means of a linear approximation, identifying the parameters a and b by the Gaussian method of least squares. This was done for each of the three zones under study.

(a) *La Mancha* (see distances and coefficients of correlation in table 2).

Normal system of equations:

$$(19^2 + 42^2 + 53^2 + 64^2)\, a + (19 + 42 + 53 + 64)\, b = 19 \times 0.921 + 42 \times 0.87 + 53 \times 0.852 + 64 \times 0.831;$$

$$(19 + 42 + 53 + 64)\, a + 5\, b = 1 + 0.921 + 0.87 + 0.852 + 0.831$$

[2] See, for example, P. C. Putnam, *Power from the Wind* (Van Nostrand, New York, 1948), pp. 71-79.

equivalent to:

$$9\,030\,a + 178\,b = 152.379$$
$$178\,a + 5\,b = 4.474$$

giving as a result the identification of the parameters:

$$a = -\,0.00256 \qquad b = 0.98598$$

so that the equation of the better fitted straight line is:

$$Y = -\,0.00356\,X + 0.98598$$

(b) *Galicia*. Proceeding similarly, we get the Gaussian normal system:

$$16\,354\,a + 140\,b = 139.34$$
$$178\,a + 3\,b = 2.58$$

which identifies the parameters a and b defining the straight line:

$$Y = -\,0.00237\,X + 1.00073$$

(c) *South*. The normal system is:

$$8\,216\,a + 140\,b = 113.96$$
$$140\,a + 4\,b = 3.56$$

which gives the straight line:

$$Y = -\,0.00319\,X + 1.00230.$$

These three straight lines are shown respectively in figures 4, 5 and 6.

The dispersion, as will be noted, is very small. In the calculations, the value 1 was assigned to the control or reference station (since there is perfect correlation between the values of the series compared with themselves). The ordinate at the origin is practically unity on all three straight lines, with the regression of La Mancha showing the greatest departure. The line of the South zone has a considerably steeper slope, while that of Galicia is the flattest. This can be explained as a result of the friction against the ground and by the prevailing wind direction in these zones; this slope represents the decrement of correlation with distance. For the effect of the wind on the surface of the ground, this distance is not the true physical variable, but its participation does modify the conditions. The three Galician stations are coastal, so that, since the friction of the airflow against the sea is less than against the land, the distance effect is here less pronounced. This fact, taken together with the prevailing wind direction, explains the slower decline of the correlation with distance in Galicia. The line for La Mancha likewise slopes more gently than that of the South zone, which can be explained by the

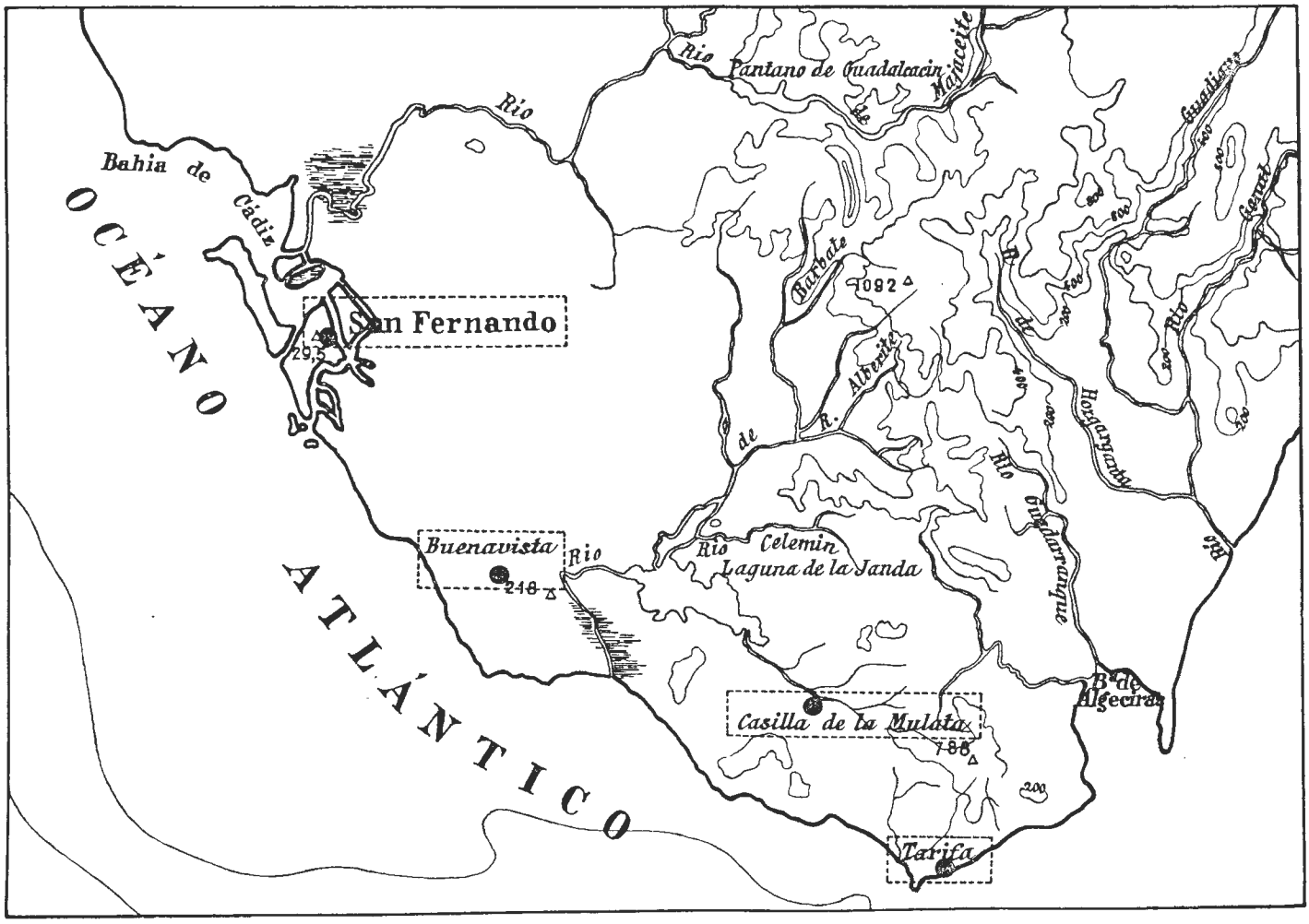

Figure 3. South zone

Table 1. Local indices

	Mean R_i	*Variance* μ_i	*Standard deviation* σ_i	*Variability* σ/R_i
La Mancha (mean values in mm/month)				
Consuegra	1 449	64 452	253.8	0.18
Puerto Lápice	1 463	59 935	244.8	0.17
Campo Criptana	1 172	22 384	149.6	0.13
El Toboso	1 091	26 204	161.8	0.15
Mota del Cuervo	1 264	25 052	158.2	0.13
Galicia (mean values in dm/sec)				
Estaca de Vares	75.91	217.02	14.73	0.19
La Coruña	47.04	97.94	9.90	0.21
Malpica de Bergantiños	70.24	180.00	13.42	0.19
South (mean values in dm/sec)				
Tarifa	81.64	50.97	7.14	0.09
Casilla Mulata	64.20	134.96	11.62	0.18
Buenavista	64.44	44.23	6.65	0.10
San Fernando	44.66	82.95	9.11	0.20

more even terrain, less dissected in La Mancha than in the South. The prevailing wind direction also plays a part. This will now be discussed.

The wind rose in Galicia has an absolute maximum in the north-east and a relative maximum in the west. The three stations of this zone may thus be considered to lie on a line practically perpendicular to this direction. La Mancha has two very similar maxima in the west and south-west. Thus, although the stations do not lie on a single straight line, they are nevertheless swept consecutively from these directions. In contrast, the South zone has a disparate régime. Tarifa, the control station, is almost a dividing point between the Mediterranean and Atlantic régimes. The Mediterranean régime has its maximum frequency in the east, while the Atlantic has almost equal maxima in the south and south-west. All these facts must be taken into account when comparing the variations of these correlations.

Following an interpretative line, we attempt to establish the "threshold" region of utilization as follows.

The study of the development of a variation, in statistics, usually refers to the analysis, not of the standard deviation but of the variance. In this sense, it would be a mistake to identify the coefficients of correlation r_{ik} as the proportions of the deviation of one variable (i) due to the variation of the other (k), since this would imply that $1 - r_{ik}$ would be the proportion of the deviation of i that is not due to k. If the variances are used instead, then the proportional influence of i on k will be precisely

$$p^2_{ik}/\mu_i \mu_k = r^2_{ik}$$

which is thus the square of the coefficient of correlation. Consequently, the component of an element not attributable to the other element will now be

Table 2. Relative indices

	Covariance p_{ik}	*Correlation coefficient* r_{ik}	*Interdependence* $p^2_{ik}/\mu_i \mu_k$	*Distance km*
La Mancha (series in mm/month. Reference station: Consuegra)				
Puerto Lápice	57 250	0.92	0.85	19
Campo Criptana	33 064	0.87	0.76	42
El Toboso	35 048	0.85	0.73	53
Mota del Cuervo	33 418	0.83	0.69	64
Galicia (series in dm/sec. Reference station: Estaca de Vares)				
La Coruña	121.70	0.83	0.69	73
Malpica de Bergantiños	149.92	0.75	0.57	105
South (series in dm/sec. Reference station: Tarifa)				
Casilla Mulata	78.79	0.95	0.90	18
Buenavista	40.12	0.85	0.72	46
San Fernando	49.16	0.76	0.57	76

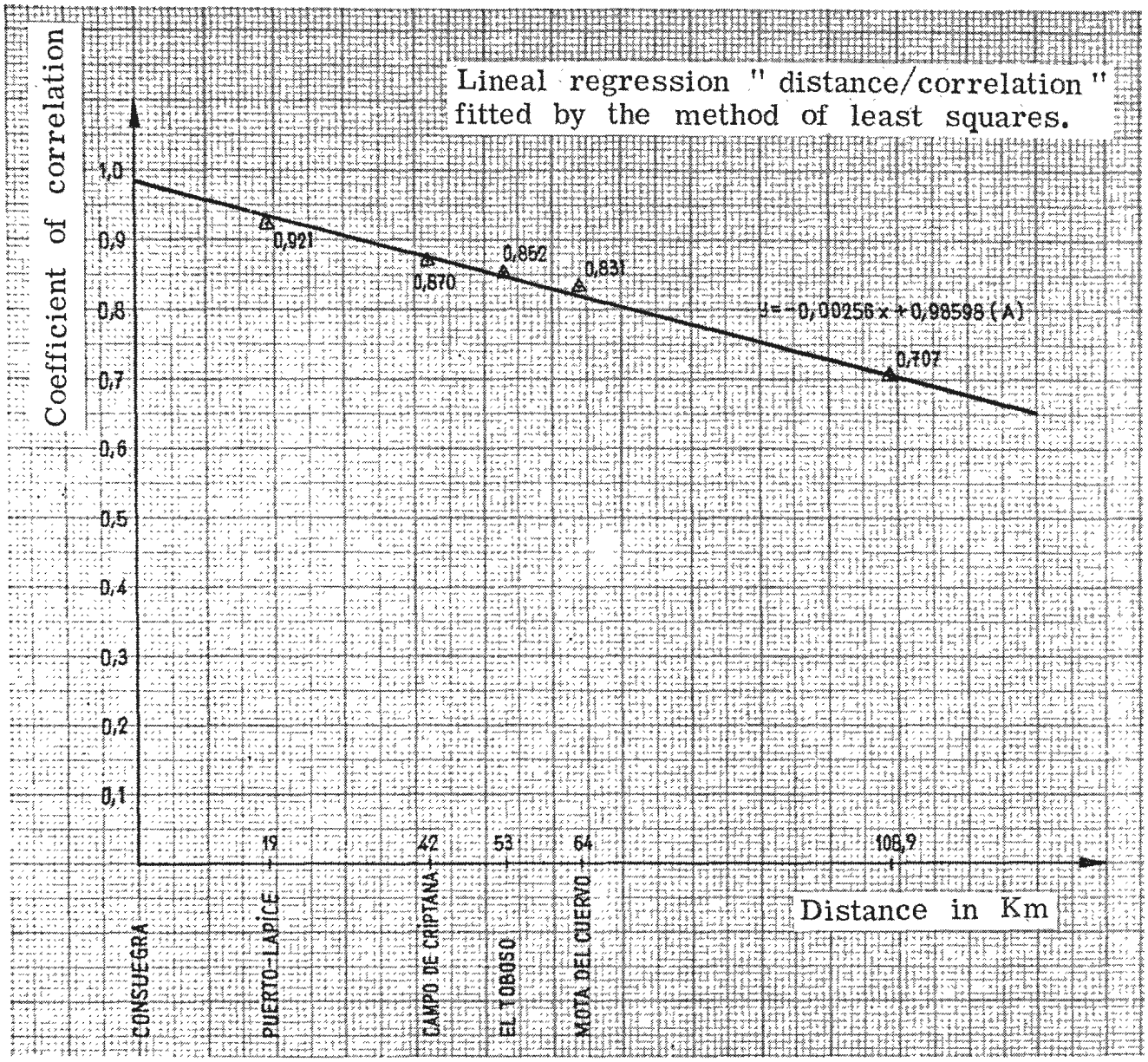

Figure 4. La Mancha

$1 - r^2_{ik}$. Elsewhere [3] we noted that the concatenation of the series should not be confined to the mere interpretation of the correlation coefficients, which would suggest a closer relationship than one would get by following the above line of reasoning.

Putting this judgement into practice, let us transfer the classifical threshold of the correlation coefficient, located at 0.5, to the level 0.70711, whose square (0.5) is located at the midpoint of the scale 0 — 1. We have thus fixed a threshold as an index of the closest interrelation. Applying this criterion to the three regressions under study, we get:

(*a*) La Mancha

$$Y_L = 0.70711 = -0.00256\,X + 0.98598$$
$$X_L = 108.9 \text{ km}$$

(*b*) Galicia

$$Y_L = 0.70711 = -0.00237\,X + 1.00073$$
$$X_L = 123.9 \text{ km}$$

(*c*) South

$$Y_L = 0.70711 = -0.00319\,X + 1.00230$$
$$X_L = 92.5 \text{ km}$$

Thus it follows that the points of intersection of the three straight lines with the "level" 0.70711 give three abscissas or distances in km, representing a geographic radius, threshold or frontier of the degree of relationship. This dependence, which is more conservative than simple correlation, is defined in the interior of each circle corresponding to these radii. Inside such circle a functional relationship above 50 per cent may be deemed to exist, while the remainder left by subtracting i from 100 represents the component subject to mechanisms or influences of random character though physical origin.

[3] World Power Conference, Sectional Meeting, Madrid, June 1960.

We discussed above certain differences of régime in the three zones. The magnitudes of X_L now make these differences more evident.

In conclusion, the threshold sought appears above or below the 100 km mark, being greater or smaller according to the nature of the terrain and the accidental factors.

This may shorten the process of site search and selection, for, given a more or less permanent station in the zone, the task may be confined to brief and economical exploration of the various localities appraised as satisfactory, knowing that direct comparison with portable or vehicular instruments will reveal the superiority of some prospective sites over others, and that prolonged experimental work can now be dispensed with, provided only that these sites are located within a circle in which the conditions are similar to those discussed above, and with a permanent station having a long series of observations. From these series, then, we may extrapolate the development of the behaviour in time. Such extrapolated development for the preferred localities will be, in general, valid, subject to the necessary consideration and detailed adaptation in each particular case.

Obviously, one must not lose sight of the inadvisability of applying the above procedure to zones with a different régime, even though they may be near each other; a preliminary study of the terrain conditions will decide whether such application is proper. But, confined to a favourable area, there may even be disparity in the mean wind speeds, and yet, if the correlations calculated are high,

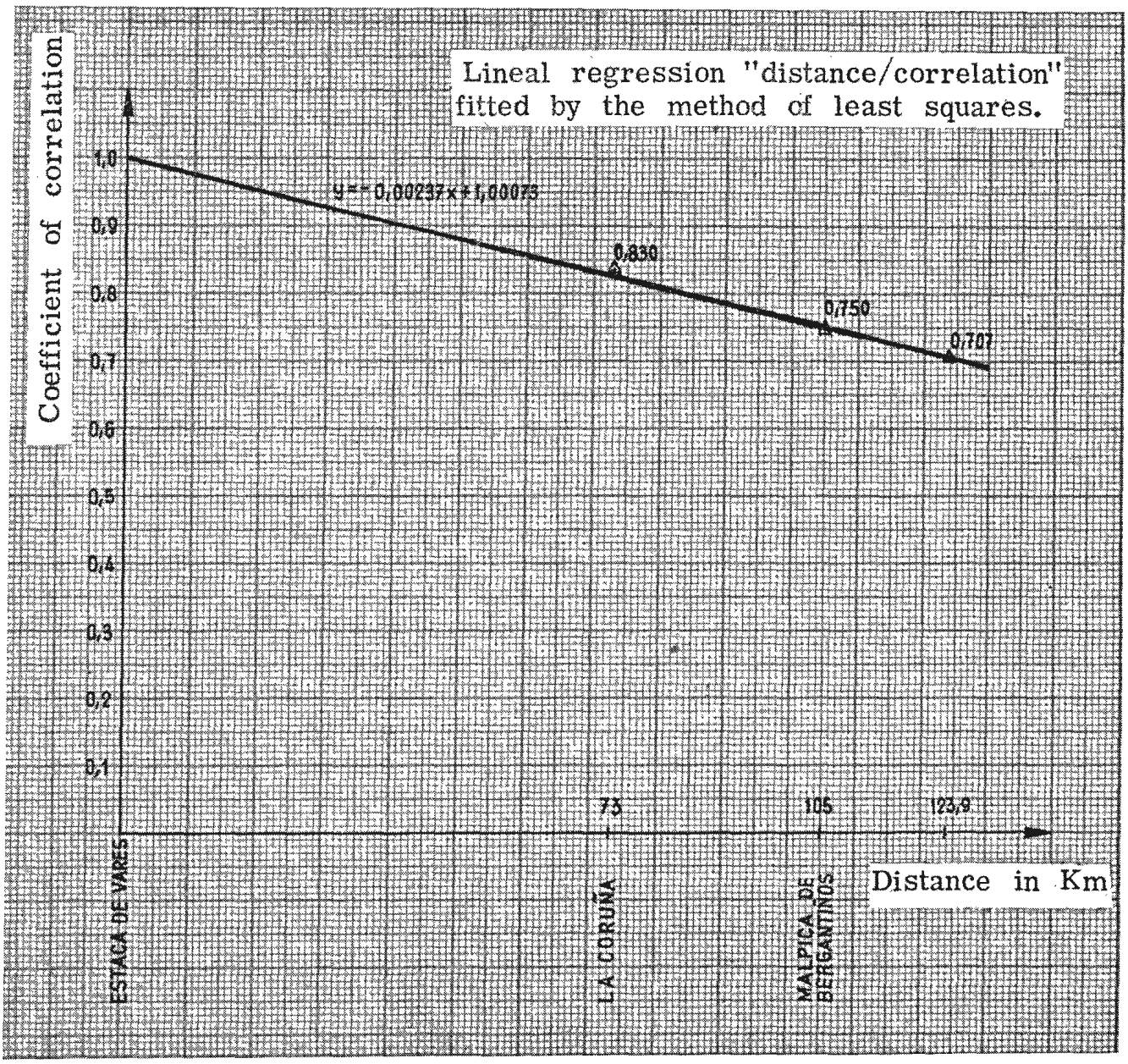

Figure 5. Galicia

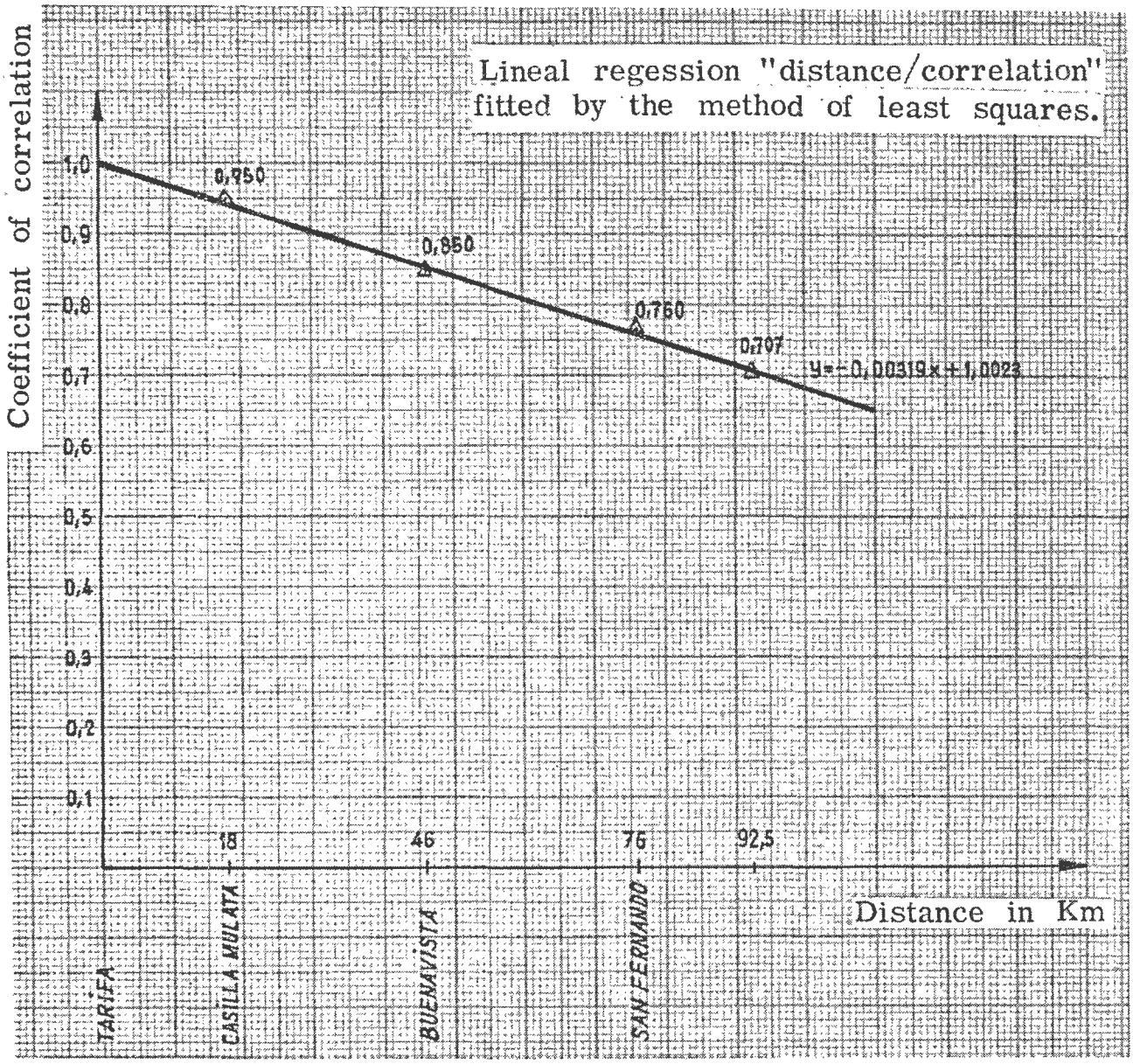

Figure 6. South zone

homogeneous wind conditions and generally common character will still be indicated.

Before concluding, we should like to add that the fact of having fitted a straight line to a set of points does not imply the assumption that the variation of correlation with distance must *a fortiori* be linear. This type of regression has been suitable enough for these introductory studies, but a more detailed examination may suggest a law of variation of higher order, or even transcendental. In this brief and modest paper, it has been our aim merely to state an idea as a point of departure into the field of speculation, supported by a few preliminary results of experiment and calculation.

ANNEX A

MEAN MONTHLY VALUES. LA MANCHA

Wind speed in mm/month				
Consuegra	*Puerto Lápice*	*Campo Criptana*	*El Toboso*	*Mota del Cuervo*
1 448	1 430	1 198	1 203	1 351
1 342	1 233	959	1 165	1 330
1 109	1 391	1 007	886	1 103
1 302	1 282	1 145	1 062	1 218
1 343	1 315	1 050	903	1 109
1 841	1 757	1 296	1 172	1 364
1 451	1 430	952	907	1 051
1 604	1 812	1 292	1 186	1 363
1 816	1 807	1 441	1 353	1 543
1 579	1 554	1 251	1 231	1 332
1 538	1 578	1 201	1 135	1 321
1 306	1 485	1 047	992	1 163
1 504	1 485	1 358	1 206	1 376
1 453	1 491	1 199	1 104	1 254
1 226	1 215	1 099	998	1 192
1 206	1 307	1 097	943	1 152
1 257	1 466	1 131	963	1 136
977	1 022	830	715	914
1 070	1 126	1 034	830	985
1 692	1 642	1 244	1 154	1 306
1 745	1 450	1 376	1 316	1 433
1 497	1 523	1 270	1 118	1 290
1 601	1 758	1 250	1 147	1 312
1 437	1 335	1 099	1 064	1 216
1 328	1 402	1 197	1 113	1 287
1 361	1 408	1 157	1 102	1 282
1 144	1 237	997	867	1 043
1 090	1 196	1 051	868	1 033
1 247	1 298	1 095	984	1 115
1 286	1 348	911	837	1 039
1 523	1 476	1 164	1 072	1 562
1 504	1 556	1 168	1 054	1 222
1 944	1 906	1 399	1 323	1 463
1 676	1 793	1 327	1 246	1 664
1 523	1 557	1 203	1 133	1 281
1 608	1 574	1 252	1 171	1 343
1 340	1 343	1 141	1 078	1 233
1 479	1 440	1 257	1 225	1 408
1 226	1 221	938	920	1 061
1 414	1 500	1 146	971	1 201
995	1 001	937	761	978
2 114	2 052	1 470	1 388	1 563
1 508	1 509	1 203	1 110	1 186
1 295	1 064	1 142	986	1 162
1 838	1 754	1 397	1 376	1 500
1 751	1 877	1 380	1 346	1 540
1 271	1 326	1 081	974	1 142
1 303	1 288	1 199	1 089	1 256
1 470	1 364	1 311	1 273	1 449
1 308	1 316	1 125	1 154	1 326
1 152	1 159	1 056	1 017	1 223
1 459	1 468	1 410	1 290	1 296
1 655	1 526	1 238	1 110	1 309
2 114	2 173	1 483	1 344	1 480

ANNEX B

MEAN MONTHLY VALUES. GALICIA

Mean monthly wind speeds (m/sec)		
Estaca de Vares	*La Coruña*	*Malpica de Bergantiños*
7.8	5.8	8.4
10.5	6.0	8.3
8.6	6.0	8.1
7.5	6.1	8.1
7.0	5.8	7.3
6.9	6.0	6.6
7.3	5.2	6.1
8.0	5.2	6.7
6.0	4.1	5.6
6.9	4.6	5.8
9.3	5.8	7.3
4.4	3.9	5.6
11.4	7.4	9.6
10.9	6.4	10.5
8.0	5.1	7.5
6.7	4.1	6.2
8.2	4.8	6.7
7.5	5.1	6.4
6.0	4.4	5.3
5.5	3.6	4.8
5.7	3.9	5.2
7.2	3.6	5.4
9.2	5.1	7.7
10.7	6.0	8.0
9.0	4.8	8.1
8.8	4.8	9.8
6.8	4.1	7.3
7.0	4.5	7.4
6.4	4.0	6.3
6.4	4.6	6.5
8.0	4.6	6.6
7.6	4.0	6.0
7.0	3.7	5.8
5.7	3.4	6.1
6.6	3.9	7.4
8.6	4.0	6.5
9.3	5.0	8.8
7.5	7.4	9.7
7.2	4.0	6.4
6.6	4.4	8.0
7.6	5.0	8.6
5.4	3.4	4.9
6.5	4.0	5.9
7.6	4.3	6.2
6.8	3.7	6.0
5.7	2.7	4.5
7.4	3.6	6.2
7.1	3.9	7.5
9.2	5.1	8.4
9.1	4.9	7.9
10.2	5.8	8.7
6.8	4.4	7.0
6.9	4.2	6.1
7.9	4.8	7.5

ANNEX C

MEAN MONTHLY VALUES. SOUTH

Mean monthly wind speeds (m/sec)			
Tarifa	*Casilla Mulata*	*Buenavista*	*San Fernando*
7.7	6.5	6.4	4.4
8.5	5.2	7.2	4.7
8.6	6.3	6.5	3.6
8.1	5.1	6.6	4.3
7.8	5.3	6.6	4.5
8.1	5.7	6.5	4.7
8.5	7.7	7.0	5.2
7.6	6.7	6.0	3.9
9.0	7.8	6.5	5.2
7.4	5.8	5.3	3.9
8.1	7.2	6.1	4.8
9.0	7.9	7.0	4.6
8.2	7.3	7.1	5.4
8.4	6.7	6.7	4.7
8.7	6.9	7.1	4.2
6.7	3.6	5.0	3.0
9.1	6.1	7.1	4.4
8.4	5.7	6.8	4.6
8.2	6.3	6.6	5.3
9.1	8.0	7.8	6.9
8.8	8.5	7.1	5.5
9.0	8.2	7.2	5.5
7.2	5.4	5.2	3.9
8.2	7.1	6.5	4.2
8.9	7.9	6.9	4.5
7.0	5.1	5.9	3.3
8.2	5.5	5.5	4.2
7.5	5.0	5.5	2.8
7.0	5.3	5.8	2.4
7.9	5.9	6.2	4.7
6.6	5.1	5.7	3.2
7.7	6.1	6.1	3.6
8.5	7.4	6.8	5.4
9.3	8.9	7.1	5.3
9.1	7.7	6.5	4.9
7.6	6.6	6.2	4.7
7.4	5.8	5.6	2.3
8.5	5.9	6.9	4.9
7.3	4.0	5.3	3.2
8.0	4.8	6.3	4.4
9.2	6.6	7.6	4.9
7.9	5.7	6.8	4.8
8.9	7.2	7.1	5.9
8.8	7.2	6.3	5.5
7.8	6.8	6.5	5.1
8.6	7.4	6.7	5.1
8.4	7.3	6.7	4.8
7.2	5.7	5.3	3.6
9.3	7.6	7.4	5.2
7.2	5.5	5.6	3.2

Summary

This paper presents an aspect of optimum site selection as a problem which permits solutions to be reached by a compromise between the two theoretical extremes: (*a*) the possibility of almost accidental discovery or identification and assuming, in the subsequent stage of refinement, the intervention of subjective estimates and favourable determining factors; (*b*) purely objective reasoning, applying rigorous scientific and experimental methods. The latter may be equivalent to "exhausting" the field of investigation and may be prohibitive from the point of view of time and expense.

From the other point of view, site selection is an exploratory stage, and what is implied in the last part of (*a*) must be taken into account. This will be a starting point for the complementary work that constitutes the lower limit of a site-survey theory whose upper limit, (*b*), would yield an indisputable answer.

The intermediate solution, of reasonable practical use, is valid for relatively uniform zones. The question to be asked is the maximum spacing between stations at which an adequate interrelationship between wind measurements still persists. No comparison of the absolute or mean wind speeds is here indicated, but merely the recognition of parallel wind behaviour.

This parallel behaviour may be evidenced by the correlation between the series of data. In this case, the question is reduced to finding the values of this correlation that would be associated with the compromise solution envisaged.

In attempting to find the sources of discrepancy between the values at different places, our attention is focused on certain physical causes. Friction and airflow conditions vary with the peculiar local circumstances, so that we can distinguish the effect of the functional nexus on the correlation from the effect of the random component, including localized and occasional factors.

A compromise solution demands a criterion to indicate a "threshold", which, in turn, defines a geographic "radius". Within the circle of this radius, the observations will have a certain degree of conventional interrelationship. In view of this, a single permanent station, coupled with mobile exploration, will be sufficient not only to establish the preferability of some sites to others but also, by extrapolation, to find the general line of behaviour.

The experimental work reported in this paper was performed in three zones of Spain — La Mancha, Galicia, and the South zone — with a series of observations from five, three and four stations, respectively. After calculating various statistical climatological indices, we calculated the coefficients of correlation between one reference station in each zone and the other stations in that zone. The correlation was then plotted against distance, separately for each zone, and a linear regression was fitted by the method of least squares, yielding the following equations of the straight lines:

$$Y = -0.00256\,X + 0.98598 \text{ (La Mancha)}$$
$$Y = -0.00237\,X + 1.00073 \text{ (Galicia)}$$
$$Y = -0.00319\,X + 1.00230 \text{ (South zone)}$$

where Y is the correlation and X is the distance from the reference station.

The difference in the slope of these regression lines is attributed to the direction of the prevailing wind at the site of observations and to the nature of the terrain.

Following the interpretative line customary in statistics, we fixed the threshold, not at the midpoint of the scale of values of the coefficients of correlation, but at the square root of that midpoint value instead (the square of 0.70711 is approximately 0.5). Calculation of the points of intersection between the regression lines and this "level" gives the three abscissas:

$$X = 108.9 \text{ km (La Mancha)}$$
$$X = 123.9 \text{ km (Galicia)}$$
$$X = 92.5 \text{ km (South zone)}$$

yielding an initial answer to the question of the order of the distances or geographic radii that constitute the frontier of interrelationship.

This position is highly critical and conservative, for, as may be seen from the figures, the coefficients of correlation are rather high, and their high values make it practicable to reduce the scale of the graphs.

The above reasoning is obviously applicable only to areas where the conditions are uniform, not to zones with different régimes, even though they may be close to each other. Finally, the fact that a straight line has been fitted does not imply that the variation in question must necessarily be linear. The linear character has of course been suitable for this initial study, which is intended merely to indicate a provisional line of departure in the speculative field.

LES MÉTHODES SPÉCULATIVES DANS LA PROSPECTION RELATIVE AUX RESSOURCES EN ÉNERGIE ÉOLIENNE

Résumé

On présente un aspect du choix des sites les plus indiqués sous la forme d'un problème qui admet des solutions représentant un compromis entre des positions qui, en théorie, sont diamétralement opposées : *a*) le caractère contingent de la découverte de ce que l'on cherche, ou encore le fait que son identification est entièrement laissée au hasard tout en admettant, dans des cas particulièrement favo-

rables, l'intervention de jugements subjectifs et de facteurs déterminants propices; et *b*) une déduction purement objective par l'application de procédés scientifiques et expérimentaux rigoureux. Dans ce dernier cas, on pourrait parler d'un « épuisement » du domaine de recherches et il s'agirait alors d'une prise de position qui exclurait matériellement toute possibilité de travail.

Suivant un autre point de vue, ce choix constitue une étape exploratoire et devra donc s'en remettre d'emblée à ce qui est sous-entendu dans la fin du considérant *a* donné ci-dessus, étape qui sert alors de point de départ pour des développements complémentaires, donc de limite inférieure pour une théorie de la prospection dont la limite supérieure *b* pourrait être une réponse incontestable.

La solution intermédiaire, dont la valeur pratique d'utilisation est raisonnable, est acceptable pour des zones relativement homogènes et il s'agit de nous demander qu'elle est la distance entre les stations, jusqu'à laquelle se rencontreront ces analogies suffisantes entre les valeurs enregistrées pour la force et la direction du vent. Il ne s'agit pas d'une comparaison entre valeurs absolues ou moyennes, mais plutôt tout simplement de la mise en lumière d'un parallélisme dans leur comportement.

Ce parallélisme peut être mis en évidence par une corrélation entre les séries de données, ce qui revient à dire que la question se ramène à déterminer quelles sont les valeurs acceptables de cette corrélation qui peuvent se conjuguer avec la réalisation du compromis envisagé.

Dans un effort visant à discerner les sources d'écarts entre les valeurs fournies par plusieurs sites, on prend note de certaines causes physiques en faisant intervenir le frottement et le régime de l'écoulement, en même temps que certaines circonstances locales spéciales. Il s'agit, en ce faisant, de distinguer entre l'injection, dans la corrélation, d'un complexe fonctionnel visible, par distinction avec toute composante aléatoire qui comporte des éléments localisés et occasionnels.

Le compromis exige un critère de définition d'un « seuil » qui définisse lui-même un « rayon » géographique dans lequel les observations puissent bénéficier d'un certain degré de dépendance du type classique. S'il en était ainsi, il suffirait d'un poste permanent, complété par des explorations faites avec des postes mobiles, pour décider non seulement de la raison pour laquelle certains sites sont préférables à d'autres, mais aussi d'une ligne d'action générale par extrapolation.

Les travaux expérimentaux ont été exécutés dans trois zones d'Espagne: la Manche, la Galicie et le Sud. Pour la première, on a procédé à l'étude des séries d'observations correspondant à 5 stations; pour la seconde, à des séries venant de 3 stations; pour la troisième, de 4. Une fois que l'on en a déduit certains indices climato-statistiques, on a calculé les coefficients de corrélation entre un poste et les autres pour chaque zone. Une fois les valeurs réduites à divers diagrammes « corrélation/distance », on a procédé à l'ajustement d'une régression linéaire par la méthode du moindre carré, ce qui a donné comme résultat les équations suivantes, qui définissent trois droites :

$$Y = -0{,}00256\,X + 0{,}98598 \text{ (Manche)}$$
$$Y = -0{,}00237\,X + 1{,}00073 \text{ (Galicie)}$$
$$Y = -0{,}00319\,X + 1{,}00230 \text{ (Sud)}$$

dans lesquelles Y représente, dans chaque cas, la corrélation et X la distance.

On calcule la différence de pente en se rapportant à la direction des vents qui sont prédominants dans le lieu considéré et à la nature de la surface du terrain.

En s'en remettant à une méthode d'interprétation qui est commune en statistique, on a fixé le seuil non pas au point moyen de l'échelle de valeurs du coefficient de corrélation, mais bien plutôt à son carré, c'est-à-dire à 0,07011 (la seconde puissance de cette valeur est sensiblement 0,5). En calculant les points d'intersection des droites avec ce « niveau » on obtient trois abscisses:

$$X = 108{,}9 \text{ km (Manche)}$$
$$X = 123{,}9 \text{ km (Galicie)}$$
$$X = 92{,}5 \text{ km (Sud)}$$

qui permettent de donner une première réponse à la question de l'ordre de distance ou rayon géographique limite qui définit le cercle à l'intérieur duquel la corrélation est possible.

Cette position est éminemment critique ou prudente car, ainsi qu'on pourra le voir sur les tables, les coefficients de corrélation sont assez grands, si bien que c'est le fait qu'on les élève au carré qui réduit l'échelle.

Ainsi qu'il va de soi, le raisonnement donné ci-dessus est applicable à des régions dans lesquelles les conditions sont homogènes et nullement à des zones dans lesquelles les régimes sont différents, quand bien même elles seraient proches les unes des autres. En fin de compte, le fait d'avoir mis au point une droite ne laisse nullement entendre que la variation étudiée doive absolument être linéaire. Ce caractère a été commode pour les fins d'une première étude qui n'a d'autre prétention que celle de présenter une ligne de départ sujette à des améliorations dans le domaine de la spéculation.

PROSPECTING FOR WIND POWER WITH A VIEW TO ITS UTILIZATION

J. A. Barasoain and L. Fontán *

As mankind's level of living rises, the demand for energy increases by leaps and bounds and the need for means of meeting it adequately becomes ever more urgent.

Although wind power does not occupy a prominent position among natural sources of energy at the present time, the foreseeable future demand for energy is so great that man cannot afford to neglect any of the forms of energy which nature freely offers him (1).

The most highly developed countries have for some years been making considerable efforts to find an economic way of harnessing wind power. Notwithstanding the immense impact of nuclear energy, the development of wind power has continued, especially in areas where conventional sources of energy are lacking or where the cost of the power produced is very high.

The problem of harnessing wind power

One of meteorology's most engaging problems is that of the general circulation of the atmosphere (2). Much, however, remains to be done before this important subject is fully understood (3).

Several attempts have been made to prepare world maps of isovents (4), and many meteorological services now have such maps for the areas they cover.

Meteorological literature includes interesting works on the appraisal of the wind power potential of the earth's atmosphere (5). We cannot hope to harness more than a very small fraction of this vast store of energy, and it is estimated — fairly optimistically — that wind power might be utilized to something like the same extent as water power. Professor Sverre Petterssen has prepared, from data furnished by ship stations, a map of equipotential lines for the wind over the oceans (6).

The problem of harnessing wind power involves a series of specific, closely interrelated variables, a favourable combination of which is essential to the economic operation of a wind power plant.

First, we must endeavour to learn the general characteristics of the wind in the area where its use is contemplated. Next, we must try to locate places with favourable characteristics. The wind's course will be affected radically by the presence of a hill in its path; consequently, from an aerodynamic study of the hill, we may be able to predict the size of the factor whereby wind speed at the summit exceeds that on the flat or in the free atmosphere, and the consequent third order effect of increasing the available power.

Since the speed at which the wind blows is constantly fluctuating, it is necessary to learn as much as possible about this fluctuation at the sites selected for wind power use, for it will materially influence the engine design (which must be adapted to the site), the calculation of the tower, the output of power, and — in the absence of an electric power line fed mainly by non-wind-driven power stations — the storage capacity required.

The problem of storage is the most difficult to be faced in connexion with wind power, and many possible solutions are currently under consideration. These include feeding the power produced into an electric power transport network, operation in con-

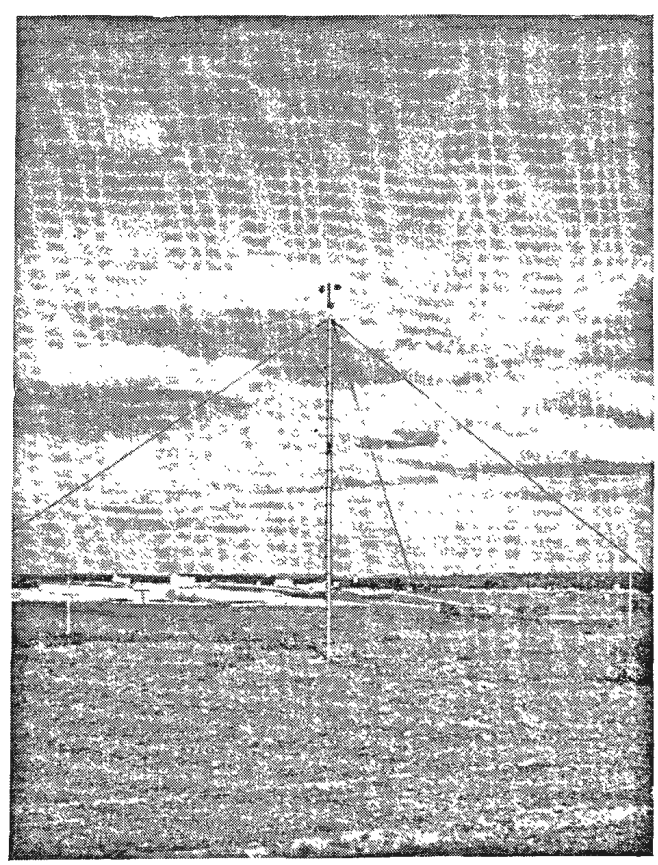

Figure 1. Cup anemometer

* Comisión Nacional de Energías Especiales, Madrid.

junction with other similar units, hydrogen production, batteries of accumulators, and water-pumping.

If the problem of producing a high-capacity, low-cost power accumulator is eventually solved, wind power will be used extensively, for its main disadvantage — irregularity of supply — will have been overcome.

Prospecting for wind power

The ultimate aim of prospecting operations with a view to the utilization of wind power is to determine the most favourable sites from the standpoint, not merely of optimum wind speed, but also of economic factors which, in the last analysis, are decisive.

Wind power prospecting can be divided into two stages. In the first stage, we must outline the wind basins enclosing the areas with the most suitable winds. In the second stage, we must locate the best sites and learn as much as possible about the wind régime prevailing there.

The flow of information collected by the observation networks of meteorological services makes, as a rule, an important contribution towards a first acquaintance with the wind distribution in a particular country. The sites for observatories on the meteorological network were not chosen primarily for their wind characteristics, but, rather, in the light of many other factors which determine the climate of an area, and so as to form a network dense enough for the general requirements of the meteorological services.

It will be seen from the foregoing that it is desirable to establish a network of wind measurements, based on the long series of data compiled by the meteorological services, which can be used to outline the country's wind basins. In this first stage, we have only to ascertain the daily wind travel at the majority of the observation points, and it will be useful to be able to record the wind in more detail at some one point as a check on possible correlations within the wind basin.

From these data of daily wind travel, we can determine the "mean speeds" and plot the "speed duration" and "power duration" curves needed for a first assessment of the maximum utilizable energy and of the approximate performance of a particular type of engine (7).

In this first stage, conventional cup anemometers, whether of the direct-reading or travel-recording type, can be used (8). The wind-power meter (9), in which the collector is a "*pan-anemo*" and the indicator a kWh/m² counter, is also used in this initial stage of prospecting. Figures 1 and 2 show the type of mounting we used for the cup anemometer and the wind-power meter.

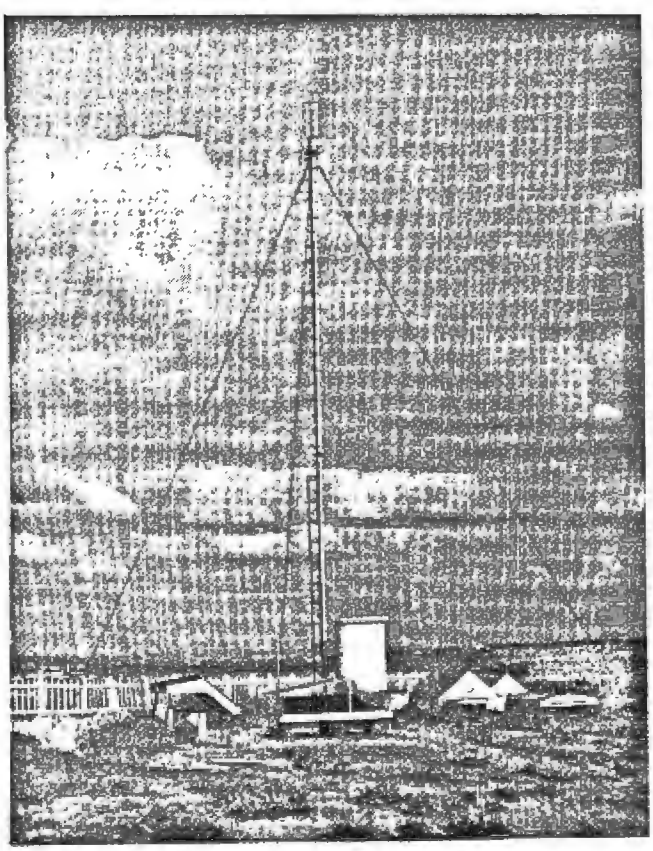

Figure 2. Wind-power meter

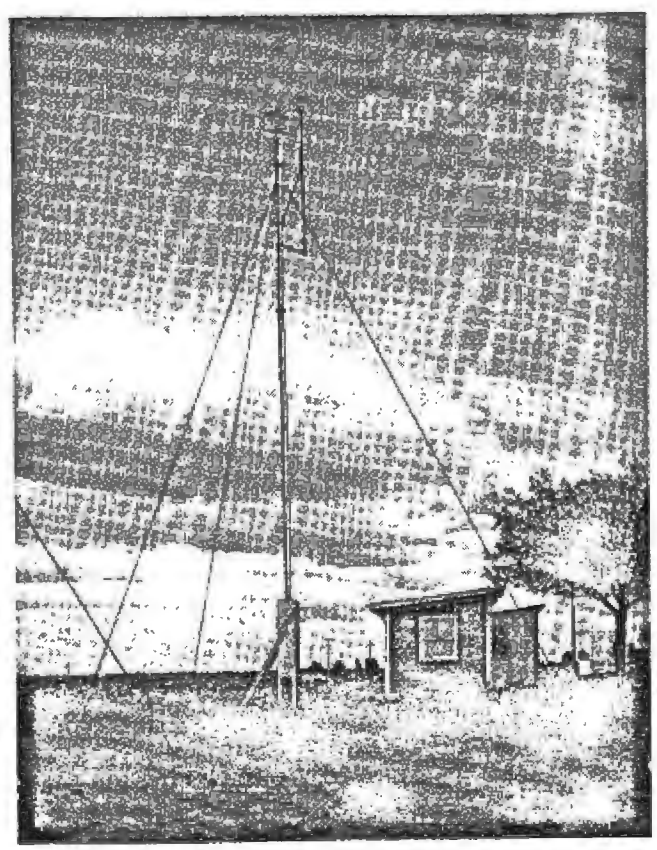

Figure 3. Anemocinemograph

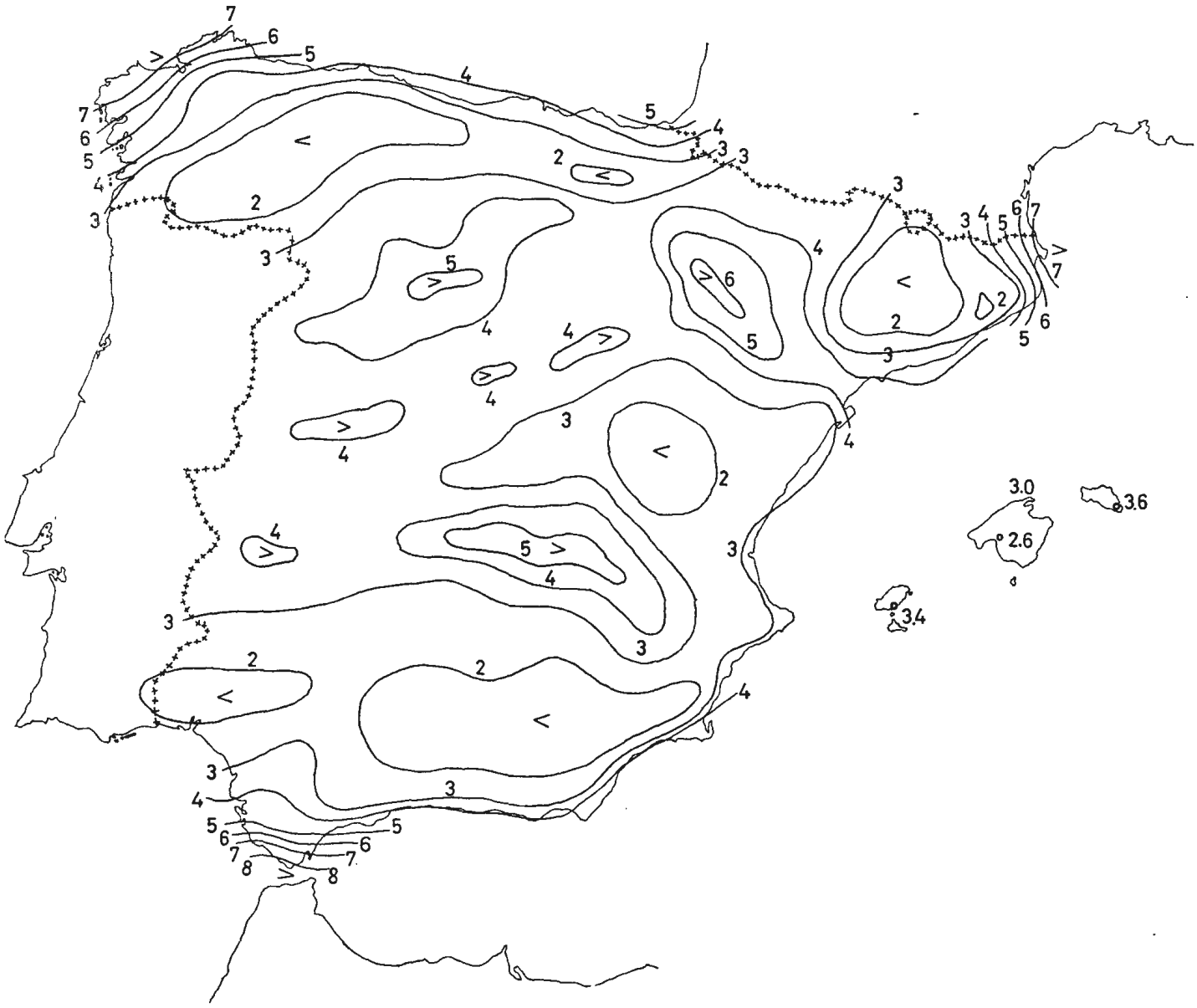

Figure 4. Annual map of isovents in mainland Spain (1931-1959)
(isovents in m/sec)

Within each wind basin, we have to seek out possible sites for wind engines, and in this connexion both the wind régime and the complex of economic factors affecting the site's viability should be taken into account. Wind behaviour at a site is determined not only by the free-air wind but also by orographic factors, for it is a well-known fact that obstacles and vegetation in neighbouring areas reduce the speed of the prevailing wind at a given place. Altitude, hill configuration and distance from the sea are very important variables to consider in selecting a site.

Table 1

Place	*Wind basin*	*Speed (m/sec)*	*Energy: (kWh/m²/year)*	*Type of instrument and height (metres)*	*Period (months)*
Estaca de Vares lighthouse . . .	North-west	7.3		Cup anemometer 7	72
Malpica	North-west	6.8		Cup anemometer 7	83
Cabo Creus	North-east	7.3		Cup anemometer 7	84
Port-Bou	North-east		6 168	Wind-power meter 11	42
Puerto Lápice	Centre	5.5		Cup anemometer 7	67
Consuegra	Centre	5.2		Cup anemometer 7	65
Tarifa Sema.	Straits	8.3		Anemocinemograph 11	61
Tarifa lighthouse	Straits		6 596	Wind-power meter 32.5	72

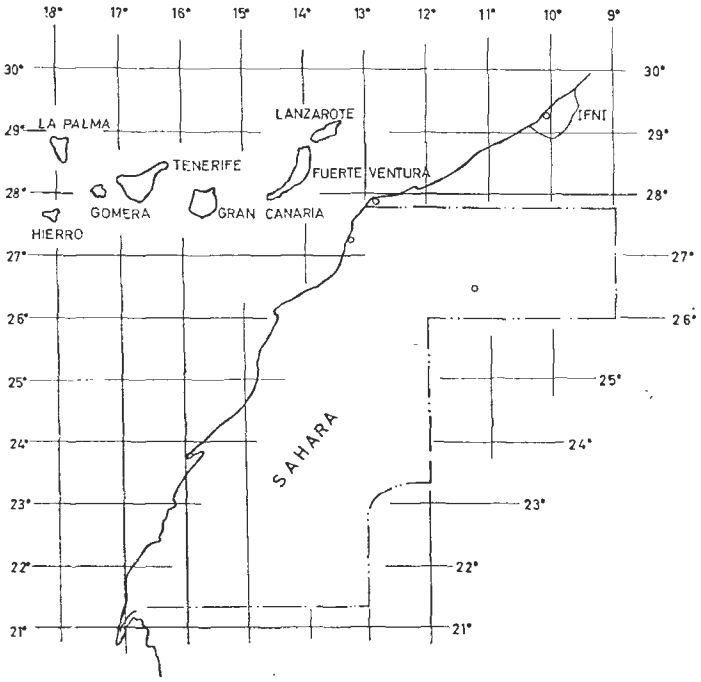

Figure 5. Map of the Canary Islands and West Africa

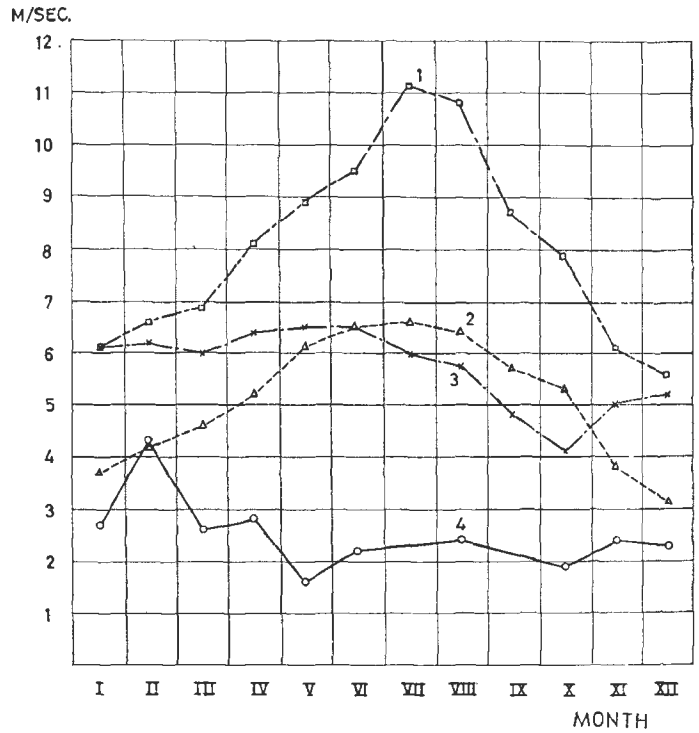

Figure 7. Annual fluctuation in monthly mean wind speed at different places in Africa: 1. Villa Cisneros (Sahara); 2. Smara (Sahara); 3. Cape Juby (Morocco); 4. Sidi (Ifni)

Much information about the wind in a locality can be gleaned from the records made by a set of instruments supplying data on the direction, mean speed and gust speed of the wind (6). We need to know the wind's behaviour in order both to calculate the power capacity of a given wind engine and to

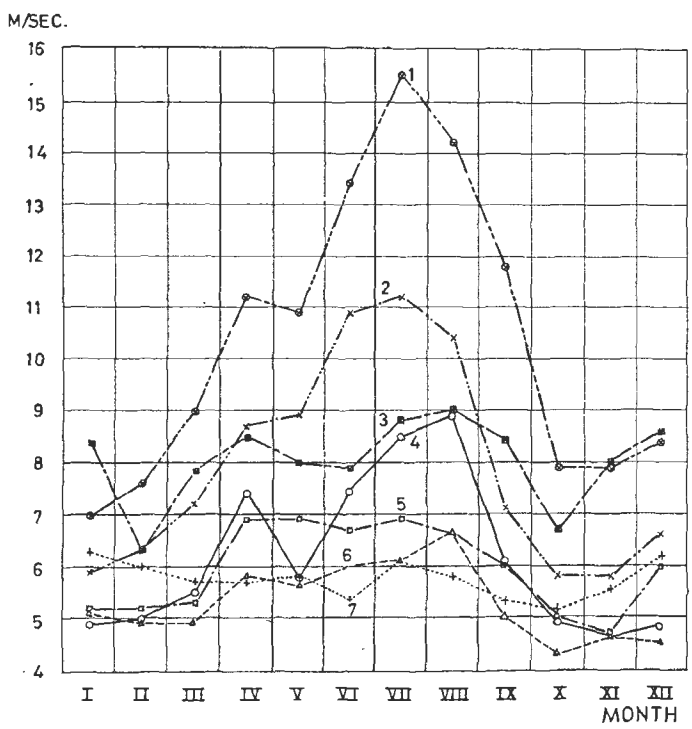

Figure 6. Annual fluctuation in monthly mean wind speed at different places in the Canary Islands: 1. Montaña del Infierno (Grand Canary); 2. Mount Taco (Tenerife); 3. Restinga (Hierro); 4. Arrecife (Lanzarote); 5. Cotillo (Fuerteventura); 6. Tefia (Fuerteventura); 7. Batería del Río (Lanzarote)

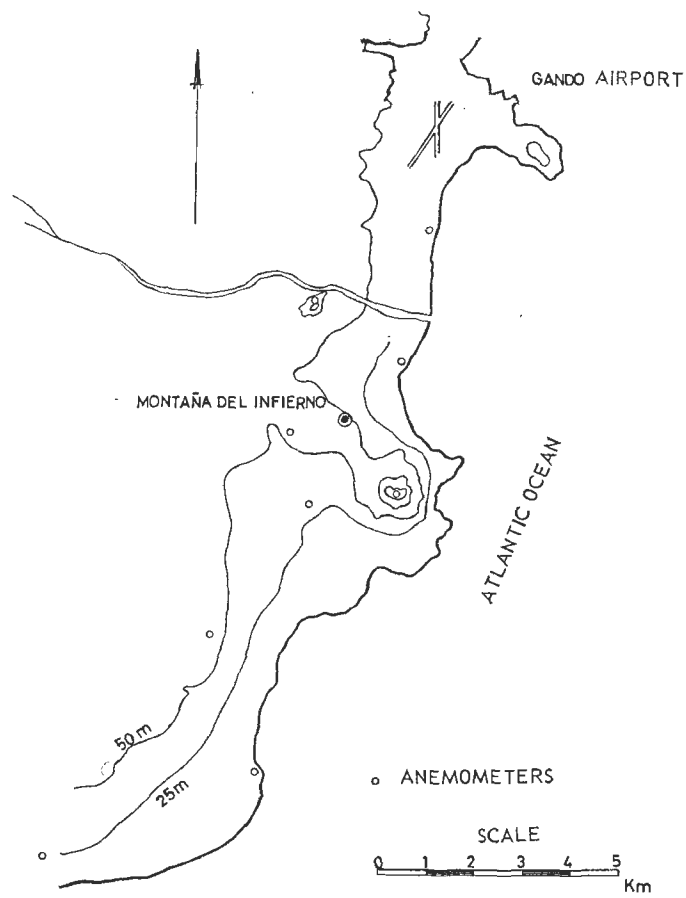

Figure 8. Map showing the position of Montaña del Infierno in the eastern part of Grand Canary

determine the wind stress on the engine and tower. The British Wind Power Generation Committee has studied and developed special types of instruments for recording the velocity vector over a very short time interval (0.1 second), with which the fine structure of the wind can be determined (10). It is also desirable to ascertain the characteristics of the wind over the whole area swept by the vanes of the wind engine, and it is accordingly advisable to install recording instruments at different heights.

Figure 3 shows one of our Fuess anemocinemographs in position.

In order to set up a wind power plant, it is not enough to know one variable — that of wind; the plant must also be economic in operation. Among the factors to be considered, we may mention the following: the characteristics and cost of the engine and ancillary equipment; the possibilities for siting other engines nearby; access to the site; distance from, and nature of, lines of communication; characteristics of the terrain as regards the feasibility and cost of fixed foundations; cost per unit area of ground; distance from electric power transport lines; power requirements in the area; distance from possible centres of consumption.

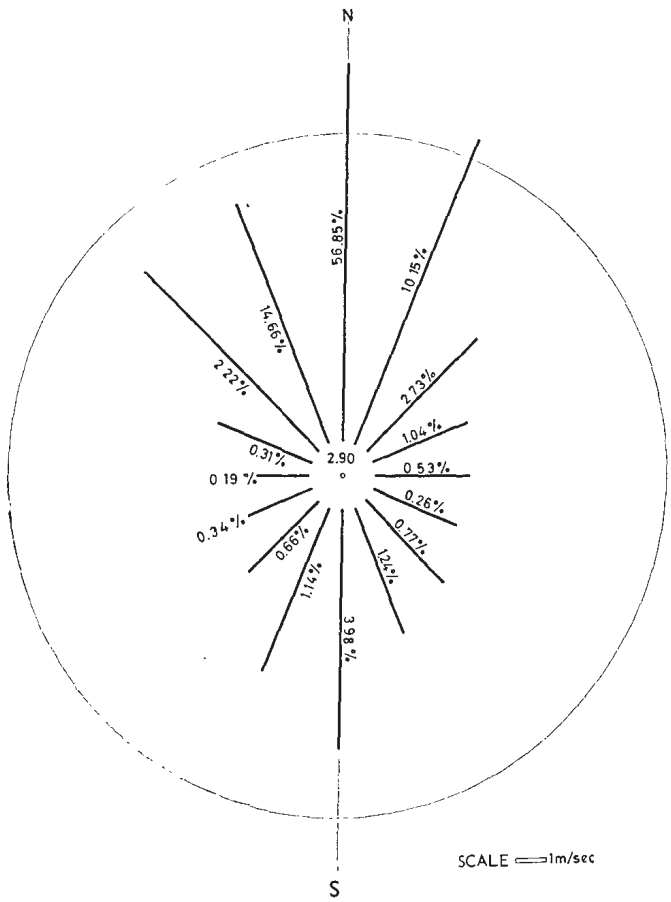

Figure 9a. Frequencies and hourly mean speeds of winds blowing from different points of the compass. Annual rose

Note on figures 9a, b and c. The distance between the dot in the centre and the end of the line represents, on the scale indicated, the mean speed of the wind in each direction. The radius of the outer circle represents the mean speed. The percentage marked against each directional line shows its relative frequency. The number in the centre gives the percentage of cases in which the air was calm.

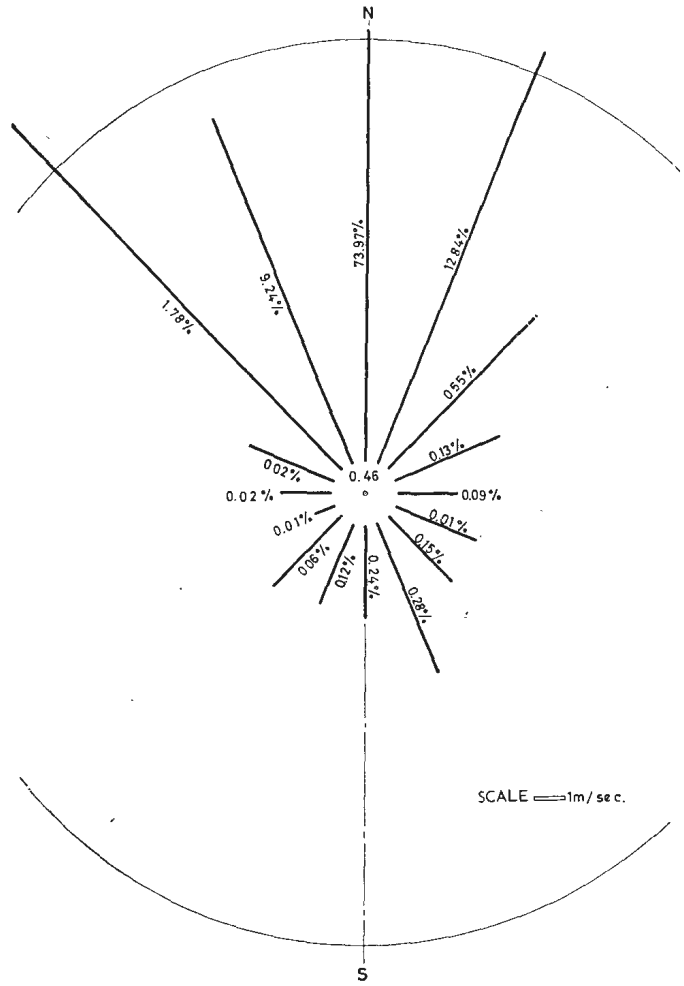

Figure 9b. Frequency and hourly mean speeds of winds blowing from different points of the compass. Summer rose (June, July and August)

Compilation of statistics relating to the use of wind power

The records made and observations taken on the prospecting network are used in preparing statistics from which the performance of wind engines can be ascertained in fair detail.

The principles applied in compiling such statistics vary greatly, but the general rules and methods are the same as those for climatological studies (11).

The main variable to be determined is undoubtedly the mean wind speed, calculated if possible from the figures obtained by measuring the distance travelled by the wind every hour. From this information we plot the speed duration and power duration curves, which are of use in making an over-all estimate of the maximum usable energy, in making a general study of the behaviour of a particular wind power plant of known characteristics, and in determining the correct starting, rated and

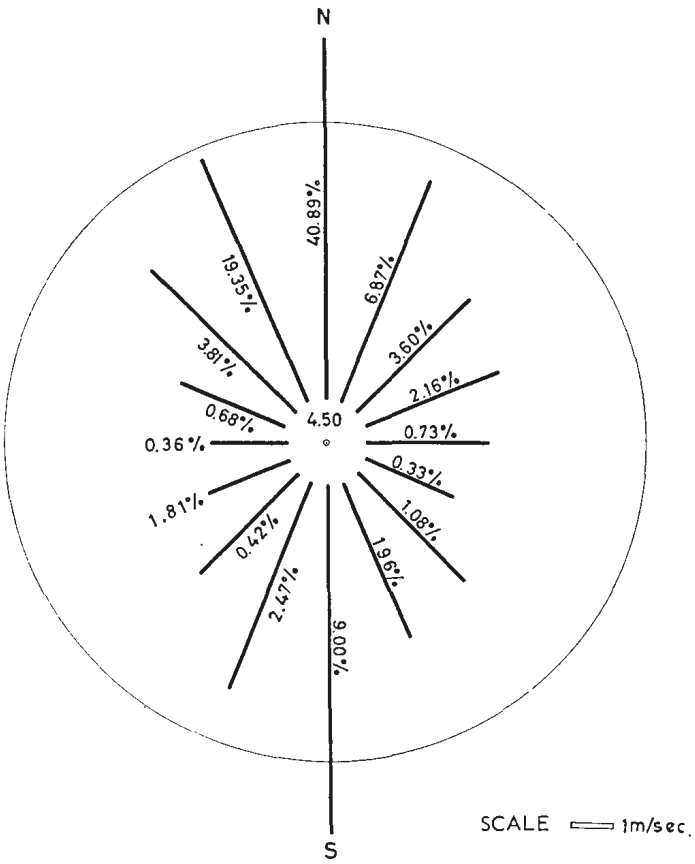

Figure 9c. Frequencies and hourly mean speeds of winds blowing from different points of the compass. Winter rose (December, January and February)

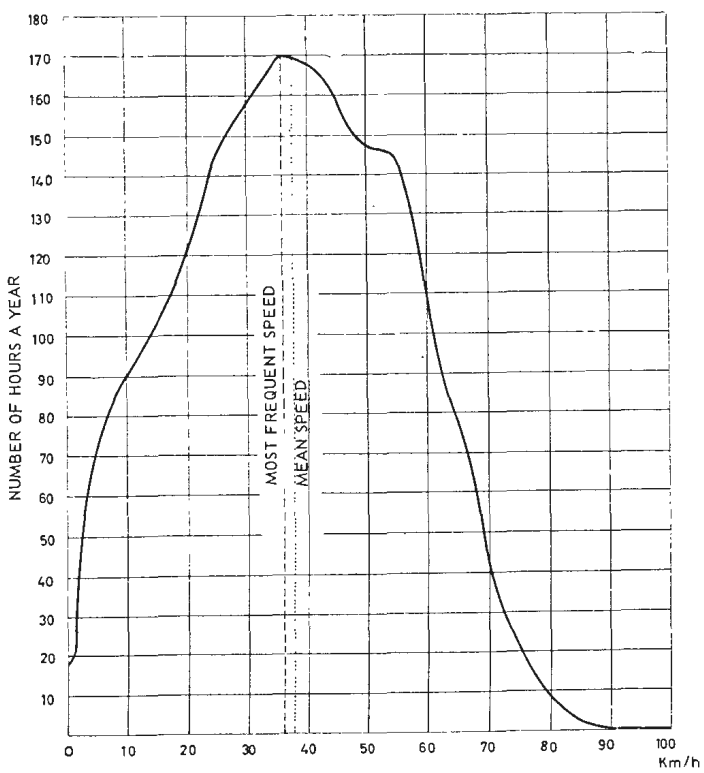

Figure 10. Distribution of hours per year over intervals of hourly mean speed. Against each speed interval of 1 km per hour (abcissa) we plot the number of hours in the year (ordinate) in which the hourly mean speed falls within that interval

furling velocities for a wind power plant designed for the site in question.

This study may be completed by determining the variation in mean wind speed with height.

A knowledge of the variation over time in the hourly mean wind speed, i.e. the daily, monthly and yearly fluctuation, is very useful as regards utilization of the power output of a wind engine, provided that sufficient information is available about the consumers and load curve to be expected.

Where a number of power plants might be sited close together in the same basin, it is also useful to compare the time-fluctuations in hourly mean wind speed at the different sites, with a view to finding ways to even out the oscillation and phase of the wind and thus improving the continuity of the power supply.

The study of energy production is completed by statistics of very high-speed and very low-speed winds.

Moment-to-moment fluctuations in wind speed are a very important factor in the study of a possible wind power plant. In the first place, they affect the power output; this applies both to such fluctua-

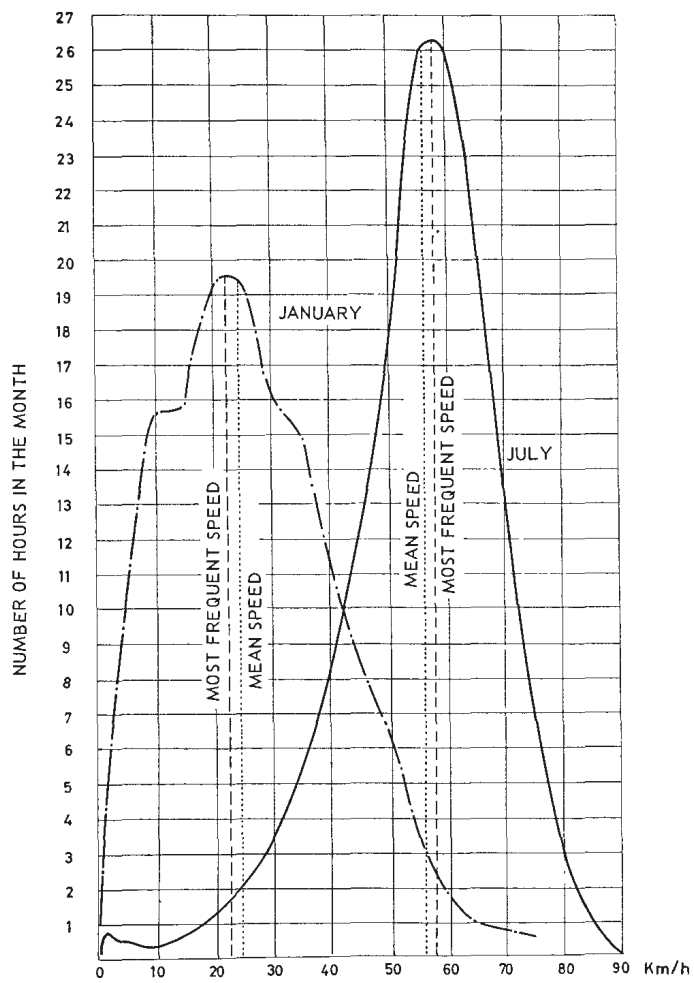

Figure 11. Distribution of hours in January and July over intervals of hourly mean speed. Against each speed interval of 1 km per hour (abcissa) we plot the number of hours in the month (ordinate) in which the hourly mean speed falls within that interval

Table 2

Place	*Wind basin*	*Speed (m/sec)*	*Energy: (kWh/m²/year)*	*Type of instrument and height (metres)*	*Period (months)*
Montaña del Infierno . . .	Grand Canary	10.4		Anemocinemograph 11	71
Montaña del Infierno . . .	Grand Canary		6 178.64	Wind-power meter 11	52
Tenefé point	Grand Canary	7.8		Cup anemometer 7	45
Mount Taco	Tenerife	7.8		Cup anemometer 7	69
F. Abona.	Tenerife		3 481.34	Wind-power meter 11	48
C. Paloma	Lanzarote	6.2		Cup anemometer 7	50
La Caleta Teguise	Lanzarote		1 203.58	Wind-power meter 11	46
Corralejos	Fuerteventura		1 273.92	Wind-power meter 11	50
Cotillo	Fuerteventura	6.3		Cup anemometer 7	84
Restinga	Hierro	8.0		Cup anemometer 7	48
Villa Cisneros	Spanish Sahara		3 528.24	Wind-power meter 11	47
Villa Cisneros	Spanish Sahara	8.1		Anemocinemograph 11	48

tions in general and also to those which occur round about the starting, cut-in, rated and furling velocities. One of the most important problems to bear in mind in designing wind power plants is the possible effect of rapid and very rapid fluctuations in setting up vibrations which may produce resonance phenomena in some component of the plant.

The frequency and mean speed in each direction indicates what kind of rotation the head of the engine will have to undergo and may, in specific cases, determine the choice of a particular type of engine suited to local conditions.

Some results of wind power prospecting in mainland Spain

The Spanish National Meteorological Service maintains a fairly extensive network of meteorological

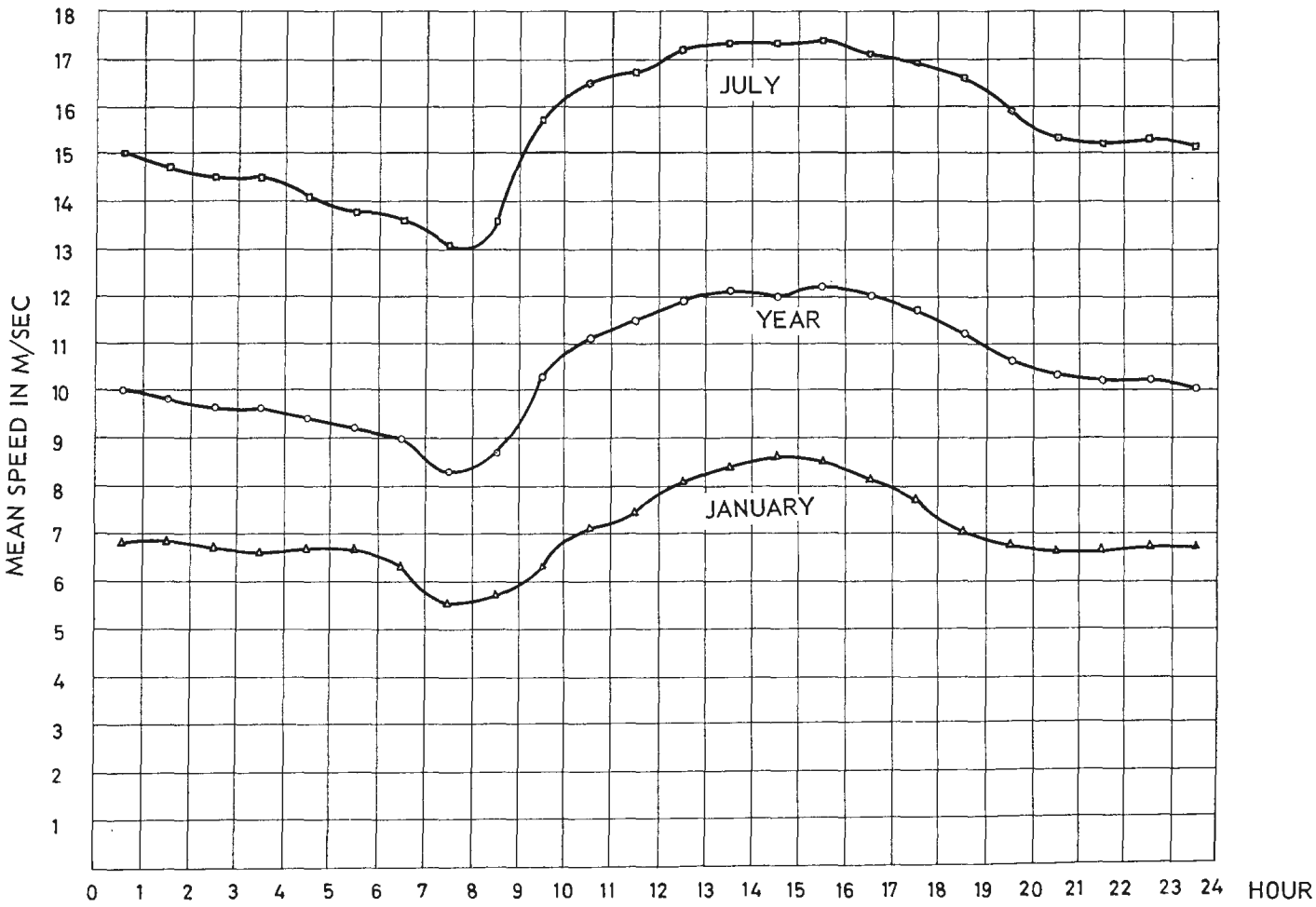

Figure 12. Daily fluctuation in hourly wind speed (year; January; July)

observatories, from which wind information is available (12). This network has provided the basis for the acquisition of a general knowledge of the wind basins. The National Commission on Special Sources of Energy has set up new installations to increase the density of observation points in the areas of greatest interest from the wind power standpoint (13). The National Meteorological Service has recently prepared a wind map of Spain on the basis of all the available data (figure 4).

The isovent maps reveal the existence, in mainland Spain, of areas of favourable wind conditions. These areas, which we term "wind basins", are described below.

(*a*) North-east Spain is buffeted by the *tramontana*, which blows very strongly from the north, north-north-west, and north-east, with considerable frequency in the course of the year. This wind is caused by a high-pressure isobaric structure in north-west Europe and a low in the Mediterranean (14). The channelling effect of the Rhone valley appears to be one reason for this wind's strength, which lasts until the Balearic Islands are reached. The most distinctive characteristic of this wind is its great violence and gustiness.

(*b*) In the Ebro basin, comparatively useful mean wind speeds are observed, although the wind is somewhat gusty.

(*c*) In southern Spain the wind strength is greatest when the *levante*, set up by barometric lows in the adjoining area of the Atlantic, is blowing, and when the reverse is the case; these two situations predominate, with fair regularity, over most of the year. The area of suitable wind conditions is largely confined to the neighbourhood of Tarifa and the nearby part of Morocco. The channelling effect of the Straits of Gibraltar must contribute to the high mean speeds recorded.

(*d*) North-west Spain is exposed to frequent Atlantic storms during which the wind blows strongly, especially from the fourth quadrant.

In table 1, we reproduce some results of wind power prospecting on the Iberian peninsula.

Wind power prospecting in Spanish Africa

It is one of the aims of the Conference that the papers presented should as a rule deal with cases closely related to real needs for the sources of energy

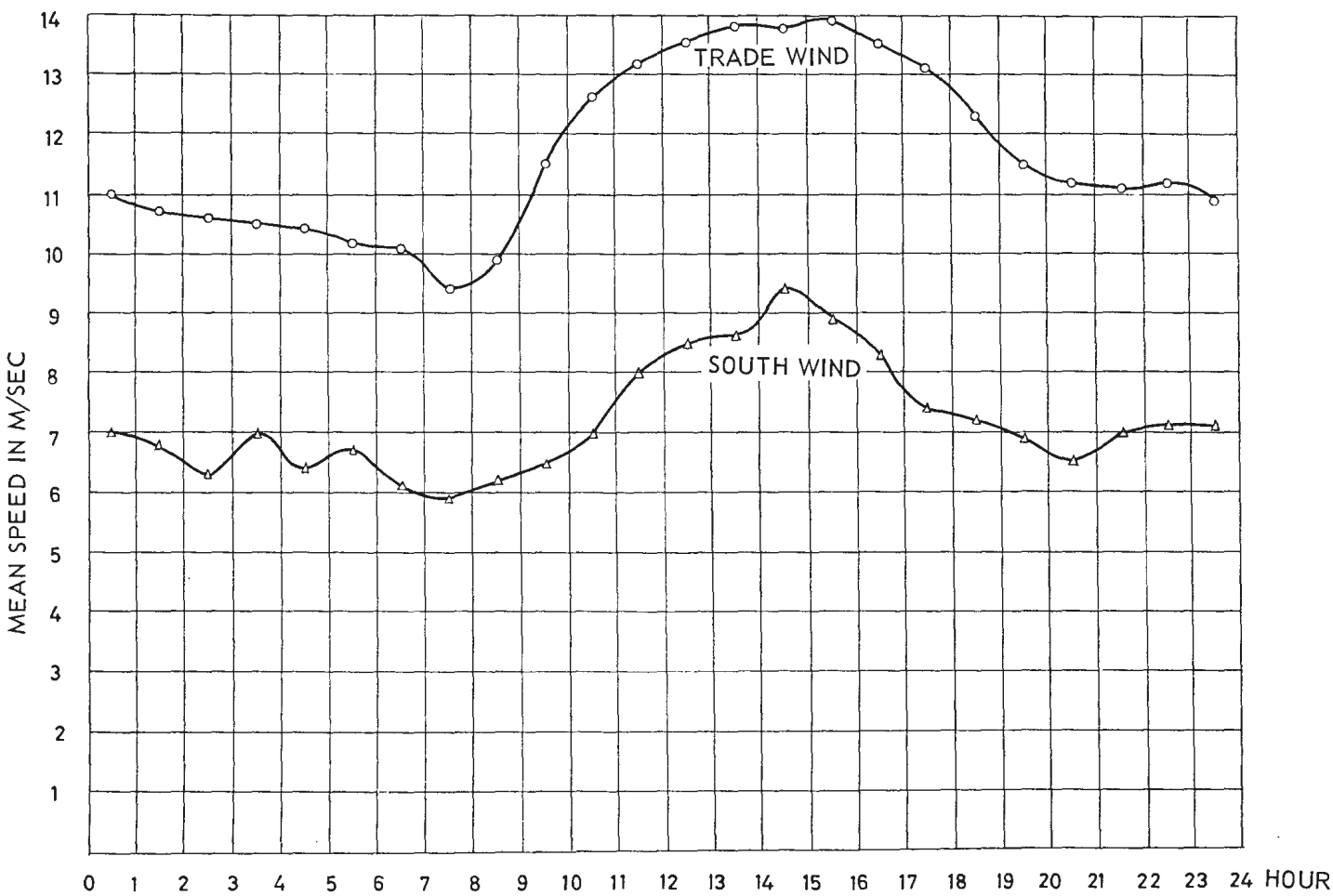

Figure 13. Daily fluctuations in hourly wind speed for sectors 30, 32 and 02, with prevailing trade wind, and sectors 14, 16 and 18, with prevailing southerly winds

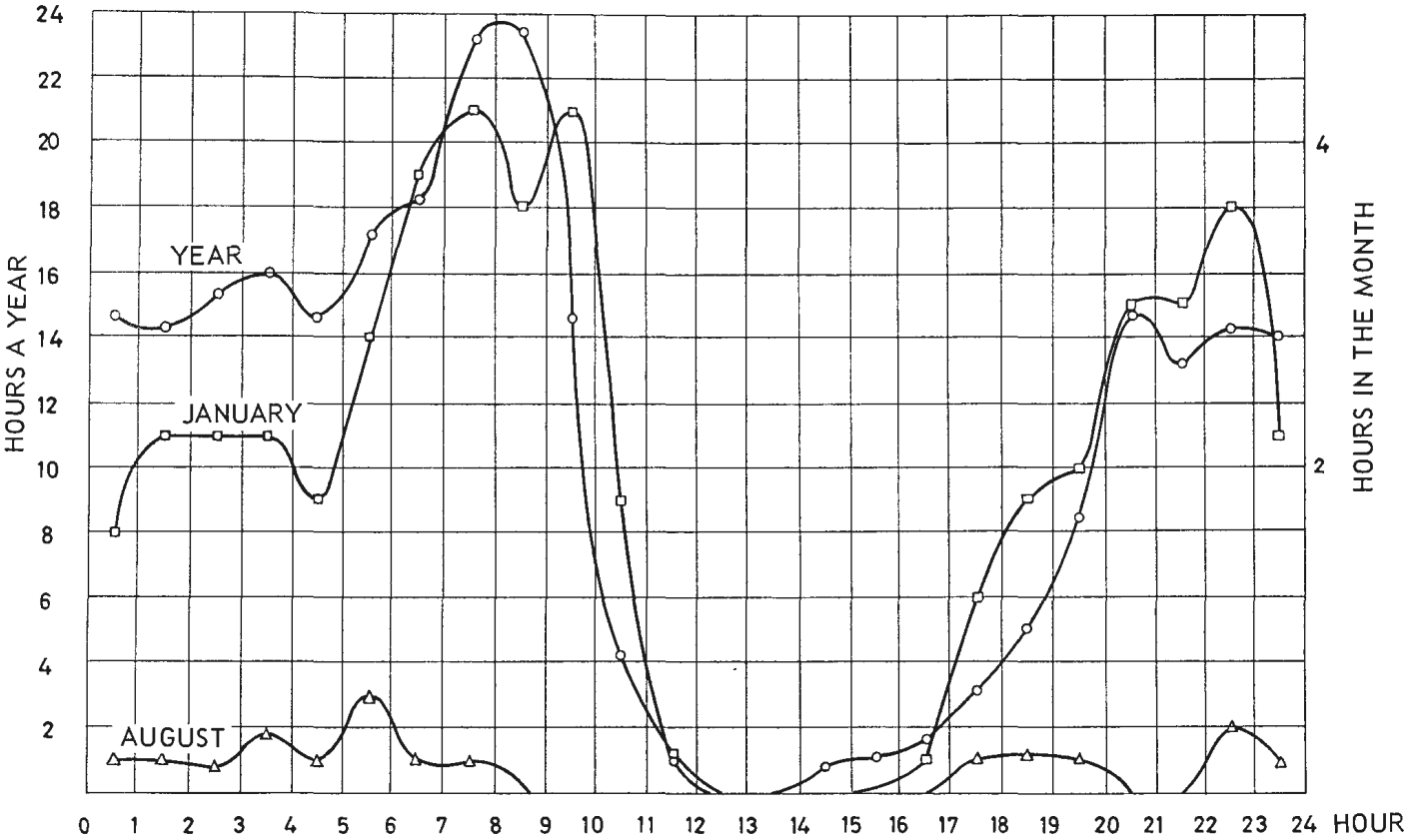

Figure 14. Daily fluctuation in number of hours of light wind (calm) (v = < 5 km per hour) for the year (ordinate scale shown in left margin), January (greater number of hours of light wind) and August (smaller number of hours of light wind) (ordinate scale for both curves shown in right margin)

considered. This is true of a wide region in western North Africa, where we have a wind power prospecting network. Most of this region, which is regarded as part of the arid zone, is devoid of conventional energy sources; we refer to the vast expanse which embraces the Canary Islands and the coastline of the Sahara desert.

We shall now describe, in broad outline, the prevailing winds of this region.

Along the coasts between the latitudes of the Canary Islands and those of Cape Verde and considerably further south, a very consistent feature throughout the year is the vigorous trade wind, whose strength and constancy are increased in the summer months by the growth of the Azores anticyclone coinciding with the deepening of the Sahara low. These winds blow from the north—north-east sector. The mechanism of this wind's formation has been the subject of much discussion in connexion with the over-all problem of the general circulation of the atmosphere, and now seems to be regarded as a circulation in the direction of the meridians, set up by forces of thermal origin and governed by the deflection or Coriolis force, as a secondary circulation conducted only by surface friction within the general system of easterly currents prevailing in the tropical zone (15).

Another wind described in this area is the monsoon (16), which is less important than the trade wind and is formed by the appearance of a continental depression as the ground is heated by the sun.

Lastly, mention must be made of the harmattan, or sandy wind, a powerful easterly air current which carries sand particles for great distances over land and sea (17).

Our wind power prospecting network is spread over the region shown in figure 5.

The network comprises forty observatories in all; table 2 lists those where high wind speeds have been observed. The period of observation is shown in months.

Figures 6 and 7 show the fluctuation over the year in the monthly mean wind speed at different observation points; generally speaking, we find at these points a regular fluctuation due to the trade wind, whose peak is reached in the summer and attains a noteworthy figure in some places. In the winter, however, wind speed drops considerably, either because the trade wind diminishes in strength or because it alternates with the other, weaker winds. This region forms a noteworthy wind basin with great possibilities for wind power use, for it is lacking in conventional energy sources and orographically suitable for the installation of wind power plants.

We thought it would be illuminating to make a detailed wind analysis at a specific point on our

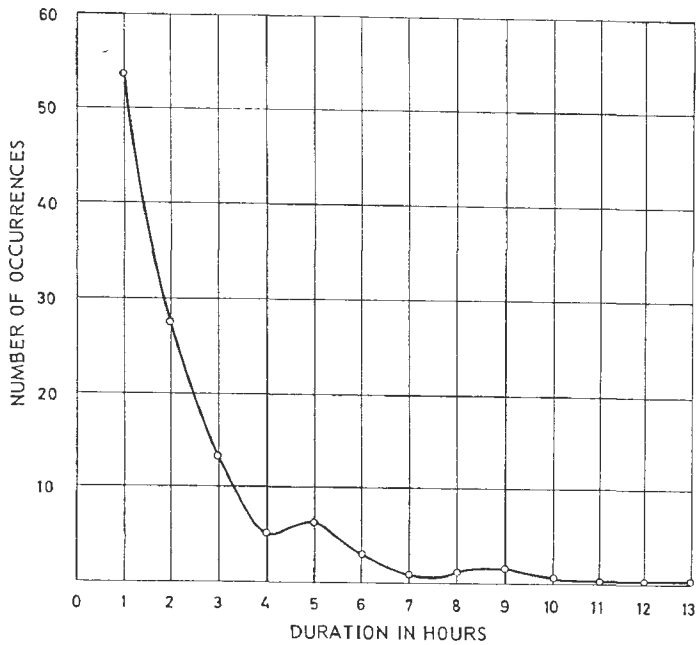

Figure 15. Curve showing the number of occurrences in the year of periods of calm, classified by duration in hours (abcissa)

prospecting network, as a potential site for a wind power plant; we chose the Montaña del Infierno observatory in the eastern part of the Island of Grand Canary (figure 8). The measuring instrument is a Fuess anemocinemograph fitted to an 11-metre post on a hill which would make a very suitable site for wind engines.

Very complete records covering a period of five years (1956-1960) were used for the wind study.

The statistics prepared were designed to provide a basis for wind power use.

The limitations imposed by the Conference rules prevent the inclusion in our paper of the numerical tables used in preparing the graphs discussed below.

Figures 9 a, b and c were prepared from the table of frequencies and mean speeds of winds blowing from different points of the compass. In the annual rose (figure 9 a), we find that northerly winds (30, 32 and 02) prevail, accounting for 82 per cent of the number of hours in the five years of observation. In the summer months (June, July and August) (figure 9 b), these winds account for 96 per cent of the hours over the same five-year period. In the winter months (December, January and February) (figure 9 c), however, the proportion of winds blowing from this sector drops to 67 per cent. The highest mean speeds also coincide with the highest frequency. The analysis and the figures clearly demonstrate the prevalence of the trade wind characteristic of this region.

By studying and compiling statistics on the distribution of hourly speeds at intervals of 1 km per hour, it is possible to plot a curve (figure 10) showing the proximity of the mean speed (37.4 km per hour) to the most frequent speed (36 km per hour).

Figure 11 shows how the distribution of wind speed frequencies differs in January from that obtaining in July.

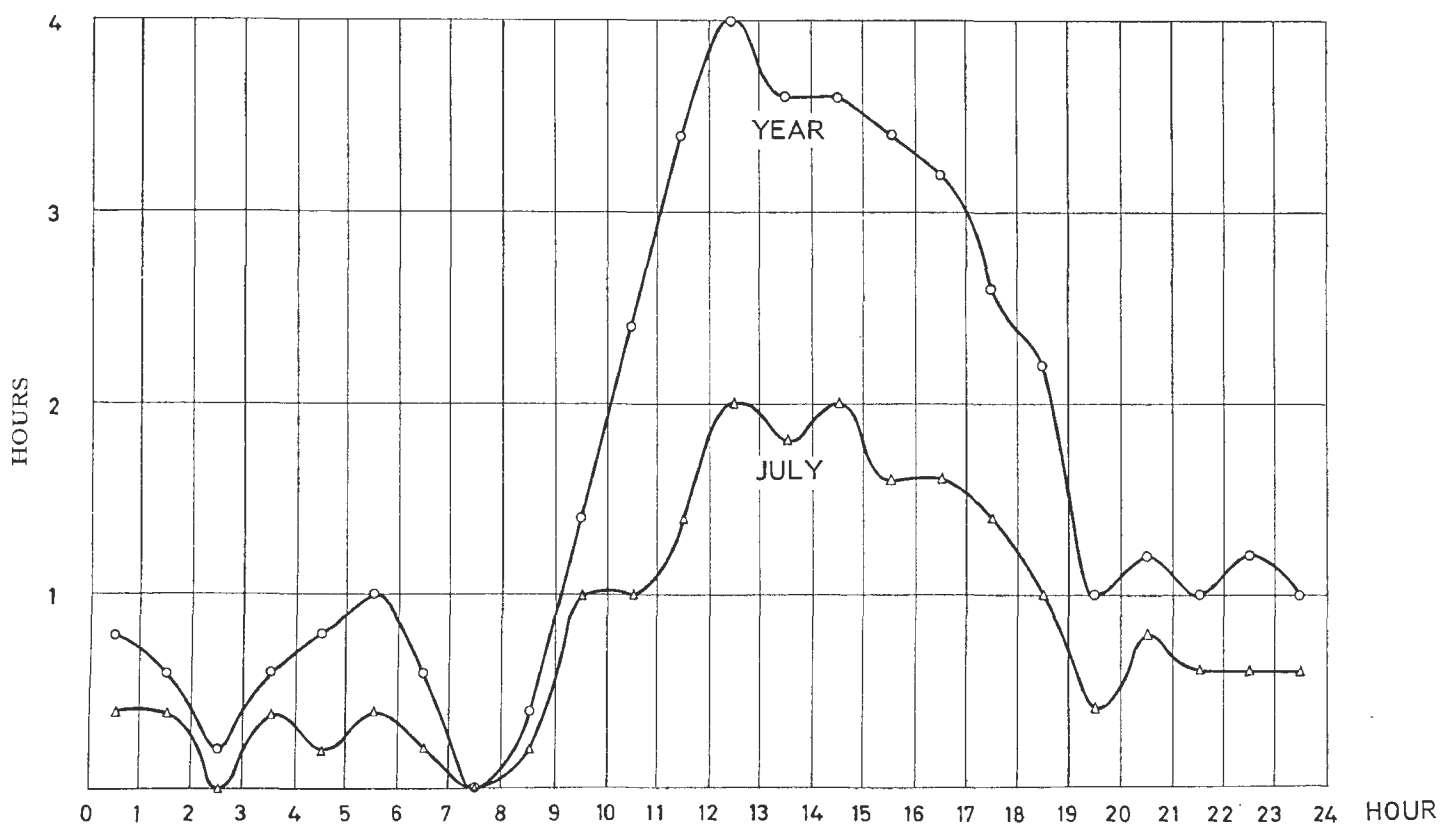

Figure 16. Daily fluctuation in number of hours of strong wind (v = > 80 km per hour) for the year and for July, the month with the greatest number of hours of strong winds

The daily fluctuation in wind speed (figure 12) shows that this quantity reaches its highest average in the afternoon, begins to decline as night falls, and reaches its trough in the early morning hours. The three curves shown (year, January and July) represent different speeds but show a very similar fluctuation.

Figure 13 shows that the fluctuation in hourly mean speed in the sectors with prevailing trade wind closely resembles that in the sectors with prevailing southerly winds.

These graphs clearly demonstrate the uniformity of the daily fluctuations in the most frequent winds and in all winds.

We have chosen to define as a calm day hourly speed of 5 km per hour or less, since most wind engines stop when the wind speed drops below this figure. The daily fluctuation of calms (figure 14) is in good agreement with that of wind speed. This graph shows daily fluctuation curves for calms in January, August and the year.

Figure 15 shows how short the periods of calm usually are and, more particularly, the rarity of calms lasting more than four hours.

We have classified as strong winds those attaining hourly speeds of 80 km per hour or more, in which wind power plants must as a rule be disconnected. Figure 16 shows the daily fluctuations of these winds,

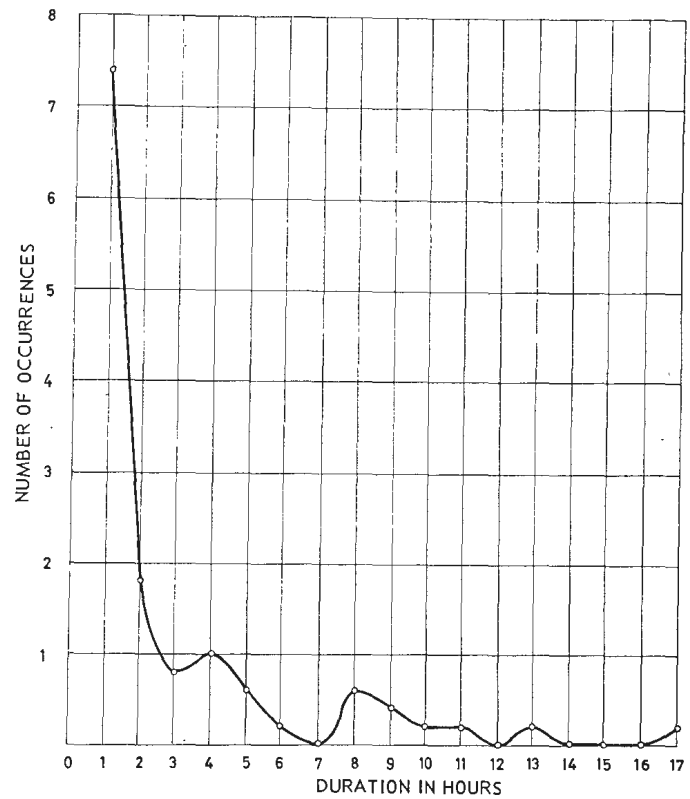

Figure 17. Curve showing the number of occurrences in the year of periods of strong wind, classified by duration in hours (abcissa)

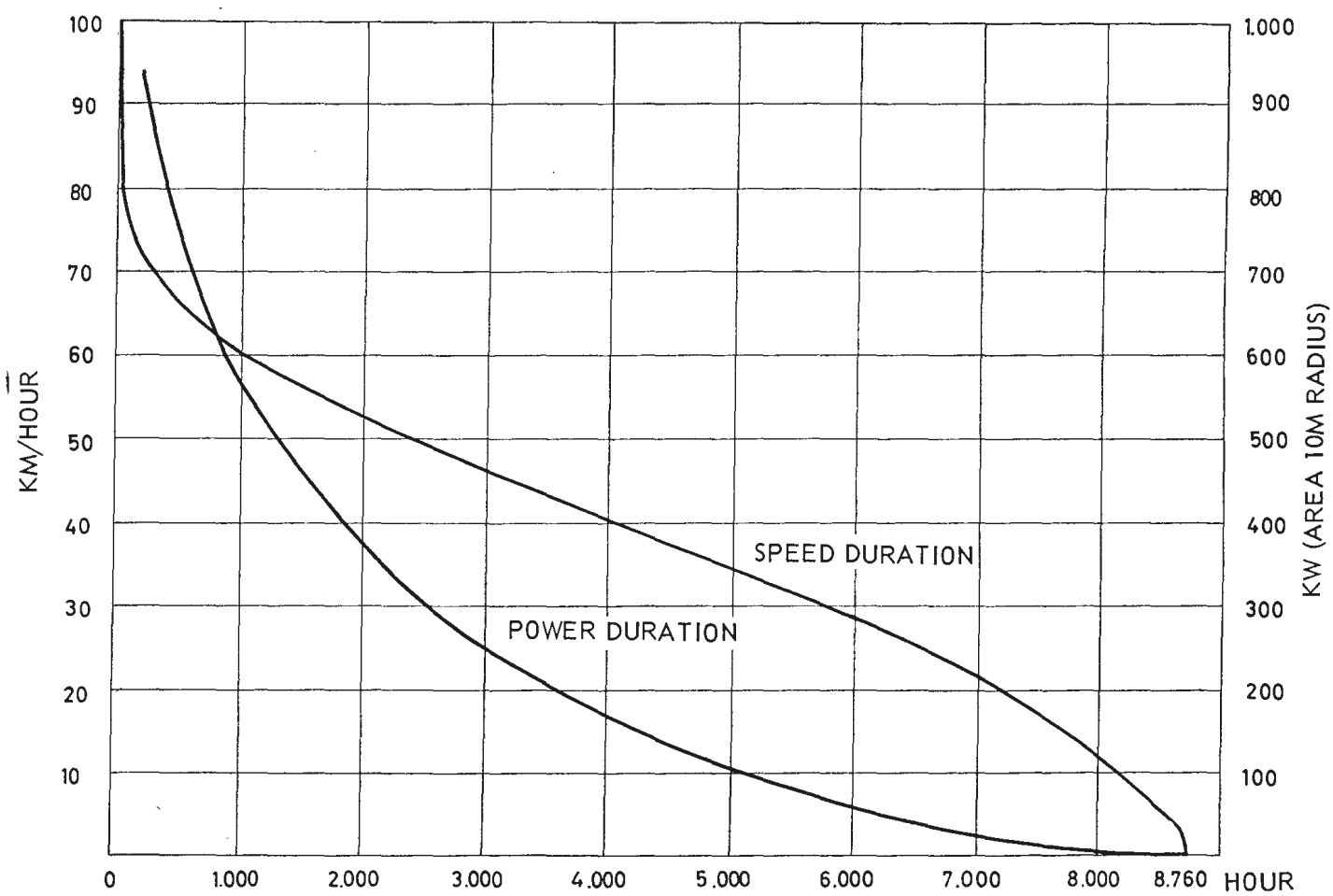

Figure 18. Curves of speed duration and usable power duration for a swept area of 10 m radius

which here again agree with that of wind speed. Curves are given for the year and for the month of July, when high-speed winds are most common. No wind speed of 80 km per hour or more was recorded in January in any of the five years considered.

Similarly, figure 17 shows that high hourly speeds lasting three hours or more occurred very rarely during the five years under consideration.

From the statistical results illustrated in the figures we have briefly described, we deduce that wind conditions at this site make it very suitable for the utilization of wind power. The wind direction and speed are sufficiently regular to provide periods of more than ten days during which the wind never drops below a speed of 8 m/sec or exceeds a speed of 25 m/sec and blows steadily from the north with scarcely any change in direction. It also exhibits a fair regularity over the course of the day, not only taking the compass as a whole but also in the prevailing north and south sectors.

Since calms of more than four hours' duration are rare, we may assume that an independent wind power plant would need little storage capacity, for there would, in addition, be few occasions on which excessive hourly speeds would make it necessary to disconnect a wind power plant of characteristic speeds appropriate to the site.

Gustiness is minimal, and we hope to supplement this study with measurements of this factor.

The speed duration and power duration curves given in figure 18 show the favourable wind conditions obtaining at the site. Although at this site, as at several others in the same area, the mean wind speed is high, we may suppose that similar sites, well suited to the harnessing of wind power, are to be found throughout the vast arid region traversed by the trade winds. In the case of Montaña del Infierno, it is possible that the mountain mass in the centre of the island has the effect of increasing the wind speed in this low coastal area.

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Summary

Although wind power does not occupy a prominent position at the present time, the demand for energy is so great that highly developed countries are making considerable efforts to find an economic way of harnessing that of the wind, for there are large areas where conventional sources of energy are lacking and where the available means of transport are very inadequate and costly.

The problem of harnessing wind power involves a series of specific, closely interrelated variables, a favourable combination of which is essential to economic operation.

First, we must endeavour to learn the general characteristics of the wind in the area where its use is contemplated; next, we must select places with favourable characteristics.

Our paper reviews the criteria applied in setting up a prospecting network in Spain. This was a two-stage operation. The first step was to outline the wind basins enclosing the areas with the most suitable

winds. The second step was to locate the best sites and to learn as much as possible about the wind régime prevailing there. Wind behaviour at a site is determined not only by the free-air wind but also by orographic factors.

In order to set up a wind power plant, it is not enough to know one variable — that of wind; the plant must also be economic in operation. The factors to be considered include the characteristics and cost of the engine and ancillary equipment, the possibilities for siting other engines nearby, access to the site, distance from lines of communication, and so on.

The paper analyses methods used in compiling, from the data furnished by meteorological services and the results obtained from specific wind prospecting networks, statistics for use in studies of wind power utilization.

Pertinent results based on all available data are given in relation to mainland Spain, and the most important wind basins are outlined and described.

Since one of the aims of the Conference is to furnish results for areas genuinely in need of energy sources, we decided to make a general study of the winds prevailing in the region which embraces the Canary Islands and the coast-line of the Sahara desert.

Our wind prospecting network in this region of Africa comprises some forty observatories in all, and the paper gives results from those which recorded high winds.

A study is made of the fluctuation over the year in the monthly mean wind speed recorded at different observation points; generally speaking, we find at these points a regular fluctuation due to the trade wind, whose peak is reached in the summer and attains a noteworthy figure in some places. Wind speed drops considerably in the winter, either because the trade wind diminishes in strength or because it alternates with other, weaker winds.

This region forms a well-defined wind basin, where the feasibility of harnessing wind power coincides with a shortage of conventional sources of energy. For this reason we thought it would be illuminating to make a detailed analysis of a specific point on our prospecting network as a potential site for a wind power plant; we chose the Montaña del Infierno observatory on the east coast of the Island of Grand Canary.

The statistics were prepared from the records, covering five years (1956-1960), made with a Fuess anemocinemograph fitted to an 11-metre post on a hill which would make a very suitable site for wind engines. The limitations imposed by the Conference rules prevent the inclusion in our paper of the numerical tables from which the graphs were prepared.

We obtained hourly figures for the variable wind speed and studied the daily, monthly and yearly fluctuations, which are informative as regards wind power utilization, provided that sufficient information is available about the consumers and load curve to be expected. The study of energy production is completed by statistics of very high-speed and very low-speed winds.

The frequency and mean speed in each direction indicate what kind of rotation the head of the engine will have to undergo and may, in specific cases, determine the choice of a particular type of engine suited to local conditions.

Moment-to-moment fluctuations in wind speed, and especially those occurring round about the characteristic speeds, have a particular influence on the running of the engine. They also affect the study of resonance phenomena.

The speed duration curve and power duration curve are of use in making an over-all estimate of the maximum usable energy and in studying the general behaviour of a particular wind power plant.

The favourable wind conditions prevailing at the site are analysed as an illustration of the possibilities of the basin in which it is situated.

PROSPECTION EN VUE DE L'UTILISATION DE L'ÉNERGIE ÉOLIENNE

Résumé

Quoique l'énergie éolienne n'occupe pas actuellement une place importante, la demande d'énergie est telle que des pays très développés consacrent des efforts considérables à chercher le moyen de capter l'énergie éolienne avec un rendement économique satisfaisant, car il existe de vastes régions qui manquent de sources d'énergie traditionnelles et qui n'ont que de rares et coûteux moyens de transports.

Le problème de l'utilisation de l'énergie éolienne met en jeu des variables particulières et interdépendantes dont certaines combinaisons sont indispensables à une exploitation économique.

Il faut tout d'abord essayer de connaître les caractéristiques générales du vent dans la zone où l'on envisage de l'utiliser, afin de déterminer ensuite les lieux qui offrent les meilleures possibilités.

Les auteurs de la communication passent en revue les critères qui ont été suivis en Espagne pour l'organisation d'un réseau de prospection. Celui-ci a été établi en deux étapes. On a d'abord déterminé les bassins éoliens qui renferment les zones possédant les vents les meilleurs. La seconde étape a consisté à localiser les emplacements qui conviennent le mieux et à connaître le plus en détail possible le

régime des vents correspondant. Le comportement purement éolien d'un emplacement est déterminé non seulement par le vent dans l'atmosphère, mais aussi par des facteurs d'ordre orographique.

Pour entreprendre une exploitation éolienne, il ne suffit pas de connaître la variable du vent, il faut aussi que l'exploitation soit économique. Parmi les facteurs à considérer on peut citer les caractéristiques et le coût des machines et de l'équipement auxiliaire, les possibilités d'installer d'autres machines à proximité, les accès à l'endroit, la distance jusqu'aux voies de communication, etc.

Les auteurs analysent les méthodes que l'on emploie pour établir — à partir des données des services météorologiques et des résultats des réseaux existants de prospection éolienne — des statistiques destinées à l'étude des possibilités d'exploitation de l'énergie éolienne.

Les auteurs exposent ensuite les résultats obtenus à ce sujet pour l'Espagne péninsulaire d'après tous les renseignements disponibles, et ils délimitent et décrivent les principaux bassins éoliens.

Puisque l'un des objets de la Conférence est de faire connaître les résultats obtenus pour des régions qui manquent vraiment de sources d'énergie, les auteurs ont décidé de faire une étude d'ensemble des vents dominants dans la région qui comprend les îles Canaries et le littoral du Sahara.

Le réseau espagnol de prospection éolienne dans cette région d'Afrique comprend 40 observatoires et la communication donne des chiffres pour ceux où les vents enregistrés ont été les plus violents.

Les auteurs ont étudié l'évolution au long de l'année de la vitesse moyenne mensuelle du vent, enregistrée aux divers observatoires; on constate en général une variation régulière provoquée par les vents alizés, qui donnent un maximum en été, car leur force est notable en certains points. En hiver, la vitesse baisse considérablement, soit parce que l'intensité des alizés diminue, soit qu'il y ait alternance avec d'autres vents moins intenses.

Cette région constitue un bon bassin éolien, car la possibilité d'utiliser l'énergie éolienne coïncide avec une pénurie de sources traditionnelles d'énergie. C'est pourquoi les auteurs ont pensé qu'il serait intéressant d'étudier en détail un point particulier du réseau de prospection en vue d'une exploitation éolienne; ils ont choisi à cet effet l'observatoire de la Montaña del Infierno, situé sur la côte orientale de la Grande Canarie.

Les statistiques ont été établies d'après les bandes de cinq années (1956-1960) de l'anémocinémographe enregistreur Füess installé sur un poteau de 11 mètres de hauteur planté sur une colline convenant particulièrement bien à l'installation de machines éoliennes. Les tables qui ont servi à la construction des graphiques n'ont pas été reproduites dans la communication eu égard aux limitations imposées par le règlement de la Conférence.

A partir de la vitesse variable du vent, on a calculé des chiffres horaires et étudié les fluctuations quotidiennes, mensuelles et annuelles, qui sont très intéressantes pour une éventuelle exploitation si l'on dispose de données suffisantes sur les consommateurs que l'on peut escompter, ainsi qu'une courbe représentant la demande d'énergie en fonction du temps. L'étude de la production d'énergie est complétée par des statistiques des vents à très grande et à très faible vitesses.

La fréquence et la vitesse moyenne dans chaque direction permettent de connaître le type de rotation à laquelle sera soumise la tête de la machine et de déterminer dans certains cas le genre de machine convenant aux conditions locales.

Les variations instantanées de la vitesse du vent, et notamment celles qui se produisent autour des vitesses caractéristiques, exercent une influence particulière sur le fonctionnement de la machine. Elles affectent également l'étude des phénomènes de résonance.

Les courbes de vitesse et de puissance en fonction du temps sont utiles en ce qu'elles permettent de faire une estimation globale de l'énergie maximum utilisable et d'étudier le comportement général d'un aérogénérateur déterminé.

Les auteurs analysent enfin les conditions éoliennes favorables du lieu étudié, comme exemple des possibilités du bassin dans lequel il est situé.

WIND MEASUREMENTS IN SOUTHERN ARGENTINA AND REMARKS ON WIND AND SOLAR ENERGY IN THAT COUNTRY

E. Cambilargiu *

In 1949, a one-year course in wind dynamics and wind machines was instituted at the Faculty of Engineering, University of Buenos Aires, and a study programme for the utilization of wind and solar energy in Argentina on a nation-wide scale was presented to that faculty, to the Ministry of Power, and to the National Institute of Agricultural Technology (1).

This project proposed the establishment of an experimental centre for wind and solar energy for the following purposes: (*a*) in collaboration with the National Meteorological Service, it was to study the distribution of wind and solar energy in the country, seek the sites for their optimum utilization and make long-term measurements; (*b*) it was to study, design, construct and test research models and basic experimental equipment for harnessing such energy, and subsequently, for each solution, to make a cost study as a basis for industrial bidding, under the control of a government agency that would finance mass production, so that users could acquire the necessary plant at a modest monthly cost and would also have a reliable service of technical assistance and supply.

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Characteristics of the localities examined

First of all, an initial group of most favourable localities was selected on the basis of the data available to the National Meteorological Service (2, 3). These localities are given in tables 1, 2 and 3. With the help of students who had completed the course, we examined the anemometer records of many stations that delineate the broad belt of lower mean annual relative humidity and lower rainfall in Argentina. We calculated the mean hourly, monthly, seasonal and annual wind speeds at the stations of

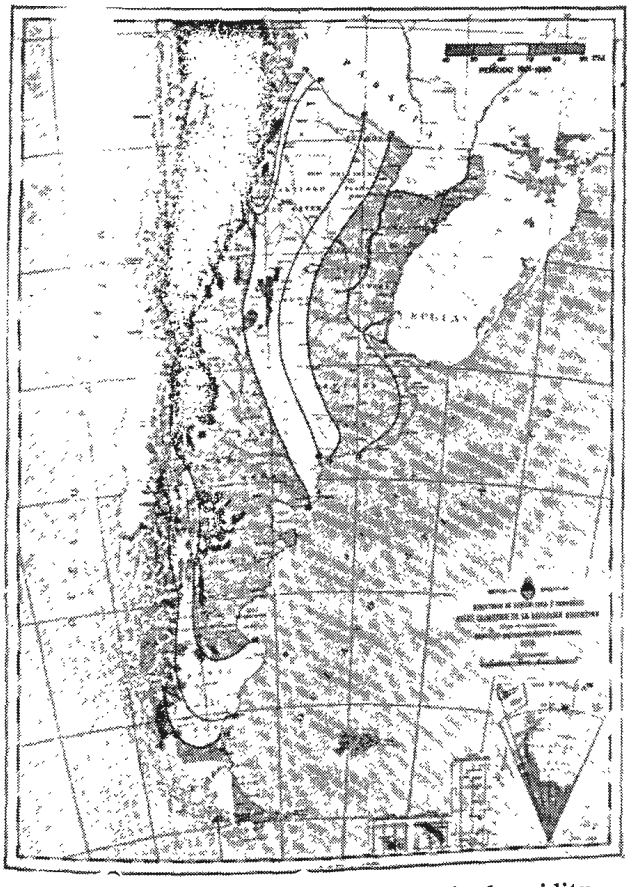

Figure 1. Curves of mean annual relative humidity (per cent)

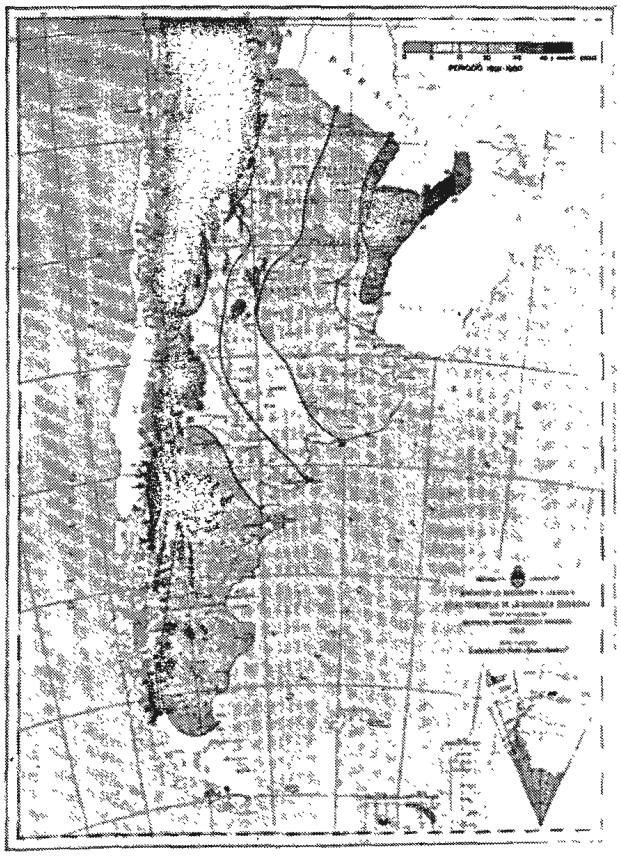

Figure 2. Curves of annual number of days with rainfall (over 10 mm)

Trelew, Comodoro Rivadavia, San Julián, Santa Cruz, and Rio Gallegos, on the Atlantic Coast from 43° 14′ to 51° 50′ S. lat, and of San Carlos de Bariloche and Esquel in the Andes, from 41° 09′ to 42° 54′ S. lat. This zone is shown in detail by the curves of figures 1 and 2.

Table 1 gives the stations of southern Argentina with prevailing winds of good energy characteristics, and those of lower cloudiness, and table 2 the stations of Northern Argentina, which in general indicate gentle breezes (only reaching monthly means of 15-18 km/h at a few stations), but which do have a low cloudiness.[1] Table 3 gives the mean pyranographic values according to the National Meteorological Service at the existing stations of this type.

The diagrams of figure 3 give the annual frequencies of the wind speed at each of the above stations. It will be seen that the wind speeds of maximum frequency, as well as the course of the curves, show a marked variation from zone to zone.

Figure 4 gives velocity duration curves of the same places. It will be noted that Comodoro Rivadavia and San Julian are the zones of highest energy for harnessing wind power.

[1] For the relation between the cloudiness and the effective incident radiation Q, see Berg, H., *Pure and applie ageophysics*, 13, 157 (1948).

Figures 5 and 6 give the diurnal march of the mean seasonal wind speed. As will be seen from these curves, at all the stations the wind speed begins to increase at sunrise, holds its maximum values during the afternoon, and declines rapidly at sunset. The night values show little difference between the four stations. In general the wind speed, especially in the hours of stronger wind, is much higher in spring and summer than in autumn and winter.

The diurnal march of mean wind speed at the stations is very important because it shows the different windiness during the hours of the day at the four stations. To allow us to plot these monthly graphs, which are more detailed and cannot be reproduced in the small space of the accompanying figures, the values of the monthly and annual means are tabulated. These tables are omitted here to save space.

Remarks on the utilization of energy

The work here presented shows what can be done with the data that are generally available to the meteorological service of a country, and which, as a rule, as in Argentina, cannot be extended to cover a larger number of stations, owing to the shortage of recording anemometers, pyrheliometers and personnel.

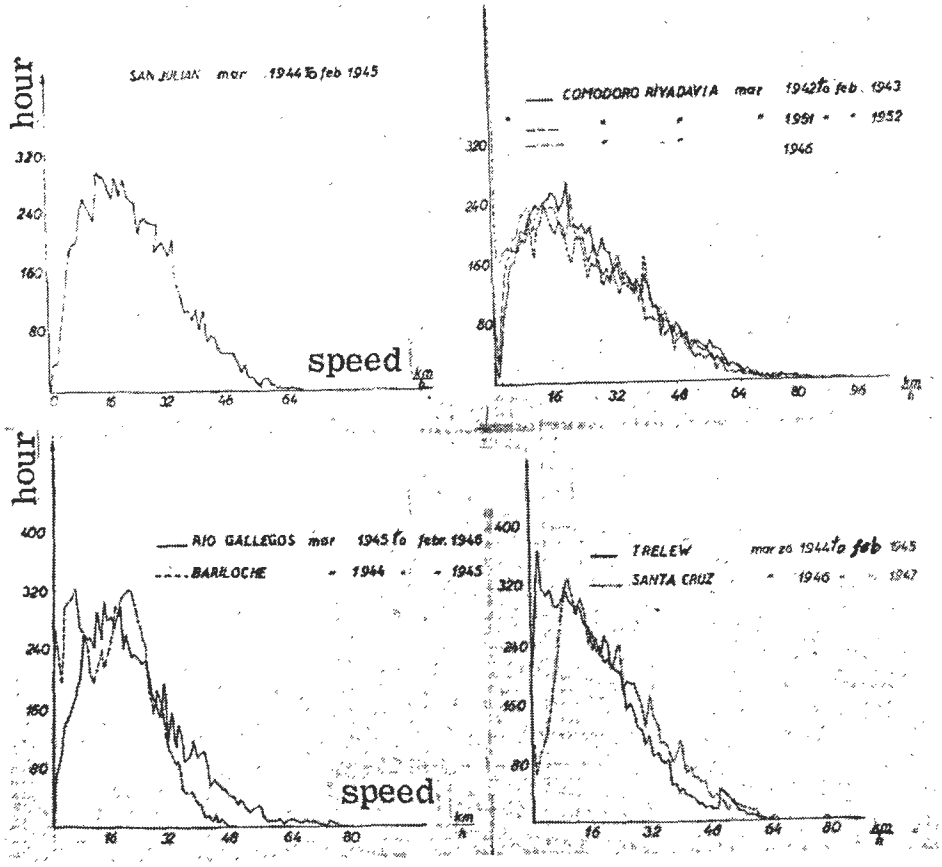

Figure 3. Annual frequency of wind speeds at San Julián, Comodoro Rivadavia, Rio Gallegos, San Carlos de Bariloche, Trelew and Santa Cruz

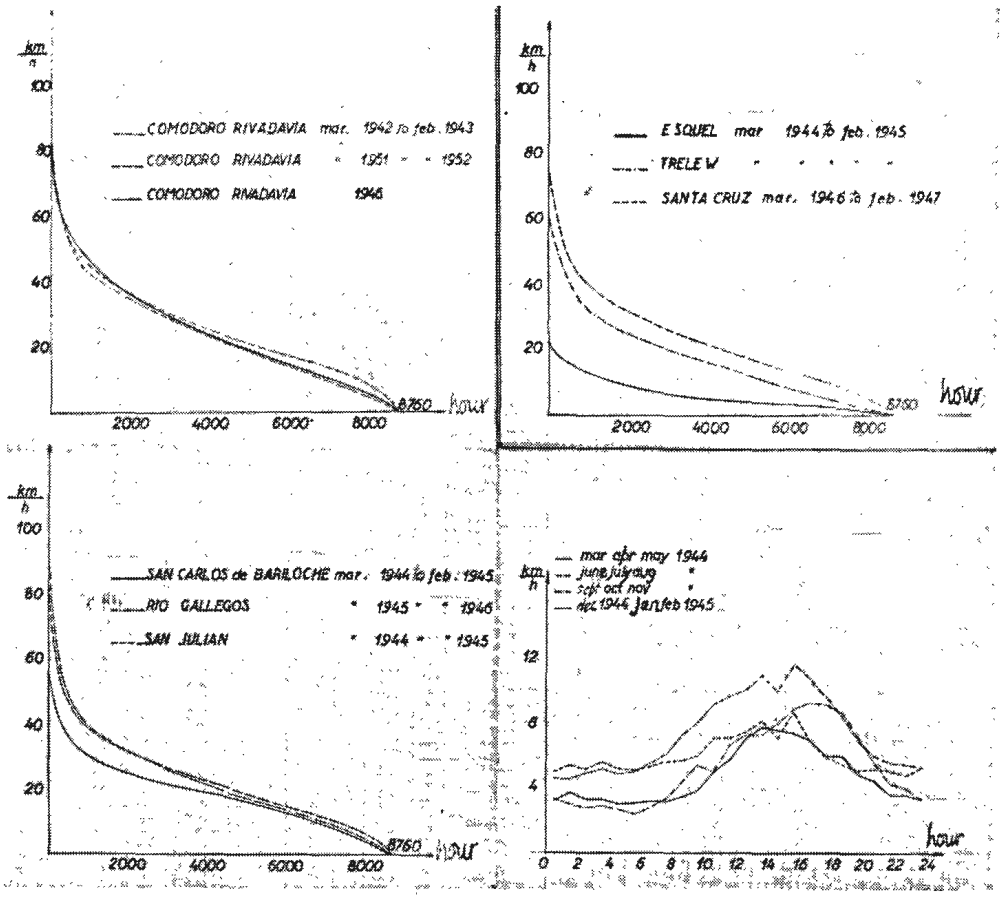

Figure 4. Velocity duration curves for Comodoro Rivadavia, Esquel, Trelew, Santa Cruz, San Carlos de Bariloche, Rio Gallegos, and San Julián; and annual frequency of velocities at Esquel

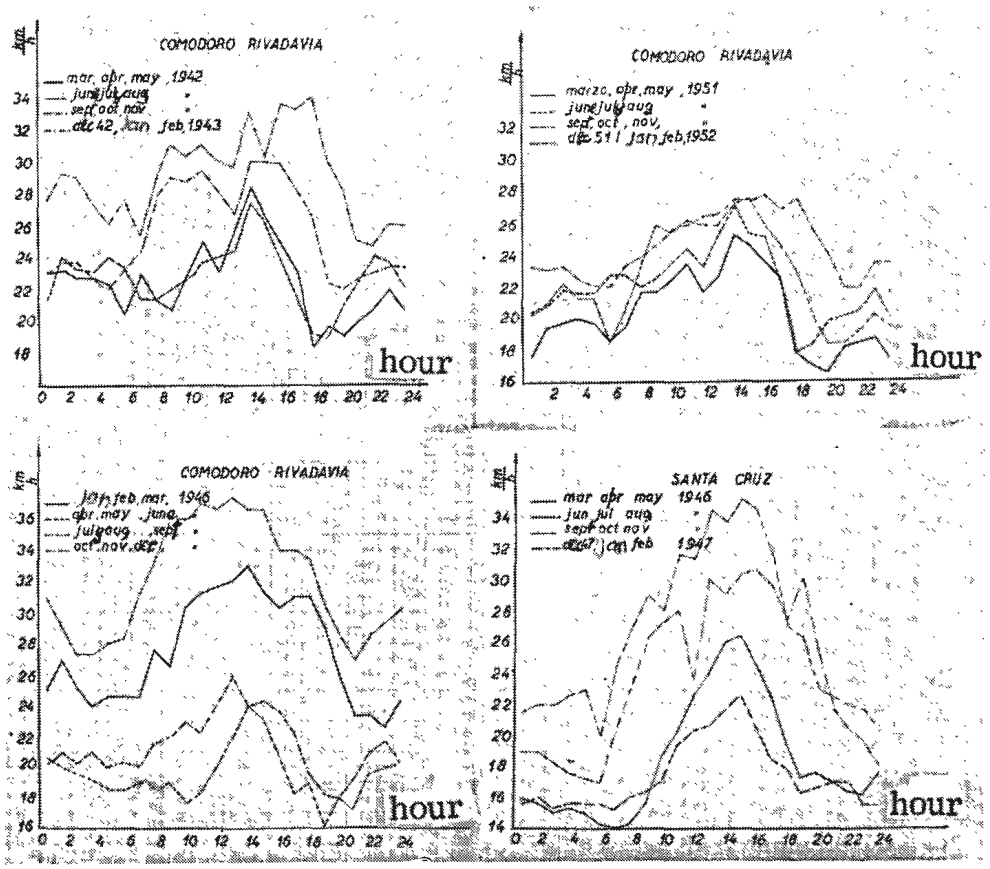

Figure 5. Diurnal march of mean wind speed at stations of Comodoro Rivadavia (1942, 1946 and 1951) and Santa Cruz

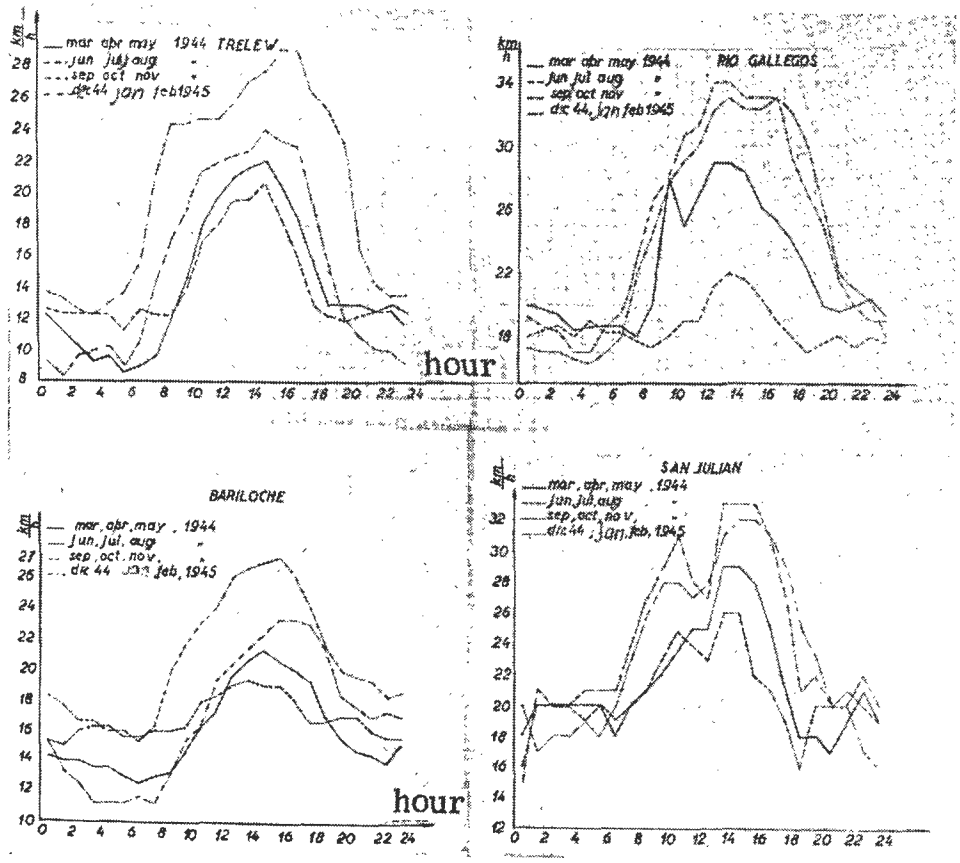

Figure 6. Diurnal march of mean wind speed at stations of Trelew, Rio Gallegos, San Carlos de Bariloche and San Julián

These stations cannot, from time to time, move from one place to another as would be necessary for an energy study, because a series of climatic data must be continuous. This is one of the reasons for having the Experimental Centre for Wind and Solar Energy make the required measurements with its own instruments and its own staffs. In studying the utilization of wind and solar energy, it must always be borne in mind that the data generally available at the meteorological services relate to stations located at the major centres of population, because of the needs of their primary work, which is climatological study and weather forecasting, instead of being located at the places that would be of greatest interest for energy utilization.

In Argentina, as in other countries with an important orographic system, it can definitely be predicted that, given research and adequate means, much more suitable sites will be found for harnessing the energy of the wind and sun than those known today.

Except for the cities and their immediate surroundings, electric power is very scarce in Argentina, and in the driest zones, indicated by figures 1 and 2, this is complicated by scarcity of water. This emphasizes the importance of an economical means that would combine the local generation of electricity with the supplying of ground and river water.

The most economical means of converting the natural sources of energy into a form directly usable in small and medium-scale installations is the harnessing of wind and solar energy.

The former is the "blue coal" of all southern Argentina, a region predominantly arid, and the latter is that of the north, where, over large areas, the existing water is too brackish for drinking or use in agriculture.

It is well known that sun and wind energy is very abundantly distributed over the earth and may be harnessed at the place of ultimate use, thus avoiding transportation costs. But there are transitory periods of shut-downs or interruption (calms and light breezes, nights and times of great cloudiness). The station averages are likewise different.

It will be seen from table 1 that the station averages of wind speed are much higher in spring and summer than in autumn and winter. For this reason, if a minimum fixed level of the power taken from the wind is required (except for the transitory periods of calm), two or three graduated levels for utilization must be established, each with its own separate equipment and suitable régimes of regulation, with storage batteries for the condition of lower power and the most necessary uses. But many important uses do not have these complications, and have the advantage of lower cost. For instance, if we compare the frequency of the wind with that of the rain in all the zones of semi-aridity and moderate rainfall, we see that the winds of useful speed are much more

frequent than the rains, and that therefore the wind can solve the important problem of water supply without storage, or with only limited storage.

In the Southern zone, as a rule, the wind remains strong enough, even in autumn and winter, to drive wind machines for family use, supplying sufficient energy in these periods for heating, cooking, lighting, refrigeration, radio, laundry, etc., and even for modest industrial work, and leaving the greater power of the spring and summer months for pumping water for agriculture and livestock.

Examining the pyranographic data for the southern zone, we see that at various stations indicated in table 3, and surely at many other places as well

Table 1. Stations with good energy characteristics in southern Argentina

(N = mean cloudiness; V = mean wind speed (km/h))

Station [a]		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
						Buenos Aires Province								
Buenos Aires (Darsena Sud) (5)	N	3.8	4.1	4.4	4.2	5.2	5.7	5.4	5.0	4.9	4.6	4.3	3.9	4.6
	V	17	15	14	12	12	11	12	13	14	15	16	18	14
Mar del Plata (24)	V	17	17	16	15	14	14	16	16	16	17	17	18	16
Copelina (192)	V	20	19	20	18	14	14	17	17	18	19	18	19	18
Barrow (120)	V	18	18	17	16	18	17	18	16	17	18	18	18	17
Trenque Lauquen (96)	N	3.7	3.8	3.7	4.2	5.0	5.3	5.1	4.5	4.8	4.7	4.3	3.8	4.4
	V	15	14	13	14	14	12	12	15	18	19	19	18	15
						La Pampa Province								
General Pico (140)	N	4.2	4.2	4.4	4.3	5.5	5.3	5.3	4.7	4.8	4.5	4.6	3.8	4.6
	V	17	15	15	14	13	12	14	16	18	19	18	18	16
Victórica (312)	N	3.4	3.6	4.2	4.6	5.4	5.5	5.4	4.8	5.0	4.1	4.3	3.6	4.5
	V	16	14	15	13	13	12	13	13	15	15	15	15	14
						Rio Negro Province								
Rio Colorado (78)	N	3.7	3.6	3.7	4.0	5.7	4.8	5.0	4.8	5.0	4.5	4.4	3.9	4.4
San Carlos de Bariloche (853)	V	18	20	18	18	17	17	14	16	18	20	22	22	18
						Neuquen Province								
Plaza Huincul (605)	N	2.1	2.0	2.9	3.5	4.9	4.2	4.2	4.0	4.3	3.4	2.9	2.4	3.4
	V	15	13	13	10	11	11	11	13	13	15	17	18	13
						Chubut Province								
Camarones (34)	V	19	18	14	13	15	15	16	17	18	21	21	22	17
Comodoro Rivadavia (61)	V	27	26	21	21	22	22	22	22	21	26	27	27	23
Punta Delgada (54)	V	16	17	18	18	20	18	19	20	18	18	14	17	18
Sarmiento (268)	V	21	18	13	13	11	12	9	12	13	22	24	22	16
Trelew (39)	V	18	16	13	12	12	12	14	14	14	17	18	19	15
						Santa Cruz Province								
Cañadón León (358)	V	17	17	13	14	12	14	13	12	14	18	19	19	15
Cerro Fitz Roy (420)	V	29	29	22	19	16	16	16	17	22	30	29	31	24
Col. Las Heras (252)	N	4.6	4.7	4.2	4.1	4.0	4.3	4.6	4.3	4.7	4.3	5.0	5.2	4.5
	V	19	22	17	4	13	15	14	15	15	20	22	24	18
Cabo Blanco (39)	V	18	20	17	17	18	18	17	17	17	18	16	17	18
Cabo Vírgenes (51)	V	24	23	20	21	19	20	19	20	19	22	22	24	21
Lago Argentino (222)	V	23	22	14	14	9	13	14	14	17	20	23	22	17
Puerto Deseado (79)	V	17	19	17	15	15	16	16	16	18	19	18	17	17
Rio Gallegos (22)	V	28	26	19	19	15	17	15	19	22	26	28	28	22
San Julián (26)	V	32	30	25	23	22	24	22	24	25	31	32	32	27
Santa Cruz (11)	V	26	27	20	18	18	20	18	20	22	25	26	26	22
						Islands								
Georgia del Sur (3)	V	17	18	18	16	16	18	17	17	17	16	18	17	17
Orcadas del Sur (3)	V	15	16	18	19	19	17	18	20	18	21	16	14	18
Tierra del Fuego (9)	V	28	28	21	21	17	19	15	19	20	30	28	28	23

[a] Figures in parentheses indicate elevation above sea level, in metres.

Table 2. Stations with good energy characteristics in northern Argentina

(N = mean cloudiness (0 — 10); V = mean wind speed (km/h))

Station [a]		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Entre Rios Province														
Alberdi (110)	N	4.2	4.0	4.5	4.2	5.0	5.5	5.0	4.1	3.6	4.0	3.9	3.8	4.3
Concordia (32)	N	4.4	4.2	4.4	4.3	4.9	5.8	5.0	4.0	4.7	3.7	4.0	3.8	4.4
Gualeguaychu (22)	N	3.9	3.8	4.2	3.8	4.5	4.9	4.7	4.3	4.3	4.1	3.9	3.5	4.2
La Paz (38)	N	4.5	4.4	4.6	4.4	5.0	5.5	5.1	4.0	4.8	4.2	4.2	3.8	4.5
Victoria (20)	N	4.4	4.0	4.2	4.0	4.8	5.4	4.8	4.2	4.7	4.2	4.0	3.7	4.4
Villaguay (52)	N	4.3	4.2	4.4	4.3	4.9	5.6	5.3	4.5	4.9	4.1	4.0	3.6	4.5
Santa Fé Province														
Angel Gallardo (18)	N	3.9	3.6	4.0	4.0	4.6	5.6	5.0	4.0	4.4	4.0	3.8	3.6	4.2
Ceres (88)	N	4.3	4.0	4.4	4.4.	5.0	5.4	5.0	3.8	4.4	4.0	4.0	3.5	4.4
Rafaela (100)	N	3.9	3.8	4.2	4.2	5.0	5.6	4.9	4.1	4.3	3.6	3.7	3.5	4.2
Vera (58)	N	4.1	4.0	4.1	40	4.4	5.5	4.8	3.7	4.9	4.0	3.6	3.6	4.2
Córdoba Province														
Ascochinga (1 200)	N	3.5	3.7	4.8	4.6	4.1	3.7	3.6	3.1	3.4	3.4	3.6	2.9	3.7
Embalsa (548)	N	4.3	4.2	4.7	4.5	4.7	4.4	4.2	3.6	4.1	4.0	4.2	3.7	4.2
Huinca Renancó (181)	N	3.1	3.0	3.8	3.7	4.7	5.0	4.8	4.1	4.2	3.6	4.4	2.6	3.8
Quilino (397)	N	4.1	3.7	4.4	4.4	4.9	4.7	4.3	3.0	3.7	3.8	3.9	3.4	4.0
Rio Cuarto (443)	N	3.7	3.4	4.0	3.8	4.6	4.6	4.3	4.0	4.5	3.9	3.7	3.1	3.9
San Francisco (114)	N	3.9	3.6	4.1	4.2	4.2	5.3	4.9	3.9	4.2	3.3	3.7	3.4	4.1
	V	15	13	15	16	15	17	17	18	19	18	16	16	16
V Dolores (533)	N	3.1	3.1	3.5	3.5	4.2	3.9	3.9	2.8	3.3	3.0	3.2	2.7	3.3
San Luis Province														
S. Luis (715)	N	3.3	3.0	3.3	3.7	3.9	4.2	4.1	3.2	3.4	3.3	3.2	2.6	3.4
Unión (372)	N	3.3	4.2	4.5	4.2	4.8	5.1	5.2	4.2	4.7	4.6	4.5	3.7	4.5
Mendoza Province														
Cacheuta (1 237)	N	3.6	3.4	3.3	3.1	4.1	3.8	4.0	3.8	3.5	3.3	3.5	2.9	3.5
Colonia Alvear (465)	N	3.6	3.6	3.6	3.9	4.8	4.9	4.8	4.2	4.0	3.9	4.0	3.0	4.0
Cristo Redentor (3 832)	N	3.1	3.0	2.8	4.2	5.5	5.7	5.6	5.3	5.0	4.5	4.2	2.6	4.3
	V	25	24	25	22	22	26	25	26	26	24	27	20	25
El Plumerillo (700)	N	3.8	3.7	3.9	3.8	4.6	4.5	4.5	3.9	4.0	3.7	3.7	2.9	3.9
Malargue (1 418)	N	1.9	1.9	2.6	3.1	3.8	3.6	3.9	3.8	3.8	2.7	2.6	1.7	3.0
Mendoza (827)	N	3.4	3.8	4.0	4.2	4.9	4.8	4.8	4.2	4.3	4.0	3.7	3.2	4.8
Puente del Inca (2 720)	N	2.5	2.5	1.8	2.7	4.4	4.3	4.8	4.6	4.3	3.6	3.4	2.0	3.4
S. Carlos (940)	N	3.5	3.4	3.7	4.1	4.6	4.6	4.6	4.6	4.2	3.9	3.9	2.7	4.0
Villa Vicencio (1 783)	N	3.9	4.1	3.7	3.8	4.2	3.9	4.2	3.9	4.1	3.5	3.6	2.7	3.8
San Juan Province														
Jachal (1 162)	N	4.8	4.5	3.9	3.9	4.3	4.4	4.4	3.2	3.6	3.4	3.7	3.7	4.0
S. Juan (630)	N	3.6	3.3	2.9	3.2	3.8	3.7	3.4	3.2	3.2	3.3	2.9	3.0	3.3
La Rioja Province														
Chepes (654)	N	3.6	3.4	3.7	3.5	4.2	3.9	3.6	2.8	3.2	2.8	3.2	2.7	3.4
Chilecito (1 101)	N	4.7	4.2	3.9	3.5	4.0	3.7	3.6	2.7	3.3	3.6	3.8	4.0	3.8
La Rioja (517)	N	4.9	4.8	5.0	4.1	4.8	4.3	4.1	3.1	3.7	4.0	4.1	4.1	4.3
Punta del Agua (2 600)	N	3.2	3.0	2.1	1.4	1.7	1.7	1.8	1.1	1.3	1.5	1.6	2.3	1.9
Santiago Del Estero Province														
Aña Tuya (107)	N	4.3	4.2	4.4	5.0	5.4	5.6	4.9	3.6	4.2	4.1	4.0	4.1	4.5
Pampa de los Guanacos (156)	N	4.9	5.1	4.9	4.7	5.1	5.4	5.0	3.4	3.9	3.8	4.4	4.2	4.6
El Chaco Province														
Villa Angela (74)	N	3.5	3.7	4.2	4.2	4.6	5.2	4.7	3.3	4.6	3.6	3.5	3.2	4.0
Formosa Province														
Formosa (65)	N	3.9	4.5	4.2	4.3	4.7	5.3	4.6	3.6	4.5	4.5	4.0	4.0	4.4
S. Francisco de Laishi (75)	N	4.3	4.5	4.5	4.1	4.7	5.4	4.4	3.6	4.4	4.4	4.3	4.0	4.4
Tacaagle (87)	N	4.0	4.3	4.6	4.3	4.6	5.4	4.3	3.4	4.2	4.4	4.1	3.6	4.2
Catamarca Province														
Andalgalá (1 063)	N	4.5	4.0	3.9	3.6	3.7	3.6	3.4	2.6	3.0	3.8	3.8	4.0	3.6
Catamarca (546)	N	3.4	3.2	3.2	3.1	3.3	3.0	2.7	2.4	2.6	3.0	3.0	3.1	3.0
Tinogasta (1 204)	N	3.7	3.4	3.1	2.3	2.6	2.3	2.5	1.8	2.3	2.6	2.8	3.2	2.7
Tucumán Province														
Villa Nougues (1 388)	V	18	18	18	17	15	15	17	18	18	17	17	18	17

[a] Figures in parentheses indicate elevation above sea level, in metres.

Table 3. Values of solar radiation on a horizontal plane measured with the Robitzsch bimetallic pyranograph at the stations of Argentina

((1) = mean values of cal cm^{-2} day^{-1} on the clear days of the month; (2) = mean monthly values of the same; (3) = number of clear days in the month. The mean values relate to the years indicated below the name of each station)

Station		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Buenos Aires (Federal Cap.) 1941-52	(1)	760	692	567	470	325	275	288	386	476	652	761	830	
	(2)	668	587	445	353	269	190	211	289	391	513	633	682	435
	(3)	6	6	4	7	5	2	3	4	2	3	6	3	
Chos Malal (Prov. Neuquen) 1950-52	(1)	859	722	625	440	329	253	254	369	542	736	864	952	
	(2)	771	609	513	347	194	153	182	281	406	595	730	823	472
	(3)	8	9	9	7	1	3	3	5	7	6	5	7	
Concordia (Prov. Entre Rios) 1945-50	(1)	699	727	546	448	339	300	292	385	498	676	718	745	
	(2)	607	533	436	346	226	177	221	271	334	519	603	560	403
	(3)	9	4	10	7	6	5	2	8	3	7	4	3	
Córdoba (Prov. Córdoba) 1940-52	(1)	659	618	511	384	324	284	285	358	440	560	649	688	
	(2)	586	530	411	350	247	220	241	310	402	492	580	604	414.4
	(3)	3	5	4	5	4	6	4	5	4	6	5	3	
Corrientes (Prov. Corrientes) 1941-51	(1)	759	716	608	450	371	364	324	426	577	678	714	705	
	(2)	564	505	426	336	273	213	249	315	382	436	539	568	405
	(3)	5	2	7	4	4	1	3	8	2	8	5	7	
La Quiaca (Prov. Jujuy) 1943-52	(1)	820	860	854	695	614	560	570	618	788	914	915	993	
	(2)	751	698	695	621	557	509	523	595	695	818	825	791	673
	(3)	1	1	4	8	15	14	13	12	7	2	1	1	
La Rioja (Prov. La Rioja) 1941-50	(1)	826	740	627	494	376	337	349	450	565	703	817	878	
	(2)	605	536	448	370	282	254	289	374	465	537	614	655	459
	(3)	7	6	7	9	6	9	8	13	10	9	7	7	
Loreto (Prov. Misiones) 1951-52	(1)	929	786	668	516	422	341	366	442	604	693	846	950	
	(2)	749	599	492	424	316	211	278	361	383	546	607	756	477
	(3)	3	2	3	2	4	2	6	3	3	2	2	2	
Mar del Plata (Prov. Buenos Aires) 1949-52	(1)	786	681	543	423	300	219	249	301	462	613	769	837	
	(2)	664	544	422	298	180	159	166	221	323	471	589	608	388
	(3)	3	2	3	2	2	3	3	3	2	2	3	2	
Mendoza (Prov. Mendoza) 1940-52	(1)	774	692	552	439	343	298	315	407	521	648	752	791	
	(2)	651	597	479	382	281	245	262	340	435	546	657	688	472
	(3)	5	6	4	7	5	4	5	7	6	6	7	7	
Neuquen (Prov. Neuquen) 1958	(2)	642	508	357	243	133	100	99	82.8	122.5	403	506	575	314.2
	(3)	10.6	10.5	8.3	7.2	4.4	4.8	3.5	6.4	6.4	9.6	9.1	8.7	
Pehuajó (Prov. Buenos Aires) 1949-52	(1)	785	700	554	445	316	262	277	366	464	640	756	847	
	(2)	657	560	412	337	185	190	189	265	341	486	596	666	398.6
	(3)	6	6	3	7	3	5	5	6	3	4	4	4	
Pilar 1945 (Prov. Córdoba) 1941-43	(1)	776	714	587	424	327	259	284	371	476	627	741	776	
	(2)	636	566	437	355	252	207	236	310	413	527	612	664	434.6
	(3)	3	4	6	9	3	8	9	7	10	5	4	4	
Posadas (Prov. Misiones) 1941-45	(1)	606	586	485	436	362	322	324	370	498	558	600	650	
	(2)	512	482	396	367	271	216	244	291	353	446.5	490	553.2	391.7
	(3)	2	1	6	10	5	3	4	4	3	7	5	2	
Salta (Prov. Salta) 1950-51.	(1)			614	480	424	371	381	453	580	689	808	800	
	(2)	524	423	428	337	326	314	334	414	438	569	504	518	412
	(3)			2	2	5	4	8	11	6	3	1	2	
Rivadavia (Prov. Salta) 1951-52	(1)	726	726	635	520	418	378	366	421	536	645	720	812	
	(2)	550	496	499	381	354	260	306	392	461	522	567	652	462
	(3)		2	4	6	2	6	13	16	10	6	1	6	

Table 3. Values of solar radiation on a horizontal plant measured with the Robitzsch bimetallic pyranograph at the stations of Argentina *(continued)*

Station		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Rosario (Prov. Santa Fé)														
1950-52	(1)	726	678	514	412	310	257	269	345	444	608	705	782	
	(2)	603	515	418	327	201	188	204	281	327	474	550	621	393
	(3)	5	3	9	6	3	3	7	10	2	6	3	5	
San Juan (Prov. San Juan)														
1958	(2)			456	379	289	367	348	343	418	548	610	548	441
	(3)	10.7	10.7	7.6	8.6	5.2	6.4	6.0	6.8	7.5	8.9	10.5	9.9	
San Miguel (Prov. Buenos														
Aires) 1951-52	(1)	758	685	540	450	297	255	231	386	429	592	690	756	
	(2)	594	518	408	308	194	178	176	250	322	428	520	591	365
	(3)	5	2	4	2	2	2	7	4	3	2	2	3	
Santa Rosa (Prov. La Pampa)	(1)	798	699	570	379	296	215	258	326	524	630	769	808	
	(2)	652	612	476	283	153	151	171	239	213	492	589	637	390
	(3)	9	5	8	7	1	3	8	6	6	6	3	5	
Trelew (Prov. Chubut)														
1950-52	(1)	841	699	544	398	256	169	224	311	434	665		852	
	(2)	700	573	454	292	149	114	159	214	345	500	598	633	394
	(3)	3	2	3	3	2	3	3	3	2	1		1	
Tucumán (Prov. Tucumán)														
1949-52	(1)	705	649	577	463	498	354	343	406	493	585	681	708	
	(2)	571	489	423	382	278	271	296	346	383	468	516	556	415
	(3)	1	1	6	7	4	5	10	10	4	5	2	1	

(especially in the mountainous areas) which do not have total-radiation recorders, there is still enough energy in autumn and winter for water heating with fixed collectors (with the greatest angle of inclination to the horizon being in winter), leaving the period of maximum available solar energy (summer) for the use of these same collectors to supply cycles of lower efficiency (space cooling, food conservation, ice production).

The most important use of solar energy in a large part of northern Argentina, however, is for demineralizing water. This can be accomplished in flat inclined collectors at a summer average rate of 2 l m^{-2} day^{-1}.

Moreover, it is obvious that one must start by developing the simplest installations at the Experimental Centre, and afterwards, gradually, with comparative tests, those that involve greater difficulties. One must convince oneself that efficient and economic results will not be attained without serious and continuous work at a scientific experiment station. Such results have been obtained, up to now, only in countries where such stations have been organized and are in operation.

References

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2. National Meteorological Service, Climatological Statistics, 1901-1950.
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Summary

A course in wind dynamics and wind machines was instituted at the Buenos Aires School of Engineering in 1959. A plan for a study of the harnessing of wind and solar energy on a nation-wide scale was submitted to the competent authorities.

This plan proposed the establishment of an experimental centre for wind and solar energy to collaborate with the National Meteorological Service in finding favourable sites for harnessing energy and to perform the long-term measurements required for that purpose. The Centre was also to study, design, build and test the basic experimental equipment for such harnessing and make a detailed cost study for the use of industrial bidders for the production of such equipment under the control of a government agency that would finance such mass

production. Consumers could thus acquire the relevant equipment at low monthly charges and would also be provided with technical assistance and supplies.

Characteristics of the sites studied

The first series of sites was selected from data provided by the National Meteorological Service (see tables 1, 2 and 3). The wind records for a number of sites bounding the zone of lowest mean relative humidity in Argentina were also analysed (see figures 1 and 2).

Figures 3 to 6 give the respective annual velocity duration curves, annual velocity frequency curves, and the diurnal march of the mean hourly wind speed at the station, for Trelew, Comodoro Rivadavia, San Julián, Santa Cruz, Rio Gallegos, Esquel and San Carlos de Bariloche. To obtain monthly curves in more detail than can be reproduced in the small figures annexed, the author has tables derived from the wind records.

Remarks on the harnessing of energy

The data usually available to the meteorological services are inadequate for windpower studies. An experimental centre for wind and solar energy is therefore required to guide and facilitate the development of such forms of energy in Argentina.

Wind power in southern Argentina reaches high levels, especially in spring and summer. The wind distribution shown in the figures relates to sites bounding a large area, most of it arid and sparsely settled. The conditions in this area can be substantially improved by using wind power to pump ground and river water and for generating electric power for local use at isolated houses or for small communities and industries, or also by large wind-driven generators connected to a grid.

There is little opportunity for the use of wind power in northern Argentina, but there is more for solar energy. The sun can contribute to agricultural and industrial development and help to raise the level of living. The use of simple and economic collectors is advisable. They would be flat, fixed collectors, facing north and inclined to the horizon at an angle equal to the solar culmination at the season of operation.

This angle might be adjusted by hand, say once a week. This would greatly simplify the mechanism and maximize collector efficiency.

This type of collector may be used for various purposes. Its efficiency is about 0.5-0.6. It may be used in large, medium and small-scale water demineralizing plants, for heating dwellings, workshops, hospitals, public buildings, etc., and for drying agricultural products, wood, etc. Its use for summer air-conditioning, with an absorption cycle having a total efficiency of about 0.10, is also advised. Industrial production of ice and refrigeration of food may be based on the same principle.

The conversion of solar energy into mechanical and electrical energy has up to now been characterized by low output and the use of equipment that is not yet economic, especially in view of the level of living in northern Argentina. The study and improvement of such equipment, however, will be one of the important functions of the proposed centre, after the development of other equipment for harnessing wind and sun in Argentina.

DIAGRAMMES ANÉMOMÉTRIQUES POUR L'ARGENTINE MÉRIDIONALE, CONSIDÉRATIONS SUR L'UTILISATION DE L'ÉNERGIE ÉOLIENNE ET SOLAIRE DU PAYS

Résumé

On a inauguré en 1959, à la Faculté technique de Buenos-Aires, un cours de dynamique éolienne et on a présenté une étude relative à des programmes visant à l'utilisation de l'énergie éolienne et solaire à l'échelle nationale à cette faculté, au Secrétariat national de l'énergie et à l'Institut national de technologie agricole (INTA).

Le projet envisageait la création d'un centre expérimental de l'énergie éolienne et solaire (CEES), qui devait chercher les emplacements les plus favorables au point de vue énergétique et prendre les mesures à long terme nécessaires, avec la collaboration du Service météorologique national (SMN) : ce centre devait aussi étudier, projeter, réaliser et essayer des éléments de base expérimentaux en vue de l'utilisation de ces énergies, pour faire ensuite une étude des frais destinée à servir de base à des licitations industrielles avec l'aide d'un organisme financier de l'état, pour la production en série. Ceci permettrait aux usagers d'acheter les installations nécessaires malgré des revenus mensuels limités et les assurerait d'un service d'assistance technique efficace et de la fourniture de pièces de rechange.

Caractéristiques des emplacements examinés

On a tout d'abord choisi, en utilisant les données du SMN, une première série d'emplacements considérés comme étant les plus favorables, indiquée aux tableaux 1, 2 et 3, et on a analysé les bandes anémométriques de nombre de postes, qui définissent une ample zone où l'état hygrométrique moyen est le plus bas de l'Argentine. Voir figures 1 et 2.

Aux figures 3 à 6, on ajoute des diagrammes annuels « durée-vitesse », « fréquences des vitesses » et « répartition des vitesses » en valeurs moyennes

pour les postes en cause et sur les 24 heures du jour, aux stations de Trelew, Comodoro Rivadavia, San Julien, Santa Cruz, Rio Gallegos, Esquel et San Carlos de Bariloche. Pour permettre l'établissement de diagrammes mensuels plus détaillés, qu'il est impossible de reproduire étant donné l'exiguïté des figures, on a donné 21 tableaux des valeurs numériques déduites des bandes anémométriques.

Considérations sur les applications de cette énergie à la production de force motrice

Les données dont on dispose généralement dans les services météorologiques sont insuffisantes pour l'étude des éoliennes et il faut créer un centre expérimental de l'énergie éolienne et solaire pour guider et faciliter le développement de la mise en œuvre de ces sources naturelles d'énergie dans ce pays.

Au sud de l'Argentine, l'énergie éolienne présente des valeurs élevées, notamment au printemps et en été. La répartition du vent indiquée dans les diagrammes ci-joints se rapporte à une zone généralement aride et peu habitée, qui peut être rendue sensiblement plus hospitalière en mettant le vent en œuvre pour le pompage de l'eau du sous-sol et des rivières et pour la production d'électricité, tant localement, pour les maisons de campagne isolées, que pour de petites communautés et des industries. On pourra également se servir de grandes éoliennes reliées à un réseau électrique.

Au nord, d'après les données dont nous disposons, il y a peu de possibilités d'utilisation du vent. Elles sont meilleures en ce qui concerne l'énergie solaire, qui peut contribuer beaucoup au développement de l'agriculture et de l'industrie de notre pays et relever son niveau de vie.

En début de programme, on recommande l'emploi de types simples et économiques de collecteurs, c'est-à-dire de collecteurs plans, fixes, inclinés d'un angle égal à la hauteur maximum du soleil aux différentes saisons. La variation de l'angle d'inclinaison peut se faire à la main par exemple, une fois par semaine, simplifiant ainsi au maximum les installations et donnant le plus haut rendement qu'on puisse obtenir avec des collecteurs plans fixes.

Ces types de collecteurs ont des emplois très variés et un rendement de l'ordre de 0,5 à 0,6. On peut les utiliser dans des installations grandes, moyennes et petites pour la déminéralisation de l'eau, le chauffage des maisons, des usines, des hôpitaux, des édifices publics, le séchage des produits agricoles, des bois, etc. Leur utilisation se prête également très bien au conditionnement de l'air en été, en se servant d'un cycle d'absorption ayant un rendement total de l'ordre de 0,10. En s'en tenant au même principe, on peut faire de la glace et assurer le refroidissement des dépôts de comestibles.

Jusqu'à présent, la transformation de l'énergie solaire en énergie mécanique ou électrique s'est faite avec fort peu de succès pratique et des installations qui ne sont pas encore justifiables du point de vue économique, particulièrement si l'on tient compte du niveau de vie moyen au nord du pays. De la même manière, l'étude et la mise au point de ces installations constitueront une des tâches importantes du CEES, une fois que d'autres installations destinées à capter l'énergie éolienne et solaire du pays auront été mises sur pied.

WIND FLOW OVER HILLS, IN RELATION TO WIND POWER UTILIZATION

J. Frenkiel *

In view of the importance of developing local energy resources in Israel, the possibility of wind energy utilization was bound to attract attention, in particular by means of large-scale generation of electricity from plants connected with the general supply network.

It was, of course, necessary to determine the most suitable locations in different parts of the country. Therefore, in 1953, a country-wide survey was begun, and some twenty points of measurements were set up where wind data were measured. These wind measuring stations were set up on the peaks of hills in order to utilize the generally assumed accelerating influence of their slopes on wind.

As a result of the survey, several sites have been selected which appear appropriate for large generation of wind power. These sites can be roughly divided topographically into two broad categories:

(*a*) A mountain ridge athwart the prevailing wind direction with a steep leeward side;

(*b*) An isolated peak in a valley in the general direction of prevailing winds.

One site in each category was chosen for a detailed investigation of wind behaviour with the purpose of correlating the topography of the site with the characteristics of the wind flow over it. It was felt that this study was not only necessary to provide a sound basis for future developments of wind power utilization in Israel, but that it could be of importance for similar developments in other countries as well, as it would give data of general value.

These data were sorely lacking. P. C. Putnam, summing up wind investigations connected with his great aerogenerator, wrote: "after five years of increasing familiarity with the problem of site selection, we can point to no analogy between the profiles of mountains and the profiles of airfoils by which one can predict mean wind velocities at hub height within limits which will be useful"; and, again: "we have found no criteria by which to make an economically useful quantitative prediction of the effects of topography upon wind flow". All he could say was: "we believe good wind-turbine sites will be found at certain points on ridges lying athwart, or nearly athwart, the flow of the prevailing wind; ... they are not likely to be found among upwind foothills, although they may be found on downwind shoulders" (1).

E. W. Golding, drawing on his extensive experience with British wind survey, fully subscribes to Putnam's views as illustrated in the first two quotations, and writes: "It would be very convenient if it were possible to use a precise formula relating the wind speed at a certain height over the summit of a hill of a given altitude and shape to the undisturbed wind speed at the same altitude but at a distance up-wind from the hill. This would facilitate the choice of sites; one might almost choose them from close study of contoured maps, if sufficiently detailed, without being familiar with the actual localities. But no such method can be followed: it is not possible to work from the formula." (2)

As to the best topography of the site, he is even less specific than Putnam. He writes: "The theory of wind flow over hills is complex and evidence is still lacking on the precise shape of hill for maximum accelerating effect." While mentioning some especially windy isolated hills (Costa Hill, Orkney; Mynydd Anelog, Caernarvonshire, North Wales; and Bloody Foreland, Co. Donegal, Eire), he says that it has proved possible from experience "to choose (such) hills, giving good — although not, perhaps optimum, results."

Obviously, the question which of the two site categories (i.e. isolated hill or a mountain ridge) is more suitable for wind power generation is intimately linked with the wind régime at the site, in particular with the frequency distribution of wind directions. For a wind régime characterized by a strongly prevailing wind direction — such as in Ei lat (3, 4), it would seem that a fairly steep ridge athwart that direction would best accelerate the wind flow over it. Such is also — although to a much lesser extent — the wind régime of the mountains of New England, where, for instance, at the site of Putnam's aerogenerator at Grandpa's Knob, some 47 per cent of winds came from a south-westerly and westerly direction (1). Where, on the other hand, no clear wind direction prevails, as is the case of open sites

Table 1. Variation of wind speed with height for wind directions over Costa Hill

Wind direction	*45° to 75° across the ridge*	*135° to 165° along the ridge*
$V_{10\,ft}/V_{65\,ft}$	0.931	0.847
$V_{35\,ft}/V_{66\,ft}$	1.012	0.940

* Technion, Israel Institute of Technology, Haifa.

along the western Scottish coast (2) there seems to be every advantage for choosing isolated hills of regular conical shape for wind power sites.

Some attempt to relate the shape of the wind power site to the flow over it was made as a result of an extensive programme of wind measurements at Costa Hill, an isolated small ridge on the north coast of Orkney mainland, undertaken at the beginning of the British wind survey (2, 5). The results are summarized in table 1.

It should be noted that the mean slope across the ridge was 14°, and that along it —6°.

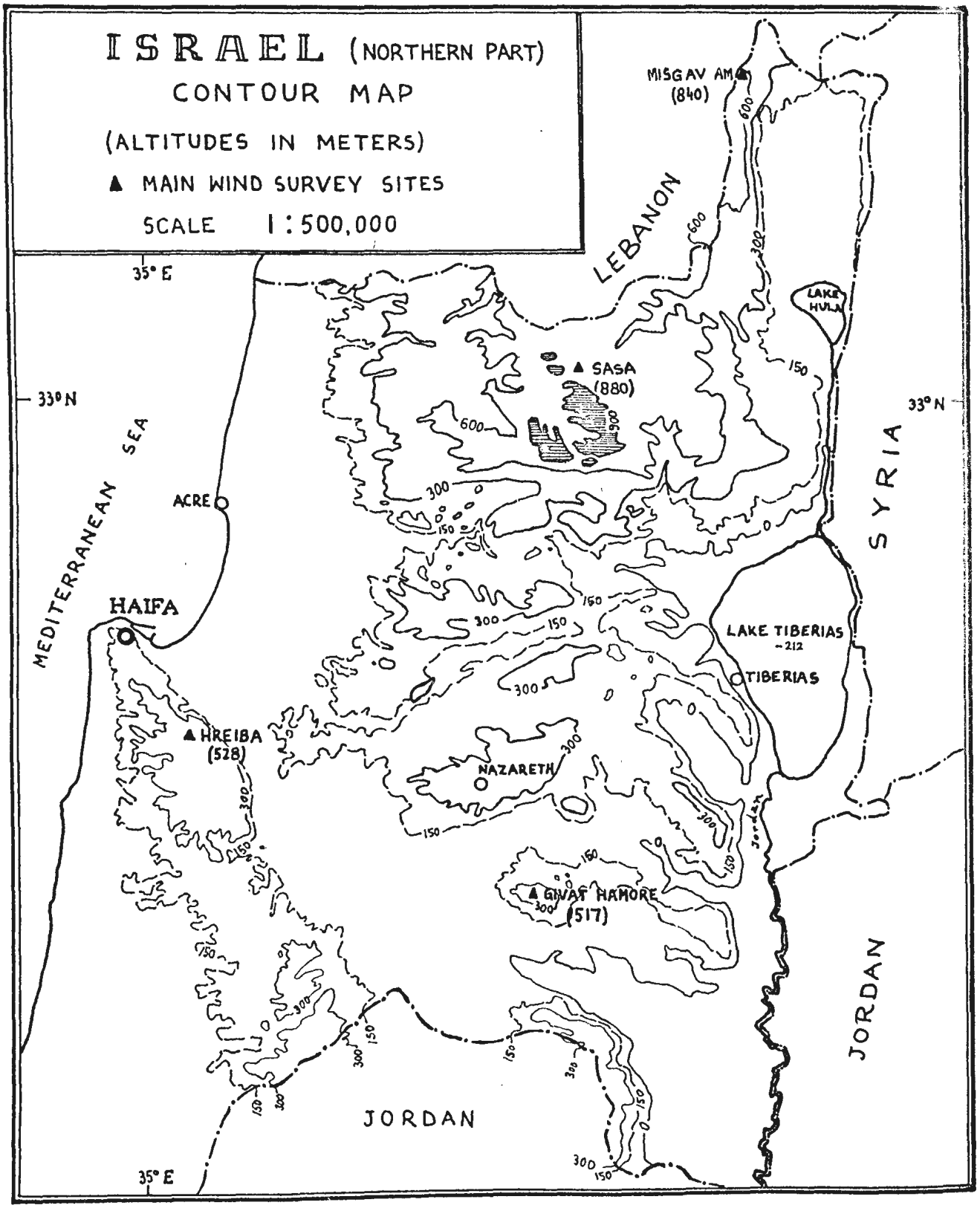

Figure 1

Wind measurements at the site were also made at the heights of 58 ft, 88 ft and 118 ft, and some twenty daily runs-of-wind were analyzed for ratio to run-of-wind at 88 ft, and gave the following average ratios 0.948, 0.978. Individual daily runs-of-wind showed considerable scatter from these values, which is not surprising as the data were not analyzed separately for different wind directions. Although no statistical evaluation was made, it seems probable that the decrease of wind speed from 88 ft to 118 ft was significant. No similar phenomenon was observed at other British wind survey sites, but this can be explained by the fact that no measurements were made at heights exceeding 66 ft, nor were wind data up to that height analyzed according to wind direction.

No wind profile observations over wind power sites were accompanied, as far as is known, by simultaneous measurements of the vertical temperature distribution which influences considerably the rate of vertical interchange of momentum by turbulence. Putnam gave the absence of these measurements as the reason for his inability to explain unusually low nocturnal wind velocities at the site of his aerogenerator as compared with those at two other Vermont hills (1).

There is, of course, a considerable literature on the interrelation between wind profile and temperature profile over level country.

Until a few years ago, the average vertical component of wind velocity was thought to be of importance when designing a wind turbine for a given site (1, 2). Recently, however, measurements with high speed gust recorders (6) have shown it to be a small and extremely variable quantity, not likely to have any serious effect on the operation of the aerogenerator. Consequently, no measurements of vertical component were made at the two sites.

Much the same can be said about wind structure, i.e. the departure of the wind from the steady flow. Wind structure may have an influence on (*a*) the energy output of an aerogenerator, and (*b*) the stresses set up in the blades of its rotor. As regards the first of these influences, although the power in the wind varies as cube of the wind velocity, this is certainly not true of the power delivered by a modern wind-driven machine; the relationship is usually quasi-linear, levelling off as the rated power is approached (7). Consequently, there is little point in gust measurements for the computation of the cube factor (or the energy pattern factor) which are entirely irrelevant for energy estimates. However, gust measurements of not too quick response can be useful when testing the performance of wind-driven generators. Villers, working with high-speed gust equipment, found that "the machine (a 10-kW unit) is insensitive to gusts of small amplitude and duration. Thus, so far as it influences the output, the speed of the mass air flow is probably represented more closely by the smoothed curve derived from one-second means of the actual wind record" (8). It is reasonable to suppose that for larger machines, even this one-second interval may be too short.

The other influence of wind-speed variations bringing about fluctuating stresses in the blades of a wind-driven machine has been considered by Wax (6). He shows that, even in steady winds, the vertical wind gradient and tower shadow will cause cyclic fluctuations of stress of the same order as those due to the more sharp-edged gusts. It follows that the blade system designed to meet these cyclic stresses will have an inherent strength sufficient to cater for most gusts that are likely to be experienced.

Sites and instruments

Sites

As stated earlier, two wind survey sites, one typical of a mountain ridge site and another of an isolated hill, were chosen for present investigations. The first site — Hreiba (528 m above sea level) — is situated some 10 km from Haifa on one of the highest peaks of the Carmel Mountain Range, which extends from Haifa in a general south-easterly direction. The other site — Givat Hamore (517 m above sea level) — is a conical hill in a broad valley (Plain of Esdraelon), some 40 km south-east of Haifa. The two sites, which are but 30 km distant from each other, can be clearly seen in relation to the surrounding country in the contour map of the northern part of Israel (figure 1). It is noteworthy that they are practically at the same elevation.

The Hreiba site and its near surroundings can be seen in some detail in the contour map (figure 2). There is a good natural exposure in all directions. Only to the south-east is the ground more or less level, nowhere rising above Hreiba's height in a

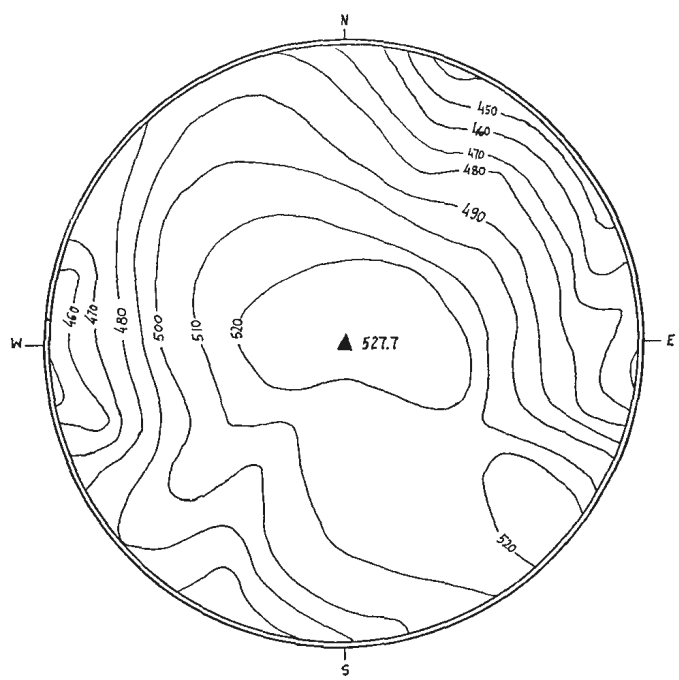

Figure 2. Contour map of Hreiba
(Altitude in meters) Scale 1 : 5 000

2 km radius. The highest elevation of the ridge is 542 m above sea level and is 3 km distant from Hreiba. The total length of the ridge, of which Hreiba is the north-western extremity, is about 7 km. The ground in the immediate vicinity of the measurements' mast is, as usual in Israel, almost bare in summer and covered with wild grass in winter. There are small patches of shrub oak and shrub pine a few meters high over the area. There is also a pine-tree forest several hundred meters south-east of the site, but at a slightly lower elevation than the site. The man-made obstructions consist of a one-storey house with a flat roof some 3 m high, about 60 m west of the site, and several antenna lattice masts at approximately the same distance in the general west-north-west direction. The 2 × 3 m hut housing the instruments was 20 m due west from the mast.

The approach to the site is very easy. There is a second-class road passing at less than a 100 m from the site, and the nature of the ground at the site lends itself to the passage of even ordinary motor vehicles.

The Givat Hamore site is shown in figure 3. The hill-top is of a regular, slightly rounded conical shape. Its origin is clearly volcanic. There is a second hill-top of almost the same height some 900 m to the east, but its slopes are less steep, and its section is in the shape of a figure eight. The site has an excellent exposure in all directions, the nearest higher peak (Mt. Tabor, 588 m above sea level) being more than 8 km distant. The hill-top is bare of trees, the only obstruction being an old sepulchre, 2 m high, some 10 m west of the observation mast. Pine trees have been planted in recent years on the slopes, but nowhere do they reach a height of more than 2 m. There are also some rows of eucalyptus trees down the eastern slope.

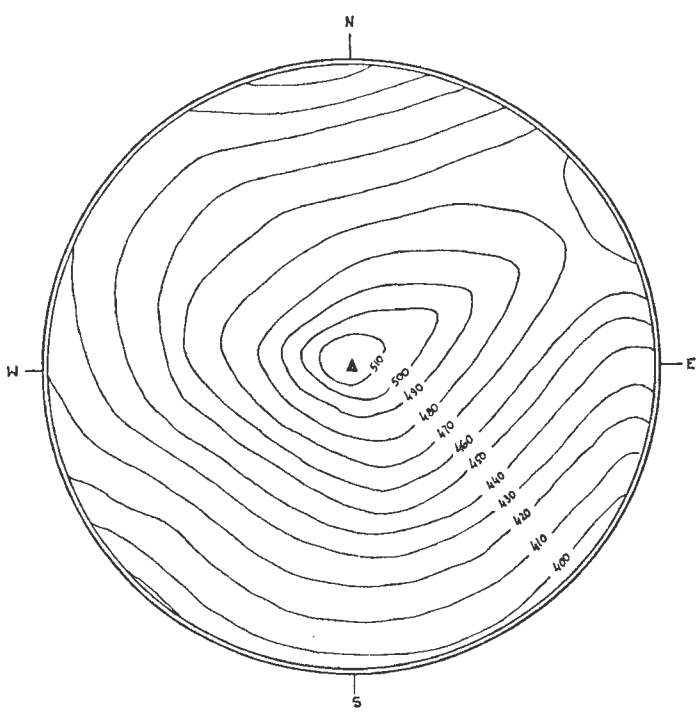

Figure 3. Contour map of Givat Hamore
(Altitude in meters) Scale 1 : 5 000

The 2 × 3 m instrument hut, some 30 m south-east of the mast, was several meters below the hill-top.

The approach to the site is not easy. The hard-surfaced road ends about 2 km (as the crow flies) from the site. From there, there is a dirt track, 3.5 km long, impassable after heavy rains even for four-wheel-drive vehicles, and ending some 350 m from the site. The last stretch has to be climbed on foot. A minimum time of 1½ hr was necessary to reach the site from Haifa.

Measurements masts

For wind-behaviour investigation to have significance for wind power development purposes, it was advisable that it should cover wind measurements up to the height of the top of any of the types of wind turbines on which research and development work is now going on in different European countries. Consequently, it was assumed that the heights likely to be of immediate interest for large-scale utilization of wind energy for electricity generation are between 10 and 40 m above ground.

The assumption as regards the height interval was derived from considerations of the probable optimal diameter of the wind machine. There is no general agreement as to the exact size of the optimal windmill, but there is little doubt that in the present state of technology, it must be somewhere between 20 and 30 m. Juul has advocated a 24 m diameter machine as the optimal windmill size ever since the early fifties (9). His Gedser windmill, built in 1957 (10), has since proved eminently successful. Vadot (11) has shown that the optimum range is between 24 and 30 m for a singly constructed aerogenerator, and about 20 m for series construction.[1] Electricité de France has chosen a 21 m and a 30 m machine for their experimental prototypes (12).

In view of the above, it seemed reasonable to choose a 30 m height interval for wind measurements.

The assumption of the height of 10 m above ground as the lower limit of the interval resulted from considerations of a minimum height below which there is bound to be an appreciable decrease in wind speed even on a good site (with the possible exception of some very steep hills with small hill-top area) with proportionally much higher increase in gustiness (6, 13, 14). On the other hand, it was thought that raising the lower limit more than 10 m above ground could not be justified economically on hill-top sites (15).[2]

On the above assumptions, and with due regard to the cost, two identical 40 m high tubular steel

[1] This calculation was made on the basis of series construction for an installed capacity of 10 000 kW. For larger series construction, the optimal diameter would no doubt be higher by several meters.

[2] In view of the results of wind measurements at Hreiba, this statement has to be qualified to apply to good hill-top sites only.

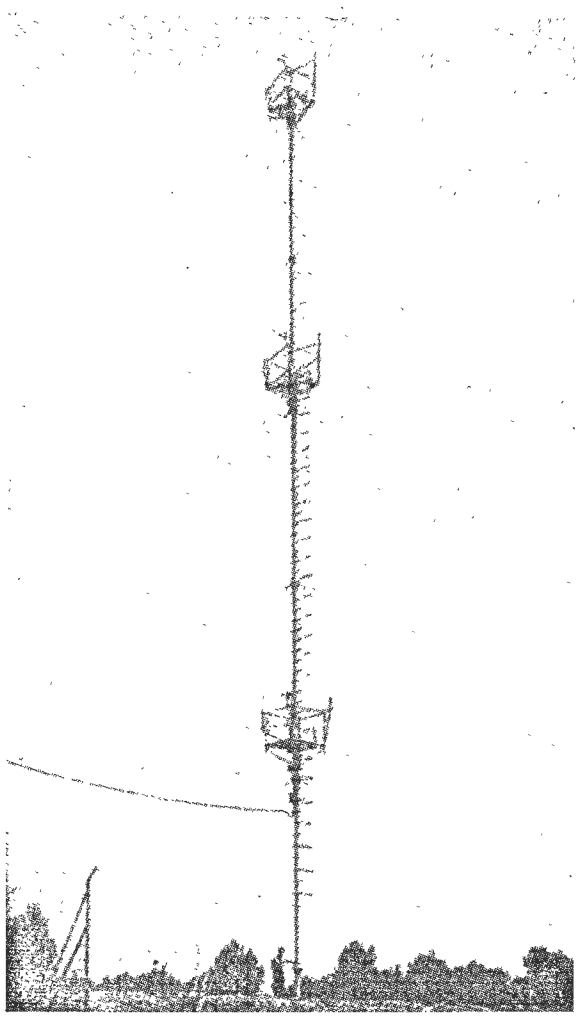

Figure 4. Observation mast, Hreiba

masts were designed, built and erected on the sites. The masts were made up of five 7.5 m long, 6 inch tube sections, joined by flanged joints. The main foundation consisted of a 1.9 cubic meter concrete block in which a short tubular section was embedded. To the latter, the main body of the mast was fastened by an elastic joint, about 1 m above the ground. The uppermost 1.5 m long section consisted of a 4 inch tube. There were three platforms at the height of 8.5 m, 23.5 m and 38.5 m, respectively, above the ground, supporting the measuring instruments. The mast was held upright by 20 guy wires, 5 guys each of the four directions perpendicular to one another.

The measurements mast in Hreiba is shown in figure 4 and that in Givat Hamore in figure 5.

Instruments

As explained in the previous section, it was decided to make wind measurements in the height interval between 10 and 40 m above ground. To determine the variation of wind speed over this interval, it was considered necessary to measure wind at three heights — 10 m, 25 m and 40 m, corresponding to the bottom, the hub-height and the top, respectively, of a 30 m diameter windmill. Furthermore, it was felt that there should be a possibility for measurements to be made at at least one more intermediate height whenever this appeared advisable in order to elucidate some irregularity of the wind profile as based on measurements at three heights only. The measurements, to have significance for energy estimates for wind power purposes, had to be made continuously on hourly bases for at least a year. The location of the sites, and in particular that of Givat Hamore, made it necessary to have equipment operating reliably with as little service and maintenance as possible. In Givat Hamore, there was an additional problem, that of electricity supply. As there was no main supply of electricity on the site, it was decided to use small wind-driven generators to charge batteries. In consequence, it was essential to limit, as much as possible, the electricity requirements of the equipment.

The above considerations governed the choice of instruments. To record wind-run continuously on an hourly basis, two different instruments were selected.

The first, chronologically, was the E.R.A. 4-channel impulse recorder, series 3, Mark II (5), in conjunction

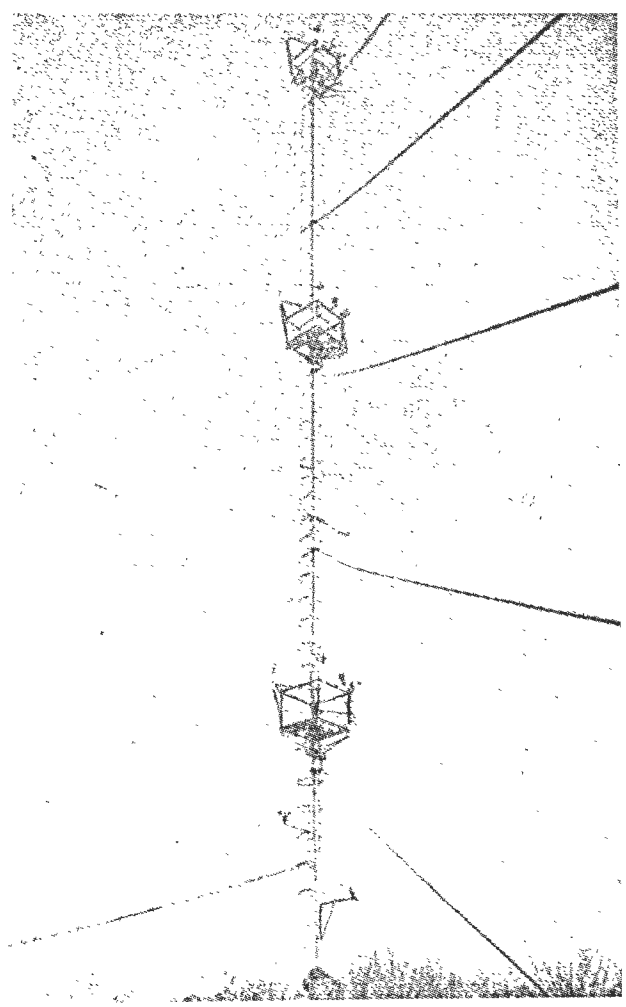

Figure 5. Observation mast, Givat Hamore

with British Meteorological Office pattern cup-counter Mark II anemometers fitted with silver contacts closing electric circuit after the passage of each 100 m of wind (16). Each channel of the recorder contains a divider mechanism which produces one electrical impulse for every forty impulses arriving from the anemometer. As each impulse occurs, it energizes a marking solenoid which, in turn, prints a dot through a typewriter ribbon on a chart driven by an eight-day clockwork at a speed of 1 in/hr. Thus, four times the number of spaces between dots, in a 1-in. run of chart gives the hourly mean wind speed in km/hr.

In addition to its standard mode of operation described above, the instrument was also used for obtaining a more detailed picture of wind structure based on 100 m of run of wind. This was done by short circuiting the divider mechanisms and running the chart at a speed of 1 in/min. In this way, mean wind speeds in km/hr over 1-min intervals were obtained by multiplying by 6 the number of spaces between dots in a 1-in. run of chart.

The other wind recorder was made by Lambrecht, Göttingen. This was the No. 1489, a 4-channel wind-run recorder and counter connected to Lambrecht light-metal alloy cup-contact anemometers closing the electrical circuit after the passage of each 1 000 m of wind. The two-week chart was driven by an A.C. synchronous motor (Hreiba) or an 8-day clockwork (Givat Hamore) at a speed of 60 mm/hr, and the recording of an impulse was made electrically by burning a horizontal line in a metal damped chart with a pointed electrode, the voltage applied being 24V. Each tenth impulse was recorded differently, facilitating the computations. In addition, total wind-run could be read on respective counters.

The wind direction recorder was provided by the same firm. This instrument consisted of a precision

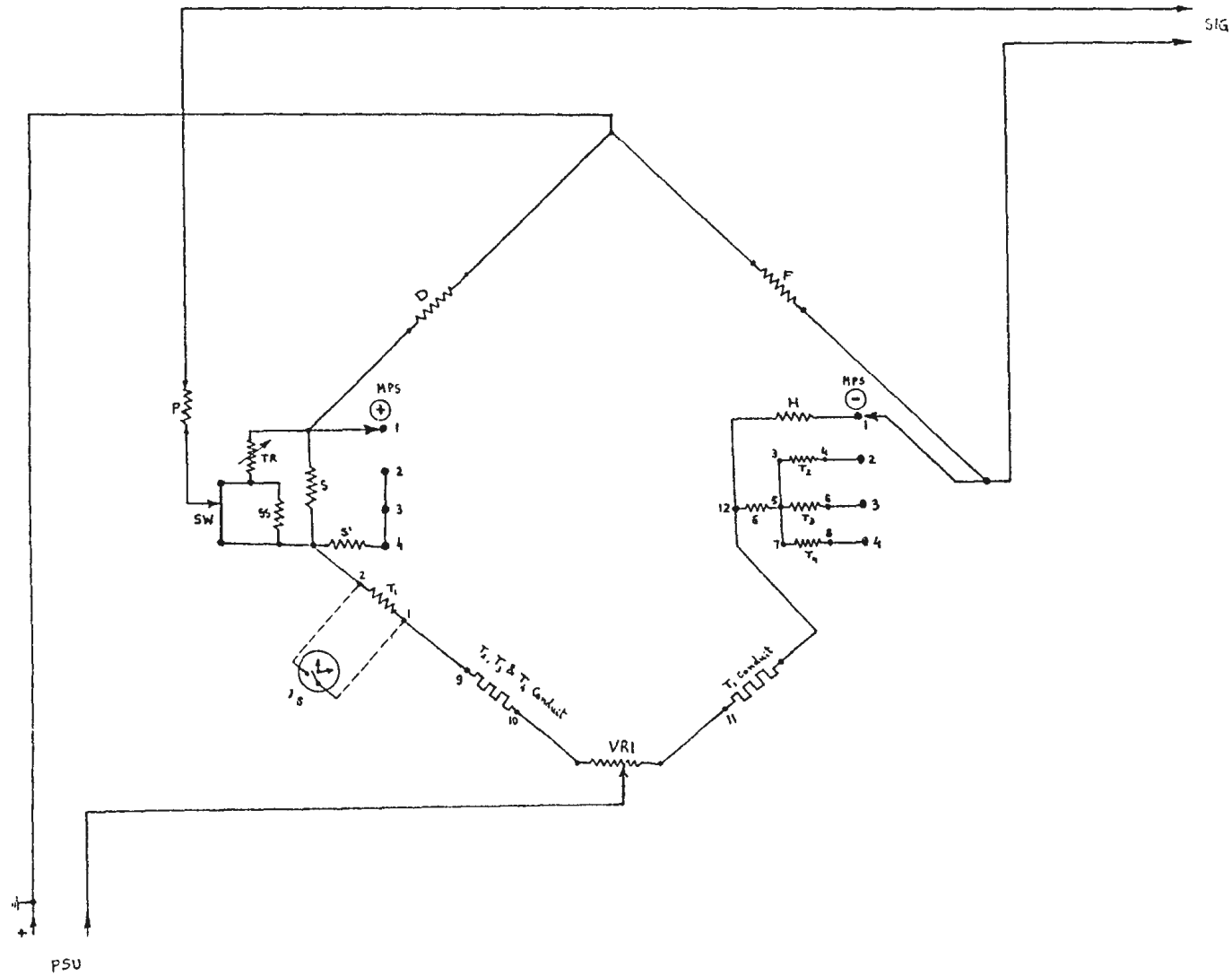

Figure 6

Direct differential temperature recorder : bridge connections

T_1, T_2, T_3, T_4 : resistance elements (designated T_0, T_I, T_{II}, T_{III} respectively in the wiring diagrams of the stations); TR : trimmer; MPS : multiple point switch; SW : slide wire; SIG. : signal; PSU : power supply unit; VRI : 1Ω potentiometer; D, F, G, H, P, S, SS, S′ : resistance bobbins; numbers on the arms of the bridge are those marked on the connection strip; TS : time switch (in Givat Hamore only)

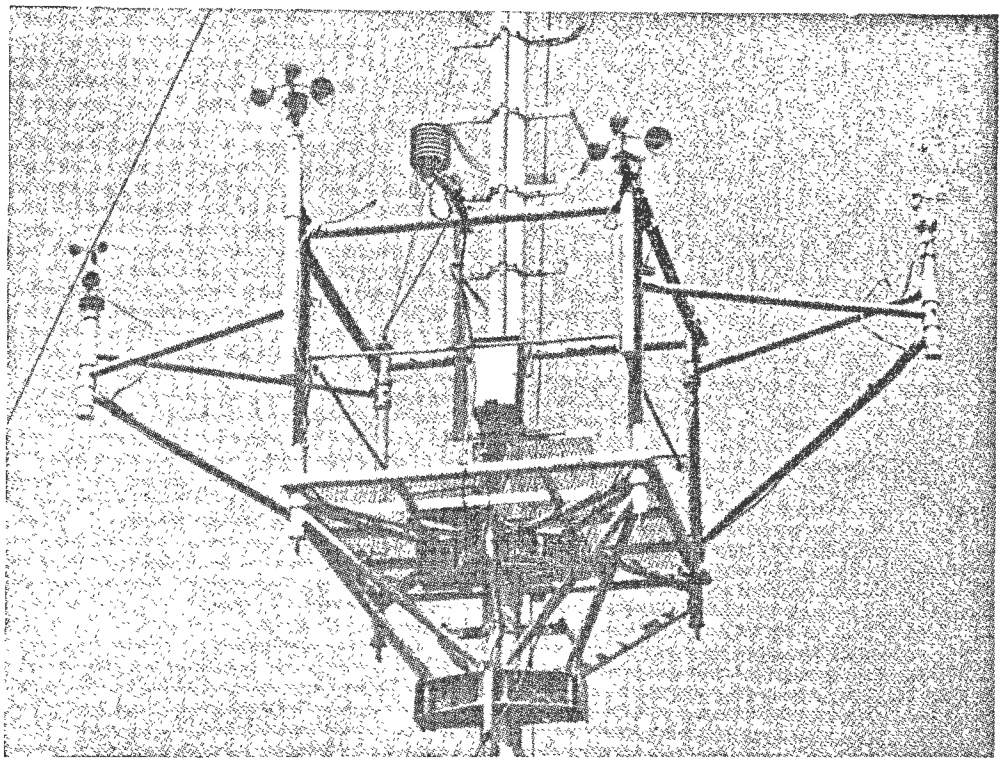

Figure 7. A platform of the measurements mast in Givat Hamore

ring potentiometer in the wind vane as transmitting unit, and a moving coil receiver unit for recording instantaneous wind direction. The chart-driving and recording mechanism were analogous to those of the wind-run recorder.

For temperature profile recording, the Elliot direct and differential 4-point resistance thermometer recorder was chosen. This was essentially what is known as Bristol's Dynamaster D.C. bridge instrument. Its sensing elements were four platinum resistance thermometers encased in multiple radiation shields. The elements were placed at heights of 3.5 m, 10 m, 25 m, and 40 m above the ground. The recorder used in the present investigation differed from the usual Dynamaster instrument by bridge connections enabling one to record, instead of the temperature at the different points, the temperature at one point only (in the present project at the height of 3.5 m above ground), and the difference of temperature between the other points and this reference point (see figure 6). Consequently, there were two chart ranges (over a width of 11 in.) : 0° to 50°C for reference temperature, and —5° to 5°C for the temperature difference relative to the reference point. The 4-week chart was driven by synchronous motor at a speed of 2 in./hour, and the printing interval between the points was 15 seconds, the instrument returning to the same point after 1 minute.

For wind gust profile recordings, Contact Pattern Sensitive Anemometers manufactured by Casella, London, were selected. This instrument was first made by Deacon (16), and modified subsequently by Crawford (17). The impulses received from the

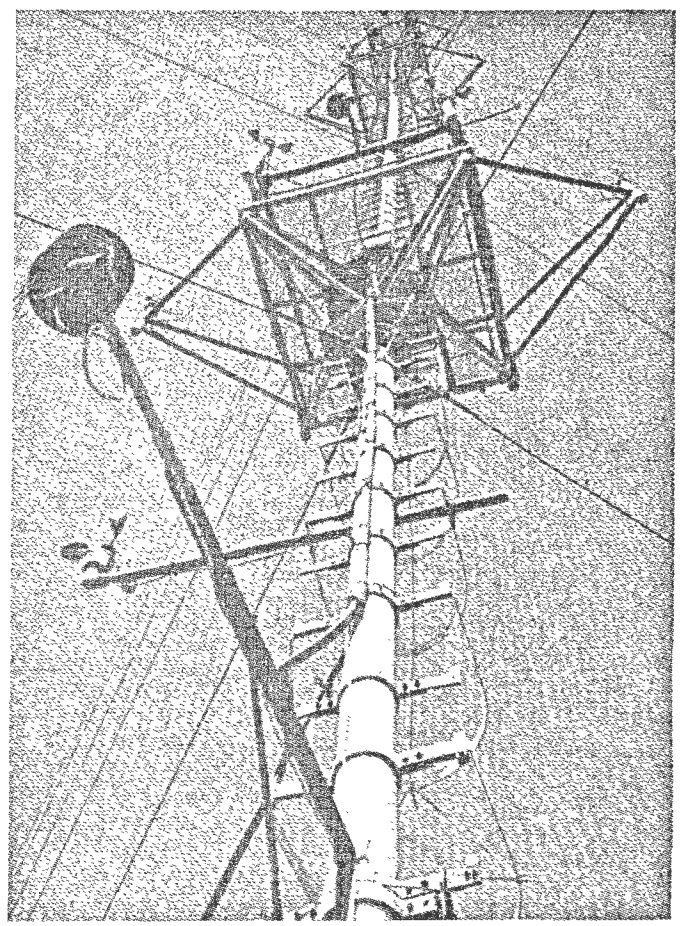

Figure 8. A perspective view of the measurements mast in Givat Hamore

anemometers, at the heights of 10 m, 25 m and 40 m above ground were fed through a D.C. (transistor) amplifier to a multi-channel Evershed time recorder. The chart was driven by a 24V D.C. motor at either 1 in./sec or $\frac{1}{2}$ in./sec.

The general lay-out of the instruments was very similar at the two sites. Both in Hreiba and Givat Hamore, the wind direction transmitter was located at the top of the mast, well above the other instruments on the upper platform. There were four anemometer mountings on each platform, two inner ones near the ends of the side of the platform facing west—the prevailing wind direction — some 120 cm (or 8 mast diameters) distant from the mast; and two outer ones on hinged struts, 190 cm from the mast and 160 cm from the nearest other anemometer mounting. The inner mountings were used for doubling instruments (usually Munro cup-contact anemometers); of the two outer mountings, one was taken by the Lambrecht instrument, and the other was reserved for Casella anemometers, which were mounted only during the observation runs. No two anemometers were mounted at the same height, to minimize the possible interference, but the relative position of different anemometers was the same at each platform. In this way, although the heights of the

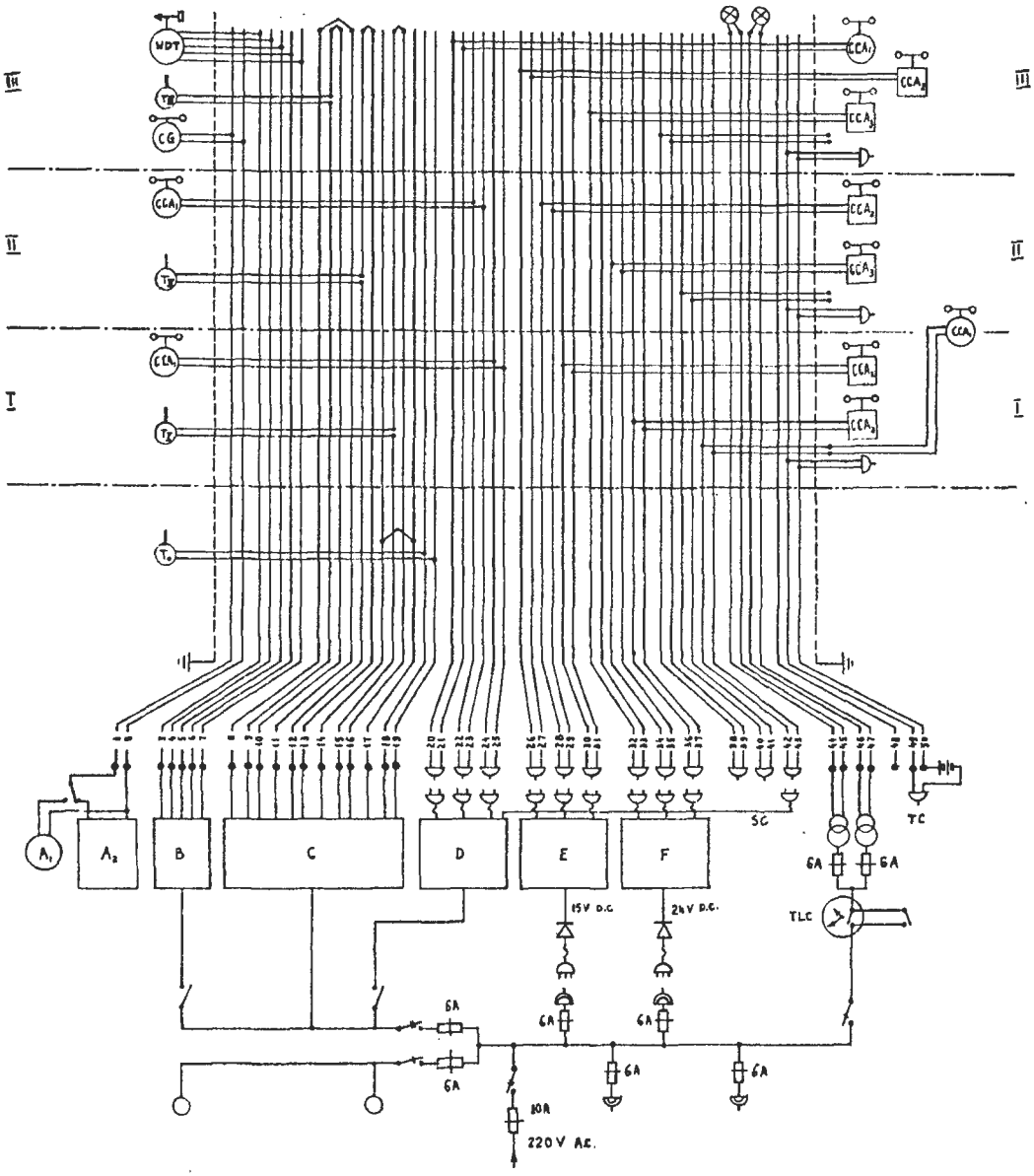

Figure 9

Research project on wind flow over hills. Hreiba Observation Station (wiring diagram)

I : lowen platform, 10 m above ground; II : middle platform, 25 m above ground; III : upper platform, 40 m above ground; A_1 : Munro wind velocity indicator; A_2: Everett wind velocity recorder; CG : cup anemometer, generator type; B : Lambrecht wind direction indicator and recorder; WDT : wind direction transmitter; C : Elliott direct and differential temperature recorder; T_0, T_I, T_{II}, T_{III} : resistance elements at the heights of 3 m, 10 m, 25 m and 40 m respectively above ground; I : D : Lambrecht wind run recorder; CCA_1 : cup contact anemometers (contact every 1 000 m of wind run); E : E.R.R. wind run recorder; CCA_2 : Munro cup contact anemometers (contact every 100 m of wind run); F : Evershed high speed operation recorder; CCA_3 : Casella sensitive anemometers; SC : spare connections; TLC : tower light control; TC : telephone connections

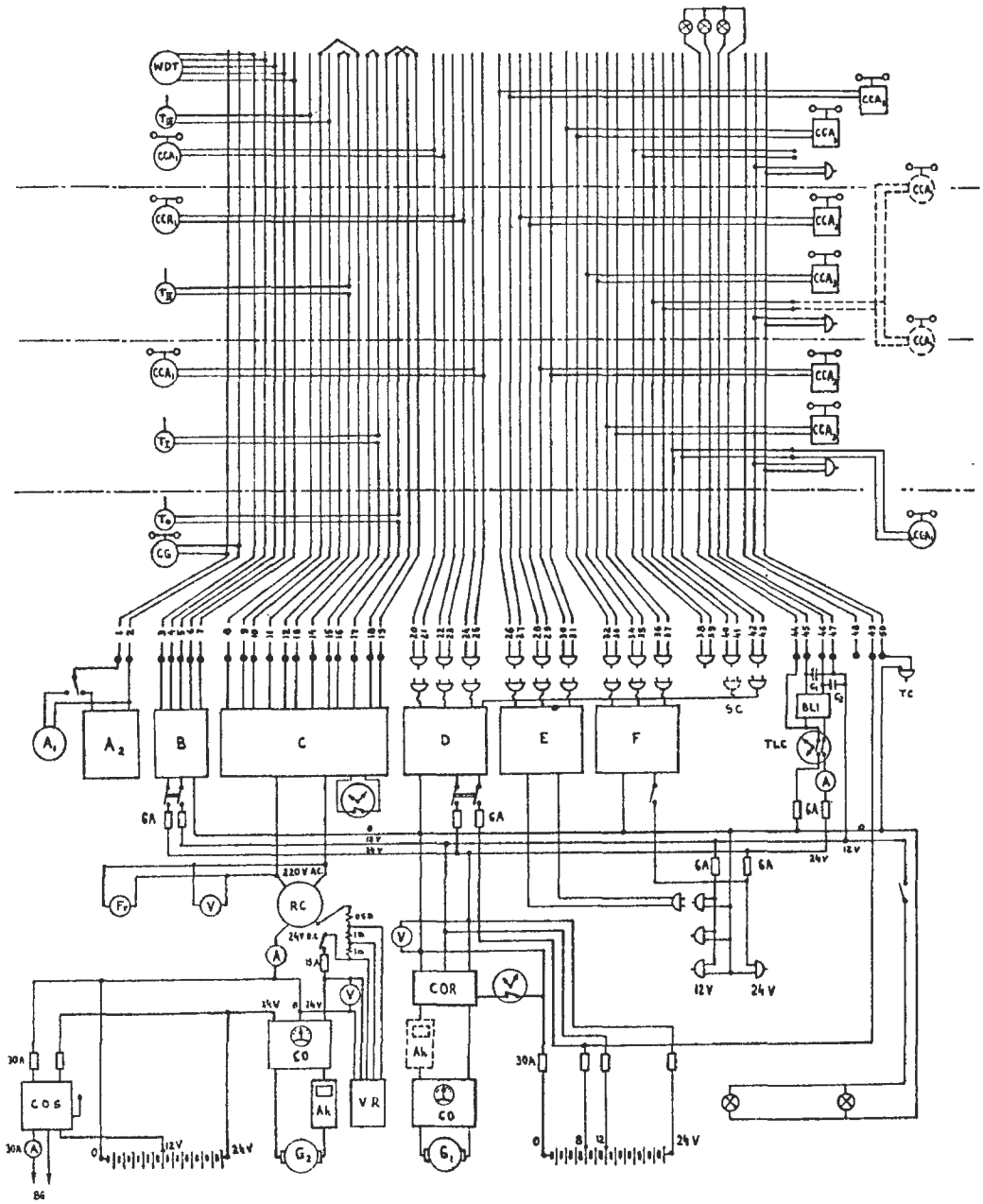

Figure 10

Research project on wind flow over hills. Givat Hamore Observation Station (wiring diagram)

I : lower platform, 10 m above ground; II : middle platform, 25 m above ground; III : upper platform, 40 m above ground; A_1 : Munro wind velocity indicator; A_2 Everett wind velocity recorder; CG : cup anemometer, generator type; B : Lambrecht wind direction indicator and recorder; WDT : wind direction transmitter; C : Elliott direct and differential temperature recorder; T_0, T_I, T_{II}, T_{III}: resistance elements at the heights of 3 m, 10 m, 25 m and 40 m respectively above ground; D : Lambrecht wind run recorder; CCA_1 : cup contact anemometers (contact every 1 000 m of wind run); E : E.R.A. wind run recorder; CCA_2 : Munro cup contact anemometers (contact every 100 m of wind run); F : Evershed high speed operation recorder; CCA_3 : Casella sensitive anemometers; SC : spare connections; TLC : tower light control; BLI : blinker; C_1, C_2 : 25μf capacitors; TC : telephone connections; RC : rotary convertor; BG : booster generator; COR : change over relay; COS : change over switch; CO : cut out; VR : voltage regulator; G_1 : Lucas 250 W wind electric plant; G_2 : Enag 800 W wind electric plant; Ah : ampere hour meter

anemometers above ground were not exactly 10 m, 25 m and 40 m (only Lambrecht instruments approximated these heights to within 10 cm), the difference in height between the same type of anemometer in successive platforms was exactly 15 m. Figure 7 gives the view of a platform of the measurements masts in Givat Hamore. The anemometers are clearly seen and so is the resistance thermometer in multiple radiation shields. Instruments installed outside the platforms can be seen in figures 5 and 8, giving a perspective view of the mast in Givat Hamore.

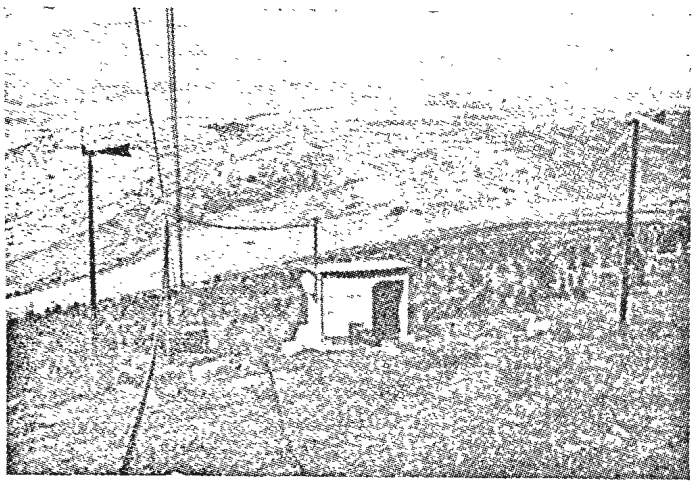

Figure 11. Givat Hamore station: the instrument hut and the wind electric plants

The complete installation in Hreiba is shown schematically in figure 9 and that in Givat Hamore in figure 10. The two wind electric plants and the instrument hut in Givat Hamore can be seen in figure 11. The instrument panel in Givat Hamore is shown in figure 12.

Calibration and evaluation

Relative calibration of anemometers was made by means of a low-speed, closed-circuit wind tunnel with a 60 by 90 cm working section by running two anemometers side by side. As the section was not large enough to accommodate two British Meteorological Office pattern cup-anemometers, these instruments were calibrated, using the inclined-tube manometers for wind speeds higher than 10 m/sec, and a sensitive two-liquid micro-manometer (19), together with a motor tachometer, for wind speeds in the 5 m/sec range. For even lower wind speeds, tachometer indications only had to be relied upon.[3] The general calibration errors for Meteorological Office pattern cup-counter anemometers with electrical contact were shown by Hartley (16) to be less than 1 km/hr over the range from 3 km/hr to 130 km/hr (1.8 mph to 80 mph), the calibration curve being linear in the range between 16 km/hr (10 mph) and 80 km/hr (50 mph).

Individual differences between Meteorological Office pattern anemometers of the same batch of manufacture when new were found to be very small and of random nature, well within the error of the calibration. Nor have appreciable changes been observed after one year's exposure.

The Lambrecht cup-contact anemometers, closing electric contact after each 1 000 m of wind-run, had a general calibration curve given by the equation:

$$V = 0.8 + 0.948\, v'$$

where V is the true wind speed and v' is the wind velocity as computed from the frequency of the contacts of the anemometer, both expressed in m/sec. It may be seen that the two are equal for $v = 15$ m/sec.

When running in wind tunnel the different anememeters from the eight-instrument batch, it was found that the departures from linearity between the true and indicated wind velocity were small; however, systematic differences were found between some of these anemometers. There were only four instruments with a spread of less than 1 per cent over the range of wind speeds from 12 km/hr to 50 km/hr. These instruments were consigned to Givat Hamore, where it was expected that the wind vertical gradient would be very small. Another four instruments, showing a spread of up to 6 per cent at the wind speed of 12 km/hr, were consigned to Hreiba. At each site, three anemometers were installed on the three platforms, and later moved twice by rotation at approximately the same intervals of time. The fourth instrument was held in reserve and later installed at some intermediate height, as explained before. After one year's measurements, the instruments were recalibrated, and again no significant departures were found from the original calibration.

The records were evaluated in hourly units to the nearest kilometer per hour. It was decided not to take account of the general calibration equation. To have done this would have meant a general up-

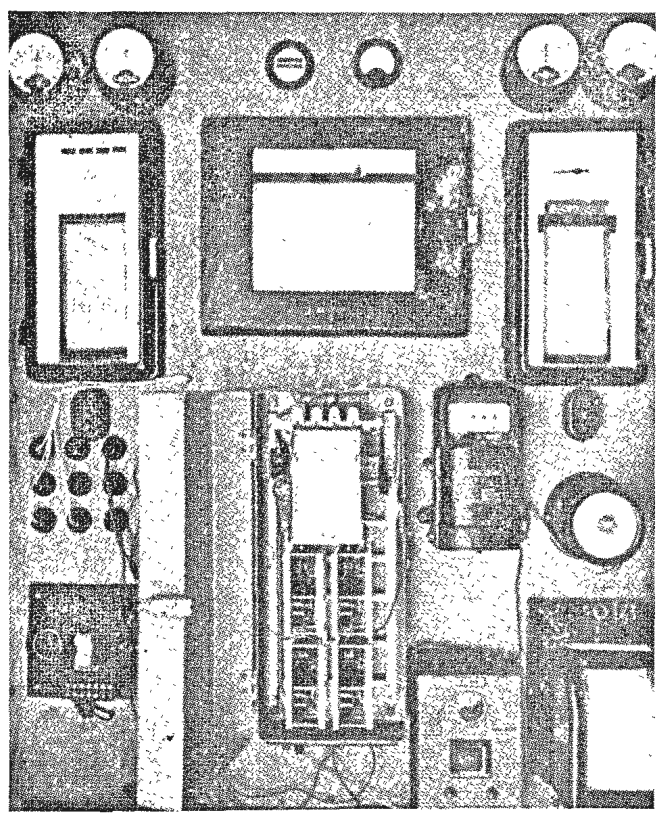

Figure 12. Givat Hamore station: instrument panel

[3] It should be noted that the wind tunnel was first put into operation a short time before the beginning of the measurements, and no precision gauges were available.

ward revision of the values obtained up to the wind velocity of 54 km/hr or a quasi-totality of wind speeds prevailing at the sites. The resulting values would have been obviously too high because of the over-estimation of the cup-anemometers in fluctuating winds. Leaving the values unrevised was equivalent to an average of 2 per cent underestimation, which was probably compensated by over-estimation resulting from fluctuating winds (13). On the other hand, for wind profile computations, individual differences in calibration had to be taken into account whenever these were more than 1 per cent. Accordingly, suitable corrections were made when computing wind profiles in Hreiba.

Wind direction records were evaluated to the nearest multiple of 10°, whenever the direction was constant during the hour. If the direction changed even by as little as 20°, the range of variation was given by two limiting directions.

Evaluated wind speeds at three heights, and the direction, were transferred to punch cards — a card for every hour — which formed the basis for all subsequent computations.

The sensitive anemometers were calibrated at frequent intervals. Although their calibration varied to some extent at very low wind speeds, they were practically constant and identical at wind speeds above 1 m/sec. The records were evaluated in terms of mean wind speeds to the nearest tenth of meter per second of each 2-sec (and later 1-sec) interval of the records. This interval was chosen in view of Villers' results quoted previously (8). A 2-sec interval was sufficient to evaluate gusts of periods greater than 5 sec within 1 per cent if the mean wind speed was 10 m/sec (13). For higher mean wind speeds, 1-sec intervals could be used to evaluate gusts of periods smaller than 5 sec.

The resistance thermometer recorder was calibrated over the whole scale of temperature differences in the laboratory and *in situ*, using two water containers and precision thermometers. Some systematic discrepancies were found, i.e. the difference at $T_{25\,m}$-$T_{10\,m}$ showed 0.1°C too high, which could easily be dealt with in evaluation. Only the temperature difference between the height 25 and 10 m, and 40 and 10 m was evaluated. This was done by reading the differences at intervals of 15 minutes of the record : on the hour, 15 min past, 30 min past, 45 min past and again on the hour, and taking a weighted mean of the five values obtained for every hour interval. Original differences were evaluated to the nearest 0.05°, and it could be assumed that the computed mean did not in general depart by more than that amount from the true mean.

The hourly mean temperature differences, $T_{25\,m}$ $T_{10\,m}$ and $T_{40\,m}$ - $T_{10\,m}$, were also transferred to punch cards alongside the wind data.

Periods of observations

The Hreiba observation station was put into partial operation at the beginning of June 1959, and from September 1959, until the beginning of November 1960, continuous recording of wind run and wind direction was made. Temperature was recorded continuously from March 2 to June 18, 1960. Some fifteen observations of gusts of 25 minutes duration each were made partly in the summer of 1960 and partly in the winter of that year.

At the Givat Hamore observation station, continuous recording of wind and direction was made from the end of October 1959 to mid-December 1960. Temperature was recorded continuously from June 25 to December 5. Gusts were observed on several occasions, both in late winter and summer 1960.

Wind régime at the sites

Both Hreiba and Givat Hamore were selected as measurement points in the early stages of the wind survey (20). In Hreiba, a cup-counter anemometer was set up at a height of 3 m above ground in July 1953, some 25 m from the present measurements mast, and in May 1954, a second instrument, a cup-contact anemometer with an impulse recorder to record hourly wind-runs, was installed on an antenna,

Table 2. Monthly mean wind speeds in Hreiba, 21 m above ground
(in km/hr)

Year	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Yearly mean (July-June)*
1954							18.6	18.2	12.1	18.4	18.5	25.7	20.1
1955	21.5	22.6	23.7	21.1	17.1	17.2	19.5	17.8	16.6	23.0	20.5	25.4	21.2
1956	22.4	26.6	23.7	26.4	20.6	20.1	20.4	18.0	21.1	18.7	19.6	24.7	20.7
1957	26.4	20.3	19.7	19.3	19.5	18.2	19.2	17.3	17.0	20.0	19.5	26.8	20.7
1958	29.8	17.8	23.3	18.2	18.5	20.0							
Mean range: 1 July 1954	25.0	21.3	22.6	20.0	18.9	18.9	19.4	17.8	18.4	20.0	19.5	25.6	20.7
Mean range: 30 June 1958	8.3	8.8	4.0	3.2	3.5	2.9	1.8	0.9	4.1	4.3	2.0	2.1	1.1
Per cent yearly mean	121	103	109	97	91	91	94	86	89	97	94	124	

Table 3. Monthly mean wind speeds in Givat Hamore, 3 m above ground
(in km/hr)

Year	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Mean*
1953								23.7	22.0	19.2	18.2	20.7	
1954	24.2	25.0	21.3	22.0	18.7	24.4	23.5	22.3	19.9	15.3	16.2	19.7	21.0
1955	12.5	16.4	17.6	18.5	14.0	20.1	22.4	23.8	21.0	10.9	16.1	17.4	17.6
1956	15.4	24.4	17.8	20.0	20.4	23.9	21.0	21.4	20.7	20.3	19.0	19.5	20.4
1954-56	17.4	21.9	18.9	20.2	17.7	22.8	22.3	22.5	20.5	15.5	17.1	18.9	19.7
Per cent yearly mean .	88	111	96	103	90	116	113	114	104	79	87	96	

at a height of 21 m above ground, some 30 m from the first instrument. This instrument had an excellent exposure; monthly mean wind speeds are shown in table 2.

The constancy of yearly mean wind speed in Hreiba is remarkable, although by no means exceptional among Israel's potential wind power sites. The same phenomenon has already been noted with respect to Eilat (7).

In Givat Hamore, a cup-counter anemometer was installed in July 1953, at a height of 3 m above ground, some 30 m south-west of the peak. The exposure was not very good, especially in the north and north-eastern direction. Even so, high wind speeds were registered. These are shown in table 3.

Here the wind régime seems to be more variable than in Hreiba. These variations, however, may have been caused to an appreciable degree by the faulty exposure of the instrument. On the other hand, mean monthly range between the windiest month and the least windy month, expressed as a percentage of the yearly mean wind speed, is practically the same at the two sites (38 per cent and 37 per cent).

Table 4 gives month-by-month mean wind speeds at the two sites.

It should be noted that there was one month only in Hreiba (October) and two months only in Givat Hamore (January and February) in which the departure from the several years' mean monthly wind speed as per cent of yearly wind speed was more than 10 per cent.

Wind velocity distribution and energy estimates

A useful way to arrive at energy estimates is by means of duration curves. These are cumulative frequency curves with cumulative frequencies plotted in abscissa in inverse sense. Thus a wind velocity duration curve gives, for each wind velocity, the number of hours in which this velocity was exceeded. By using the Law of the Cube $P = kv^3$ for power in the wind, power-in-the-wind duration curve is obtained from the velocity duration curve, and, in general, for any windmill with known power/wind velocity characteristic, a windmill power duration curve can be obtained from the velocity duration curve (7). The area under the curve then gives the expected energy production by the windmill.

The duration curves for wind velocity, power in the wind and the power of the Gedser 200-kW windmill — the only large-scale wind-driven machine in operation with published characteristics (21) — were drawn, from wind-velocity frequency data, on a monthly basis for the heights of 10 m, 25 m and 40 m above ground separately at each observation station. Altogether, 72 diagrams were made, of which 4 are reproduced in figure 13. These refer to the height of 25 m above ground, and both the windiest and the least windy months have been chosen for each station.

The energy estimates computed from monthly duration curves are summarized in tables 5 and 6.

The relationship between specific output and mean wind speed on a monthly basis is investigated

Table 4. Monthly mean wind speeds in Hreiba and Givat Hamore (Nov. 1959-Oct. 1960), 25 m above ground
(in km/hr)

	Nov.	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Mean*
Hreiba	21.3	28.2	26.1	21.1	26.0	21.7	21.5	21.6	20.5	19.7	17.6	17.8	21.9
Per cent of yearly mean . . .	97	129	119	96	119	99	98	99	94	90	80	81	
Per cent departure from monthly mean (table 2) . .	+ 3	+ 5	+ 2	— 7	+ 10	+ 2	+ 7	+ 8	0	+ 4	— 9	— 16	
Givat Hamore	21.9	26.6	26.6	22.6	25.0	24.5	24.7	29.0	29.2	26.4	23.7	29.8	25.0
Per cent of yearly mean . . .	88	106	106	90	100	98	99	116	117	106	95	79	
Per cent departure from monthly mean (table 3) . .	+ 1	+ 10	+ 18	— 21	+ 4	+ 5	— 9	0	+ 4	— 8	— 9	0	

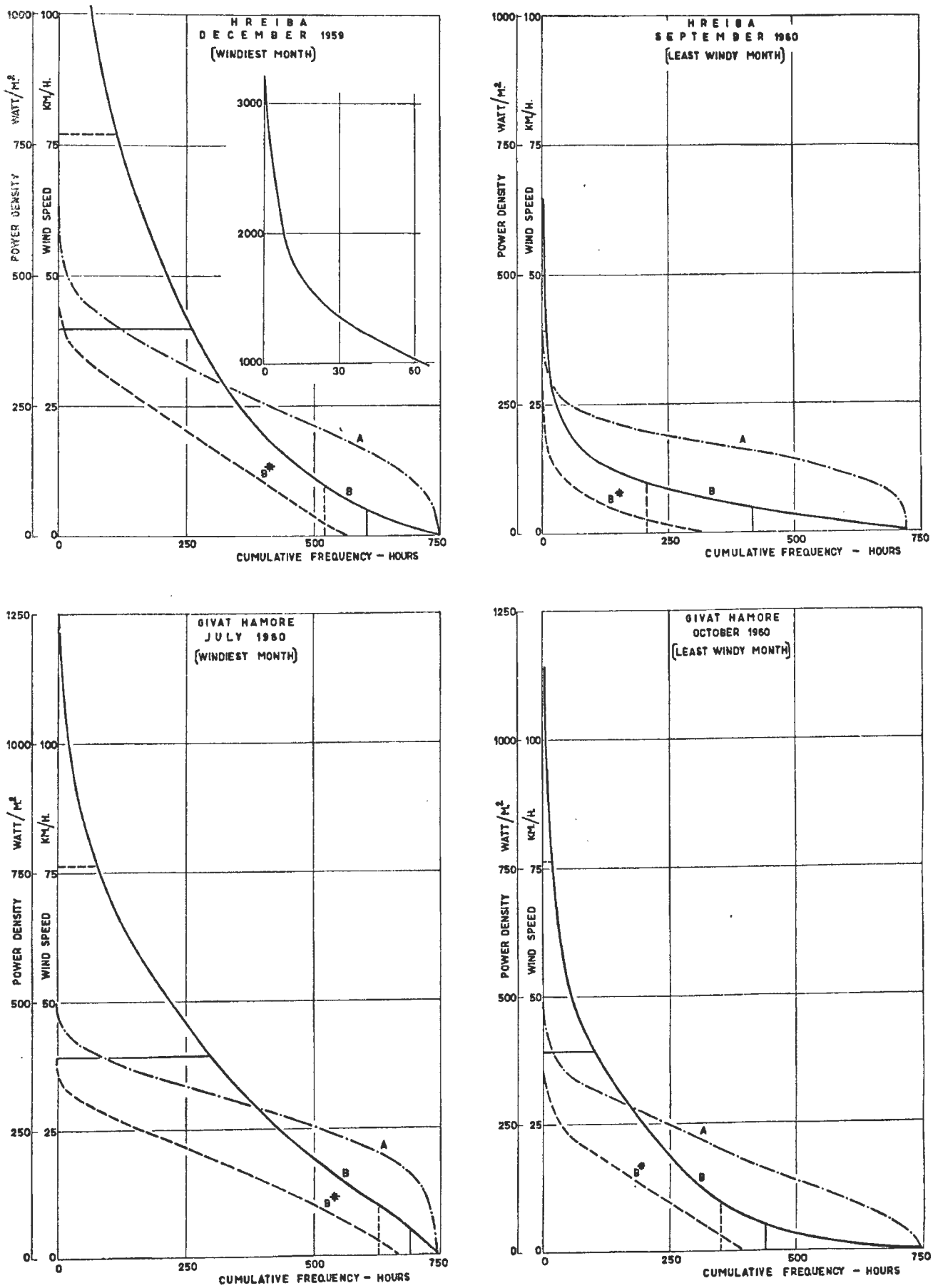

Figure 13

Duration curves (25 m above ground); A : wind velocity duration curve; B : power-in-the-wind duration curve; B* : Gedser windmill power duration curve

Table 5. Energy estimates : Hreiba

(1) Period	Height above ground (m) →	(2) Energy in the wind (kWh/sq.m)			Ideal windmill (v_r — 32 km/hr) (3) Specific output (kWh/kW)			(4) No. of working hours			Ideal windmill (v_r — 40 km/hr) (5) Specific output (kWh/kW)			(6) No. of working hours			Gedser experimental windmill (7) Extractable energy (kWh/sq.m)			(8) No. of working hours		
		10	25	40	10	25	40	10	25	40	10	25	40	10	25	40	10	25	40	10	25	40
4th quarter 1959 (2 208 hrs)		290	491	625	565	843	939	1 182	1 493	1 600	295	528	618	779	1 121	1 232	104	150	214	968	1 304	1 421
1st quarter 1960 (2 184 hrs)		379	663	743	641	944	1 029	1 217	1490	1 545	372	643	724	888	1 213	1 288	133	226	258	1 045	1 348	1 424
2nd quarter 1960 (2 184 hrs)		220	417	457	417	759	818	1 095	1 581	1 662	196	414	468	638	1 120	1 202	70	158	169	855	1 360	1 45[illegible]
3rd quarter 1960 (2 208 hrs)		144	245	282	290	555	608	919	1 473	1 597	107	244	301	448	892	1 052	44	92	113	655	1 160	1 340
Year 1 Oct. 1959 - 30 Sept. 1960 (8 784 hrs)		1 033	1 816	2 107	1 913	3 101	3 394	4 413	6 037	6 404	970	1 829	2 111	2 753	4 346	4 774	351	626	754	3 523	5 172	5 640

REMARKS : Column (2) gives energy in the wind per sq. meter of the swept area of the windmill rotor based on hourly wind velocities;
(3) and (5) give number of kWh per kW installed; the numbers in these columns divided by the number of hours in the respective periods give an average utilization factor in these periods;
(4), (6) and (8) give total number of working hours (both full and partial operation); (3) divided by (4) and (5) divided by (6) give an average power factor during operation;
(7) gives energy at the busbars of the Gedser experimental windmill per sq meter of the swept area of the windmill rotor.

in figure 14. It is found that the relationship is linear and can be expressed by the following regression equations (T_s = specific output) :

$$\text{Ideal windmill. . . .}\begin{cases} V_r\text{—32 km/hr} & \begin{array}{ll} H & T_s = 0.0364\,\bar{v} - 0.421 \\ GM & T_s = 0.0364\,\bar{v} - 0.403 \end{array} \\ V_r\text{—40 km/hr} & \begin{array}{ll} H & T_s = 0.0333\,\bar{v} - 0.506 \\ GM & T_s = 0.0275\,\bar{v} - 0.342 \end{array} \end{cases}$$

$$\text{Danish 200-kW windmill . . . . . .}\begin{cases} H & T_s = 0.0235\,\bar{v} - 0.336 \\ GM & T_s = 0.0192\,\bar{v} - 0.217 \end{cases}$$

The first two lines are parallel; the other two pairs of lines meet for v = 27.7 km/hr.

Table 6. Energy estimates : Givat Hamore

(1) Period	Height above ground (m) →	(2) Energy in the wind (kWh/sq.m)			Ideal windmill (v_r — 32 km/hr) (3) Specific output (kWh/kW)			(4) No. of working hours			Ideal windmill (v_r — 40 km/hr) (5) Specific output (kWh/kW)			(6) No. of working hours			Gedser experimental windmill (7) Extractable energy (kWh/sq.m)			(8) No. of working hours		
		10	25	40	10	25	40	10	25	40	10	25	40	10	25	40	10	25	40	10	25	40
4th quarter 1959/60 [a] (2 208 hrs)		641	667	629	596	927	904	1 374	1 405	1 357	607	634	610	1 127	1 168	1 160	212	223	216	1 232	1 282	1 27[illegible]
1st quarter 1960 (2 184 hrs)		705	775	767	1 002	1 052	1 060	1 488	1 526	1 525	695	759	752	1 247	1 303	1 307	247	266	264	1 353	1 423	1 409
2nd quarter 1960 (2 184 hrs)		645	701	707	1 120	1 193	1 203	1 712	1 745	1 765	722	794	798	1 447	1 497	1 525	248	273	275	1 580	1 640	1 645
3rd quarter 1960 (2 208 hrs)		606	675	640	1 165	1 279	1 266	1 851	1 900	1 903	716	815	783	1 572	1 671	1 674	252	282	273	1 725	1 795	1 790
Year 1 Nov. 1959 - 31 Oct. 1960 (8 784 hrs)		2 597	2 818	2 743	4 183	4 451	4 433	6 425	6 576	6 550	2 740	3 002	2 943	5 393	5 639	5 666	959	1 044	1 028	5 890	6 140	6 119

[a] November and December 1959, October 1960.

REMARKS : See table 5.

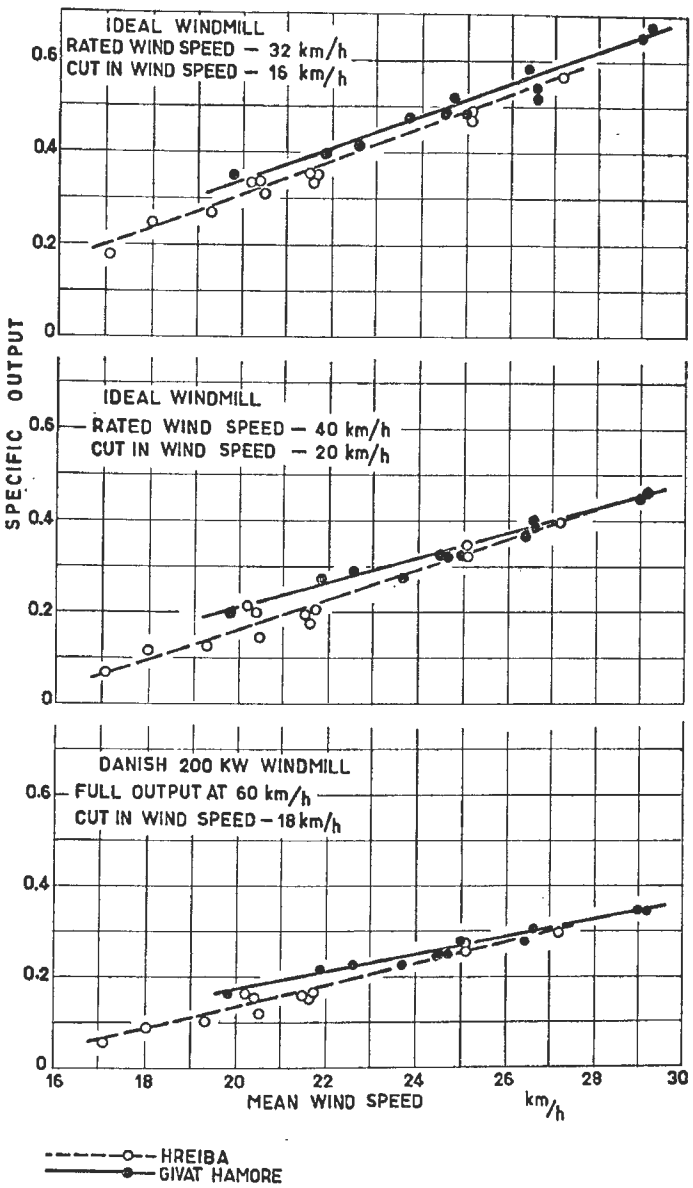

Figure 14

Specific output (as a fraction of full output) *vs.* monthly mean wind speed at Hreiba (Oct. 1959-Sep. 1960) and Givat Hamore (Nov. 1959-Oct. 1960) at 25 m above ground

Mean wind and temperature profiles

Diurnal variation

Diurnal variations of monthly mean hourly wind speed ratios $V_{25\,m}/V_{10\,m}$ and $V_{40\,m}/V_{10\,m}$ for Hreiba (October 1959-September 1960) and Givat Hamore (November 1959-October 1960) are shown in figures 15-17. For months in which the temperature recorder was in operation, the diagrams include also the diurnal variations of monthly mean temperature gradients $T_{25\,m}$-$T_{10\,m}$ and $T_{40\,m}$-$T_{10\,m}$.

The relationship of mean wind profile and mean temperature profile

Although the diagrams of diurnal variations of monthly mean hourly wind ratios and temperature gradients point to at least a statistical relationship between these two quantities, a closer examination reveals that this is not the case. This is illustrated in figure 18.

The absence of this relationship in the two sites obviously points to the existence of at least one more factor contributing to wind and temperature profile configurations, namely, that of the hill geometry. The influence of this factor is considered in the next section.

The effect of the shape of the hill on mean wind profile

To examine the effect of the shape of the hill on the flow over the top of it, vertical profiles have been drawn of the two hills, through the sites of measurements masts, by 10° intervals. These profiles are shown in figures 19 a and 19 b for Hreiba, and in figures 20 a and 20 b for Givat Hamore. The scale both horizontal and vertical is 1 : 40 000.

Table 7 gives mean wind profiles at the two stations according to wind direction. For every wind ratio, two numbers are given : the first refers to all the hours in which wind blew in a steady direction; the second, only the hours of interest for wind power utilization, i.e. for which $V_{25\,m} \geqslant 18$ km/hr were taken into consideration.

Table 7 shows that there is hardly any influence of the wind speed on directional wind ratios. In general $A \approx B$. Only in the case of very regular slopes with few protuberances is B slightly smaller than A. Again, in some cases of very rough and irregular slopes, B may be slightly larger than A. In general, it can be said that there is no need to analyze wind ratio for different wind speeds, and that ratios obtained from the continuous record of wind-run at different levels will apply with a good degree of approximation to the operational range of wind speeds of a given aerogenerator.

There is a definite variation, however, of the ratios with the direction. The range of this variation (for all wind speeds) in Hreiba is from 1.135 to 1.399 for $V_{25\,m}/V_{10\,m}$ ratio, and from 1.179 to 1.499 for $V_{40\,m}/V_{10\,m}$ ratio. The lower limit corresponds to $\alpha = 0.138$ for $V_{25\,m}/V_{10\,m}$ and $\alpha = 0.079$ for $V_{40\,m}/V_{25\,m}$, while the upper limit corresponds to $\alpha = 0.366$ for $V_{25\,m}/V_{10\,m}$ and $\alpha = 0.148$ for $V_{40\,m}/V_{25\,m}$.[4] The departures from the power law in practically all directions are considerable. Only in the 90° direction is the power law observed with $\alpha = 0.262$, which is not surprising in view of the fact that this is the direction with the longest fetch (150 m) of level ground. The high value of α is explained by the nature of ground in this direction — a small pine forest and some patches of scrub oak. This value is identical to that found by Panofsky (22).

The very high value of the power law index ($\alpha = 0.366$) in the 10 to 25-m height interval in the

[4] α = the power law index for the variation of mean wind speed with height : $V/V_0 = (h/h_0)_\alpha$.

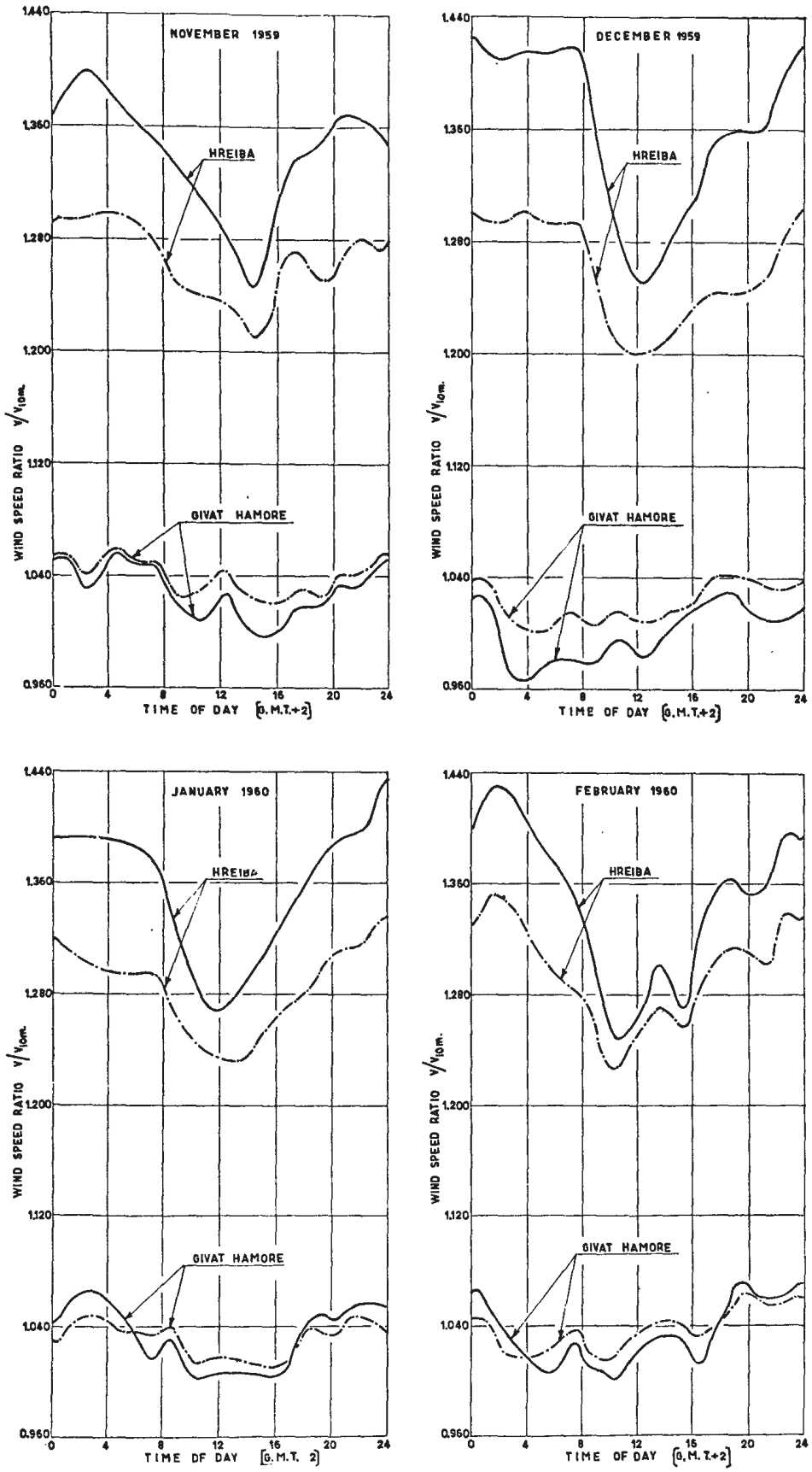

Figure 15

Diurnal variation of wind profile in Hreiba and Givat Hamore

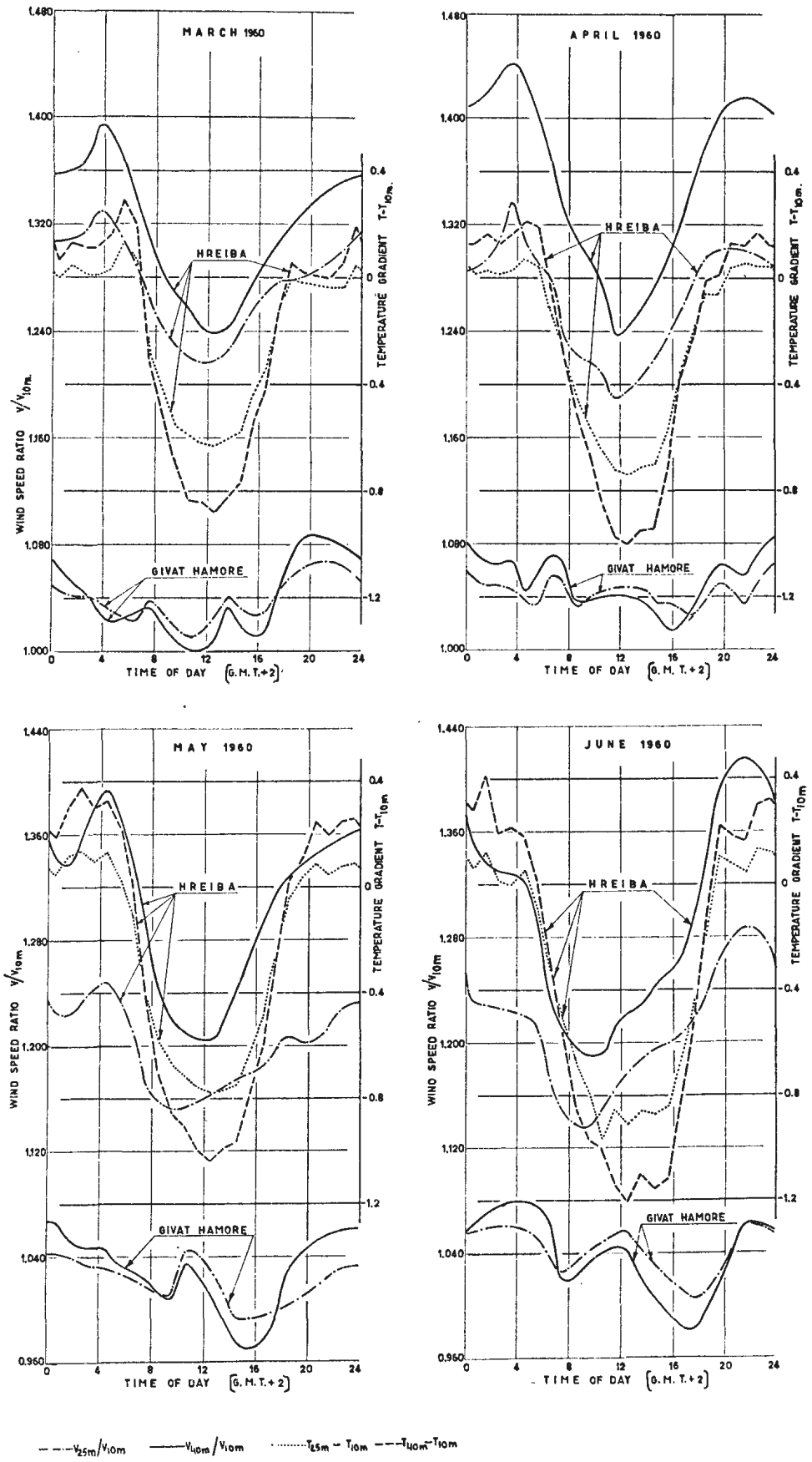

Figure 16

Diurnal variation of wind profile in Hreiba and Givat Hamore and temperature profile in Hreiba

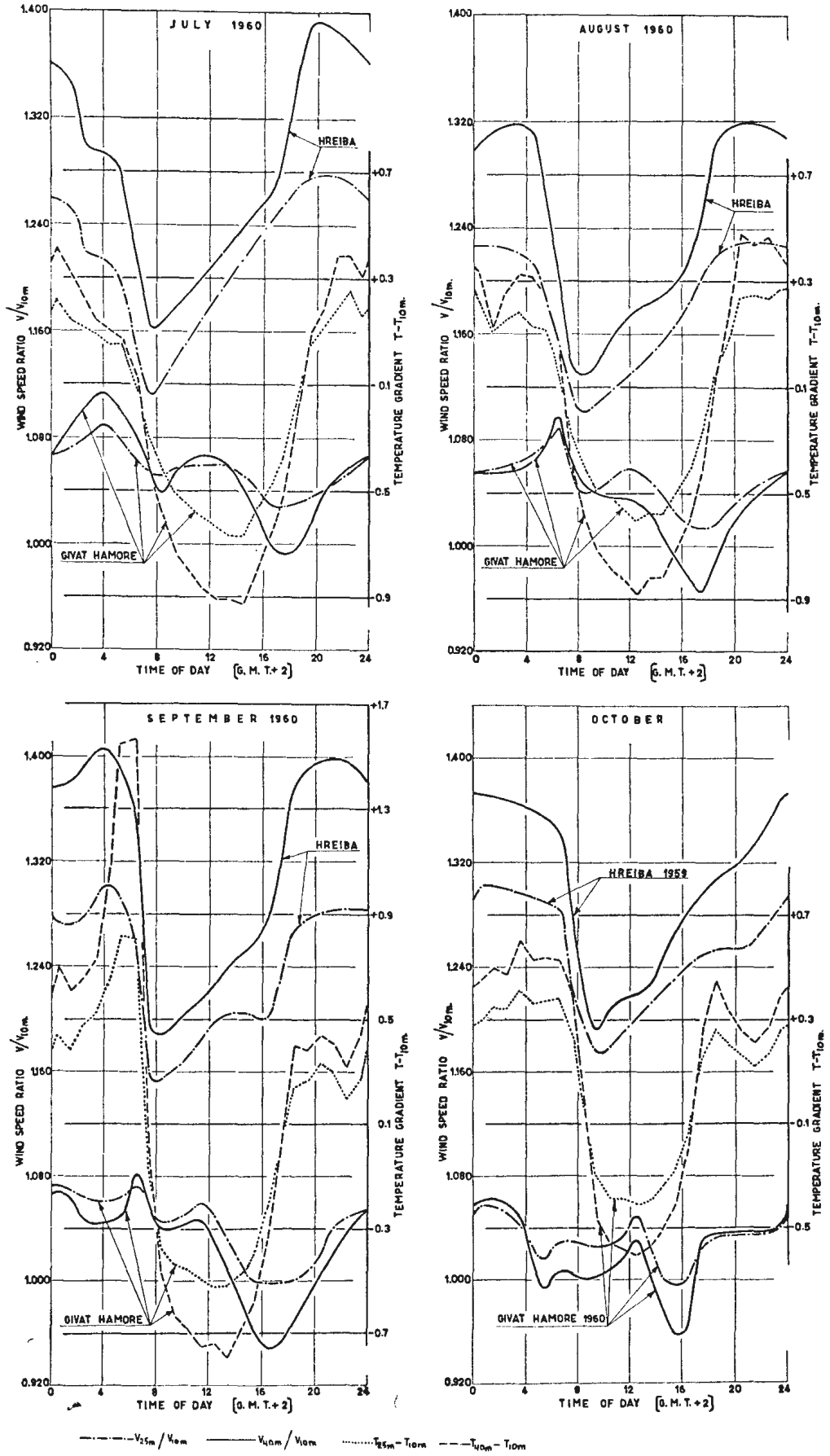

Figure 17

Diurnal variation of wind profile in Hreiba and Givat Hamore and temperature profile in Givat Hamore

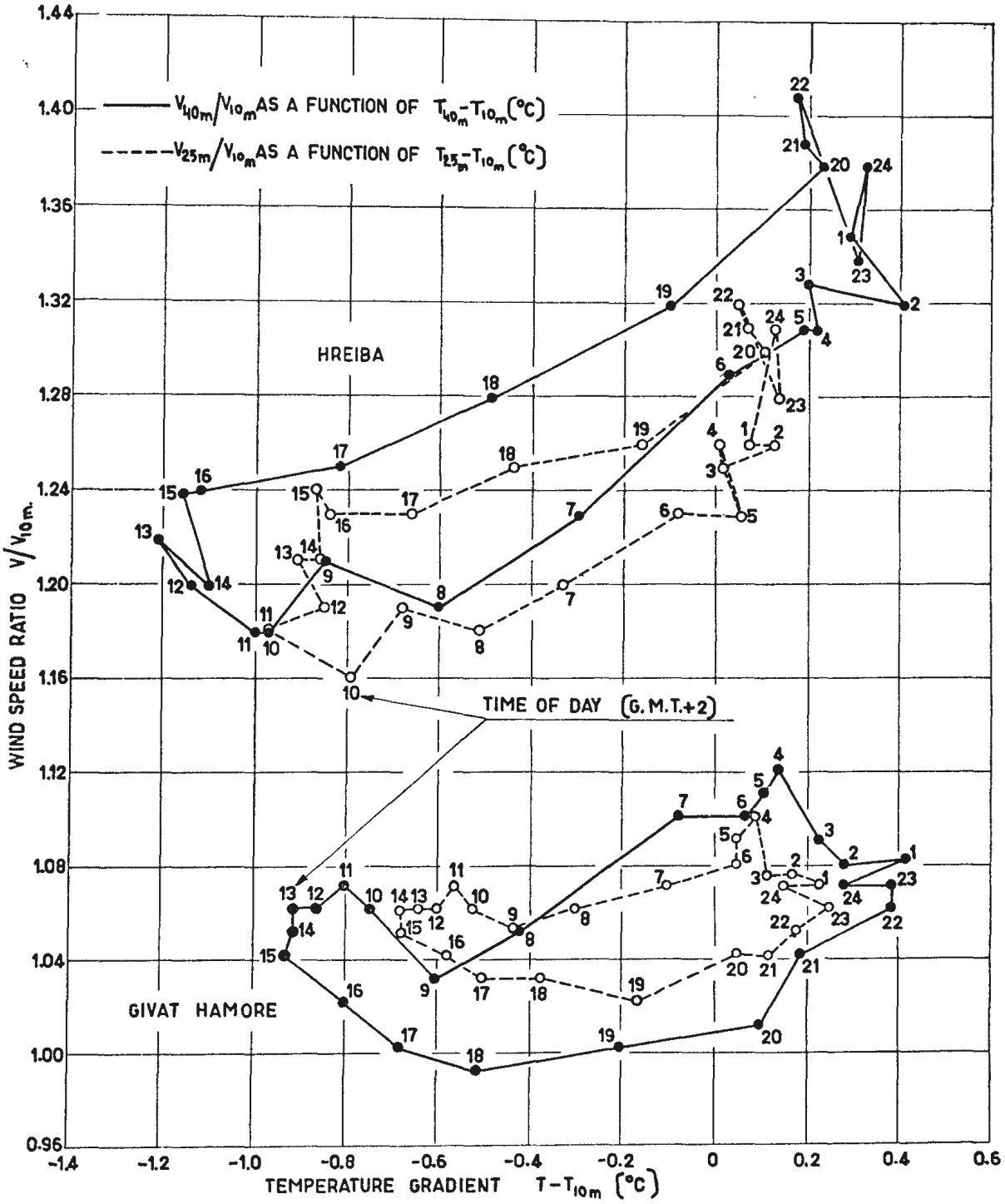

Figure 18

Wind speed ratio *vs.* temperature gradient in Hreiba (June 1960) and Givat Hamore (July 1960)

270° direction, which is topographically not unlike the 90° direction, may have been caused — apart from the fact that the measurements mast is some 50 m to the east of the hilltop, although only 0.8 m below it — by the general convexity of the slope, which could have resulted in some separation of flow taking place. On the other hand, no full explanation in terms of hill profile can be given for low values in some directions (10°, 150°, 220°), and the question will be examined later, taking into account the thermal stratification.

The variation of wind ratios with the direction is much less pronounced in Givat Hamore than in Hreiba, reflecting more regular features of the former. The range of these ratios is from 0.988 to 1.075 for $V_{25\,m}/V_{10\,m}$, and from 0.969 to 1.096 for $V_{40\,m}/V_{10\,m}$. The high values of the ratios in the 30° direction, as well as in the 250°-270° group of directions, are readily explained by irregular features of the hill profile in these directions. The lowest values of these ratios again cannot be fully explained by hill profiles. However, there is in this

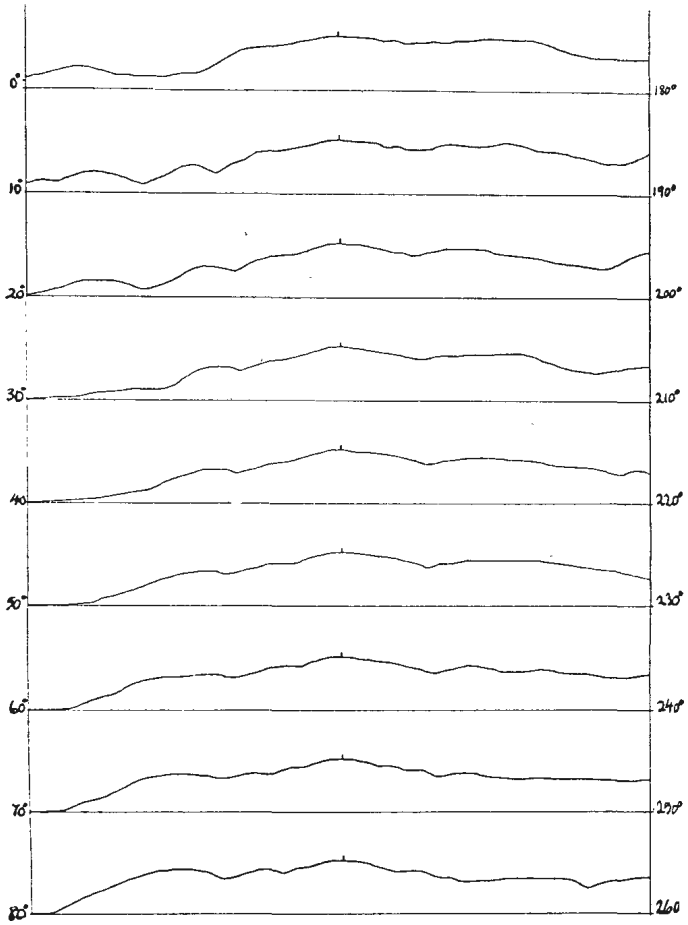

Figure 19a

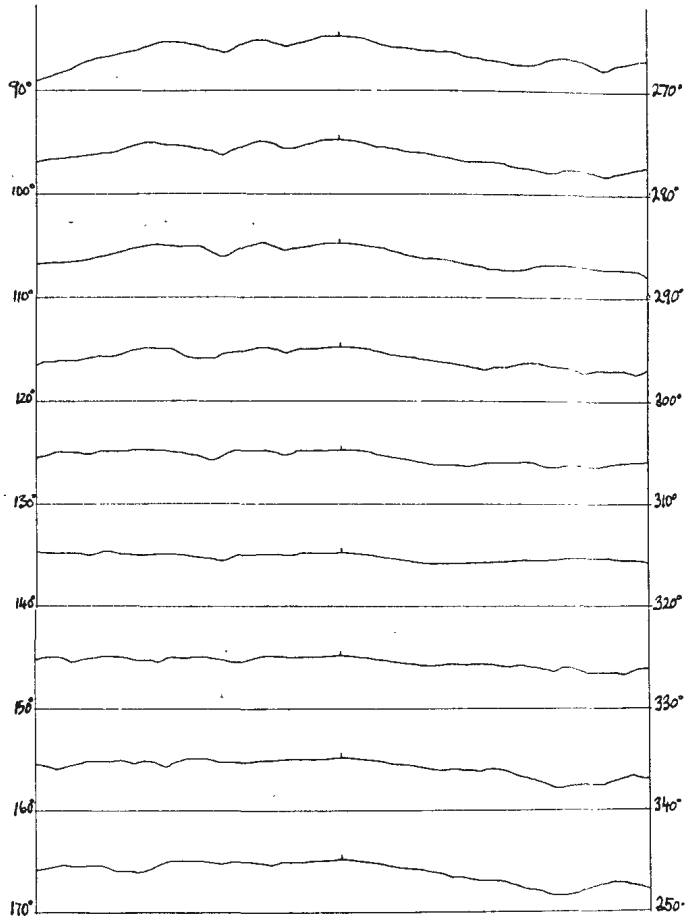

Figure 19b

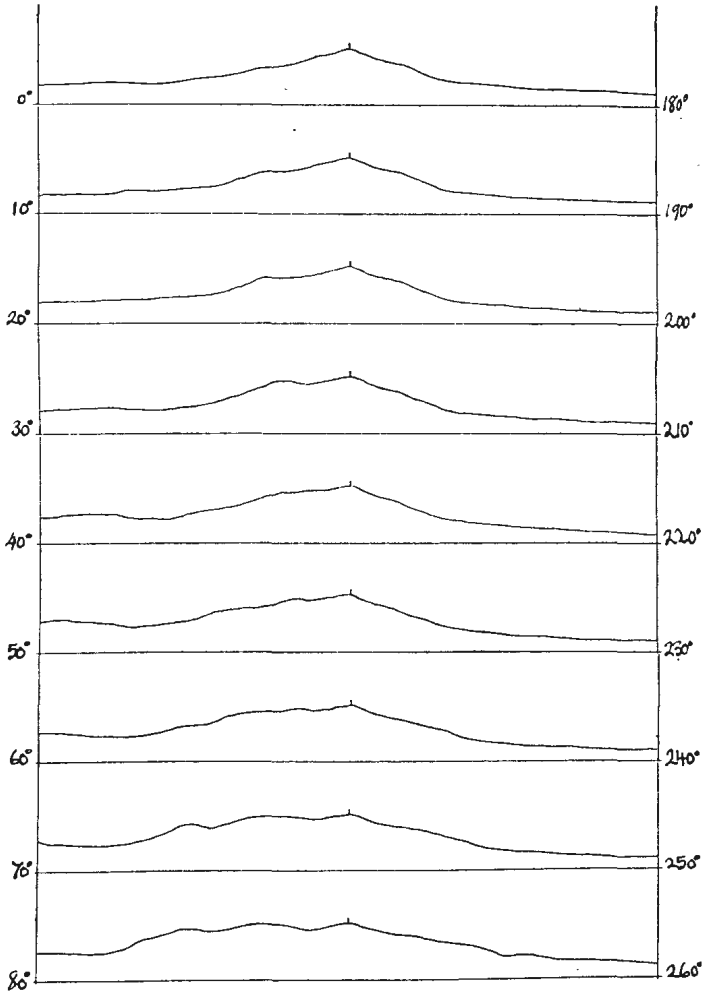

Figure 20a

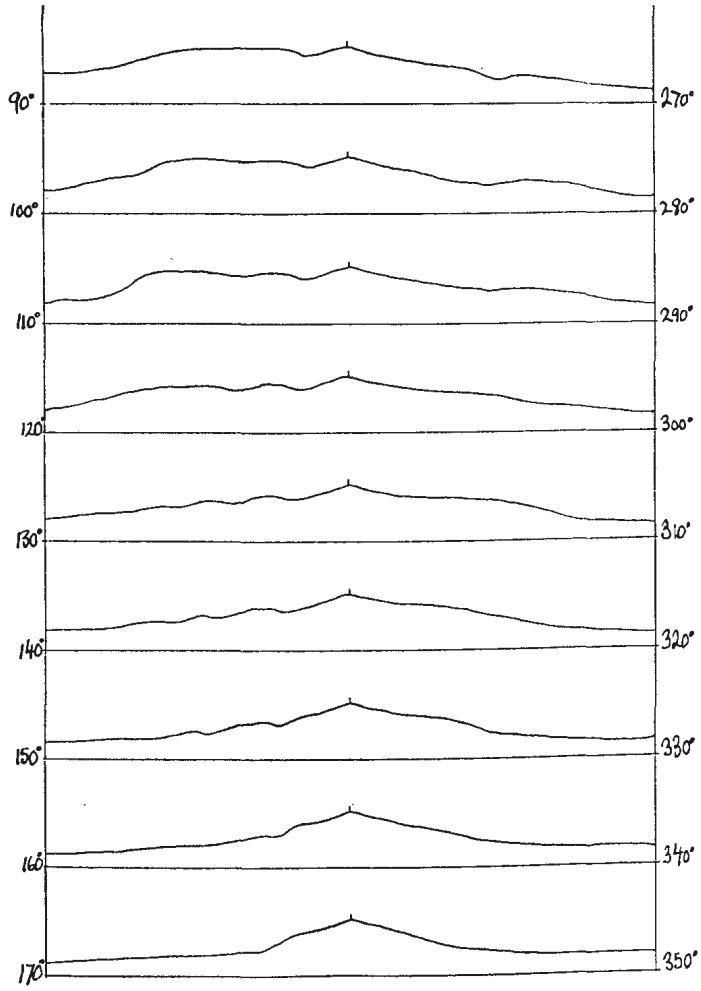

Figure 20b

respect a difference between the two sites. In Hreiba, the low values of wind ratios are still above 1, and at these values the differences between wind speeds at different levels are at their minima; in Givat Hamore, on the other hand, they are below 1, which means that the difference between wind speeds at different levels are at their maxima, albeit secondary ones. Consequently, it would appear that, in Hreiba, the conditions of maximum lapse rate would be conducive to the formation of minimum wind ratios; in Givat Hamore, however, the required conditions might well be different : there could be an optimum value of lapse rate corresponding to minimum wind ratios. These hypotheses are examined in the next section.

Effect of thermal stratification on directional wind profile

The records of hourly wind-runs taken during the operation of the temperature recorder were sorted for wind direction and temperature gradient for the height interval between 40 and 10 m above ground. For every group, the mean wind ratios $V_{25\ m}/V_{10\ m}$ and $V_{40\ m}/V_{10\ m}$ were computed.

When analyzing the dependency of directional wind ratios on thermal stratification, account must be taken of the weight of the mean ratios. A single ratio may be off its true value by as much as 10 per cent, and its probable error is about 3 per cent. A mean ratio of five observations would then have a probable error of about 1.5 per cent, and in general only mean ratios with at least that number of observations were used in the analysis. The only exception to this rule was when a certain general trend was observed when based on mean ratios of fewer than five observations.

In figures 21 and 22, the variation of directional wind ratio with thermal stratification is given. Only directions for which there were at least four

Table 7. Directional mean wind profiles

(A = all wind velocities; B = wind velocities for which $V_{25} \geqslant 18$ km/hr)

Hreiba						
Direction	V_{25m}/V_{10m}		V_{40m}/V_{10m}		h_A (hours)	h_B
	A	*B*	*A*	*B*		
10	1.152	1.148	1.214	1.222	477	314
20	1.160	1.157	1.239	1.242	314	250
30	1.202	1.202	1.254	1.273	135	64
40	1.295	1.328	1.328	1.389	75	28
50	1.256	1.288	1.314	1.363	73	29
60	1.245	1.251	1.317	1.318	37	17
70	1.287	1.303	1.402	1.399	58	36
80	1.239	1.251	1.360	1.354	56	36
90	1.270	1.273	1.437	1.439	156	132
100	1.319	1.322	1.485	1.487	272	251
110	1.264	1.265	1.384	1.390	172	154
120	1.227	1.227	1.327	1.331	216	183
130	1.163	1.165	1.232	1.244	56	42
140	1.138	1.131	1.198	1.195	35	25
150	1.135	1.137	1.187	1.220	17	11
160	1.151	1.157	1.157	1.188	43	36
170	1.188	1.186	1.232	1.229	42	35
180	1.253	1.256	1.304	1.309	70	63
190	1.360	1.330	1.409	1.380	142	128
200	1.310	1.323	1.376	1.377	160	145
210	1.157	1.151	1.208	1.198	334	254
220	1.138	1.141	1.179	1.175	245	160
230	1.206	1.202	1.244	1.235	569	404
240	1.227	1.230	1.273	1.272	488	319
250	1.282	1.279	1.328	1.316	544	365
260	1.327	1.328	1.377	1.368	367	241
270	1.399	1.407	1.499	1.487	331	171
280	1.359	1.359	1.466	1.461	303	153
290	1.305	1.291	1.431	1.400	195	82
300	1.249	1.266	1.370	1.366	239	99
310	1.260	1.217	1.390	1.319	140	43
320	1.275	1.270	1.386	1.406	163	58
330	1.270	1.275	1.349	1.357	108	57
340	1.207	1.193	1.291	1.284	97	57
350	1.163	1.156	1.234	1.224	194	129
360	1.158	1.154	1.224	1.217	389	238

Table 7. Directional mean wind profiles *(continued)*

Direction	Givat Hamore					
	V_{25m}/V_{10m}		V_{40m}/V_{10m}		h_A (hours)	h_B
	A	B	A	B		
10	1.004	1.009	1.029	1.054	37	9
20	1.012	1.005	1.039	1.045	58	16
30	1.051	1.067	1.096	1.135	41	10
40	1.024	1.033	1.081	1.074	40	11
50	1.027	1.007	1.061	1.065	58	21
60	1.019	1.017	1.058	1.055	81	50
70	1.019	1.022	1.012	1.011	111	81
80	1.033	1.033	1.015	1.013	154	133
90	1.027	1.028	1.003	1.004	239	208
100	1.012	1.017	0.973	0.977	150	115
110	1.006	1.007	0.969	0.967	123	102
120	1.005	1.009	0.983	0.990	72	55
130	1.010	1.009	0.989	0.990	79	53
140	1.004	1.004	0.996	0.999	123	80
150	0.993	0.996	0.982	0.984	121	85
160	0.988	0.990	0.970	0.974	100	66
170	0.995	1.000	0.993	0.996	58	19
180	0.997	0.997	0.995	1.006	36	11
190	1.007	1.000	1.022	1.017	18	11
200	1.003	1.002	1.007	1.008	62	41
210	1.027	1.022	1.037	1.037	70	54
220	1.027	1.025	1.045	1.040	125	94
230	1.035	1.032	1.048	1.047	110	90
240	1.037	1.036	1.052	1.049	171	142
250	1.071	1.067	1.079	1.072	198	163
260	1.072	1.070	1.076	1.073	249	210
270	1.075	1.075	1.075	1.072	508	435
280	1.063	1.062	1.063	1.060	347	281
290	1.059	1.059	1.052	1.051	380	337
300	1.047	1.050	1.044	1.046	371	307
310	1.047	1.047	1.037	1.035	275	218
320	1.014	1.012	0.991	0.987	316	257
330	0.999	0.996	0.986	0.981	263	207
340	1.003	1.000	0.982	0.977	238	176
350	1.013	1.009	1.012	1.008	134	94
360	1.017	1.016	1.060	1.053	160	91

groups of mean ratios of five observations or more each are shown. It is seen that, as expected, the curves of wind ratio as a function of temperature gradient in Givat Hamore all exhibit a clear minimum for about $T_{40\,m} - T_{10\,m} = -0.5°$, or a little more than one and a half the dry adiabatic lapse rate. More surprising is the fact that a similar minimum exists for Hreiba as well, although there it is found in much higher lapse rates. There is also a hint of the existence of a maximum at large temperature inversion conditions. Such maxima near the level ground for low wind speeds only were found by Deacon (13), who attributed the decrease of wind ratios to shallow air currents of katabatic origin gaining importance. This phenomenon is evidently manifest on a much larger scale over hills.

Effect of the hill profile on wind profile in neutral conditions

In table 8, the directional wind ratios $V_{25\,m}/V_{10\,m}$ and $V_{40\,m}/V_{10\,m}$ applying to mean neutral conditions (adiabatic lapse rate) $T_{40\,m} = T_{10\,m} \approx -0.3°C$ are given.

These ratios give a much clearer picture than mean directional ratios, and it is a pity that the period of measurements could not be lengthened, so that more directions could be included in this table. The following results, however, are not affected by the absence of some directional ratios.

Two salient facts emerge :

(*a*) The decisive importance of the hill profile in the immediate neighbourhood of the measurements mast;

(*b*) The importance of the hill profile further upwind in relation to that near the measurements mast.

As regards (*a*), it is readily seen that the high values of wind ratios in Hreiba, as compared to those in Givat Hamore, were caused by the flatness of the hilltop of the former. To prove this point it suffices to compare the two extreme directional ratios, that of 270° to that of 20°. In both cases, the

Table 8. Directional wind ratios in mean neutral conditions

Direction (°)	Hreiba		Givat Hamore	
	V_{25m}/V_{10m}	V_{40m}/V_{10m}	V_{25m}/V_{10m}	V_{40m}/V_{10m}
10 . . .	1.15	1.25	—	—
20 . . .	1.09	1.17	—	—
100 . . .	1.24	1.37	—	—
110 . . .	1.23	1.35	—	—
120 . . .	1.23	1.34	—	—
210 . . .	1.17	1.23	—	—
230 . . .	1.23	1.29	1.03	1.04
240 . . .	1.28	1.35	1.04	1.04
250 . . .	1.32	1.39	1.07	1.05
260 . . .	1.38	1.46	1.04	1.06
270 . . .	1.50	1.63	1.05	1.03
280 . . .	1.49	1.65	1.02	1.02
290 . . .	1.35	1.53	1.04	1.02
300 . . .	1.26	1.40	1.05	1.03
310 . . .	1.24	1.37	1.03	1.00
320 . . .	—	—	1.00	0.96
330 . . .	—	—	0.98	0.94
340 . . .	—	—	0.99	0.95
350 . . .	1.13	1.23	0.99	0.94
360 . . .	1.16	1.28	—	—

slopes further up-wind are on the average 1 in $3\frac{1}{2}$ and fairly regular. The difference lies in the last 100 m from the mast; in the 270° direction, it is flat with a slight rise 50 m from the mast; in the 20° it is steadily descending at a very slowly accelerating rate : 30 m from the mast, the slope is 1 in 10, descending to 1 in 3 1/2 some 100 m from the mast. Had this slope reached the immediate vicinity of the mast, the wind ratio would have gone down to below 1, as is the case in Givat Hamore, in the direction 350°.

Similarly, the differences in the profile in the immediate neigbourhood of the mast explain the low ratios for the 150° and 210-220° directions in Hreiba, and they largely account for the differences in wind ratios in Givat Hamore.

The demonstration of (*b*) above is found in the gradual decrease of ratios from the direction 280° to 310° (and probably continued to 330°) in Hreiba. This decrease does not come because of any significant differences in the slope in the next 100 m from the mast. It comes as a result of gradual decrease of steepness further up-wind, gradually eliminating the slope gradient between the two regions.

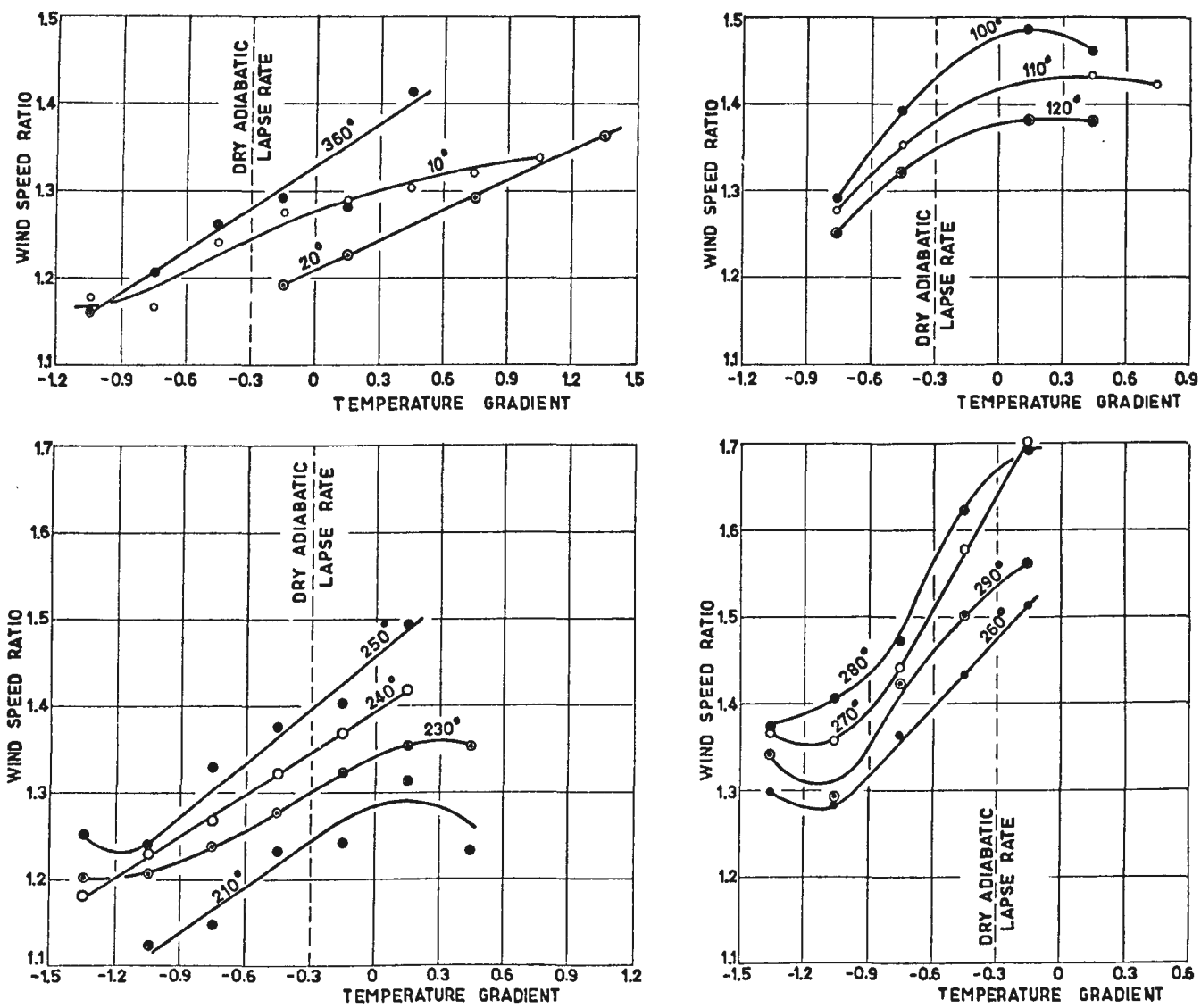

Figure 21. Directional wind ratio V_{40m}/V_{10m} *vs.* temperature gradient $T_{40m} = T_{10m}$ in Hreiba

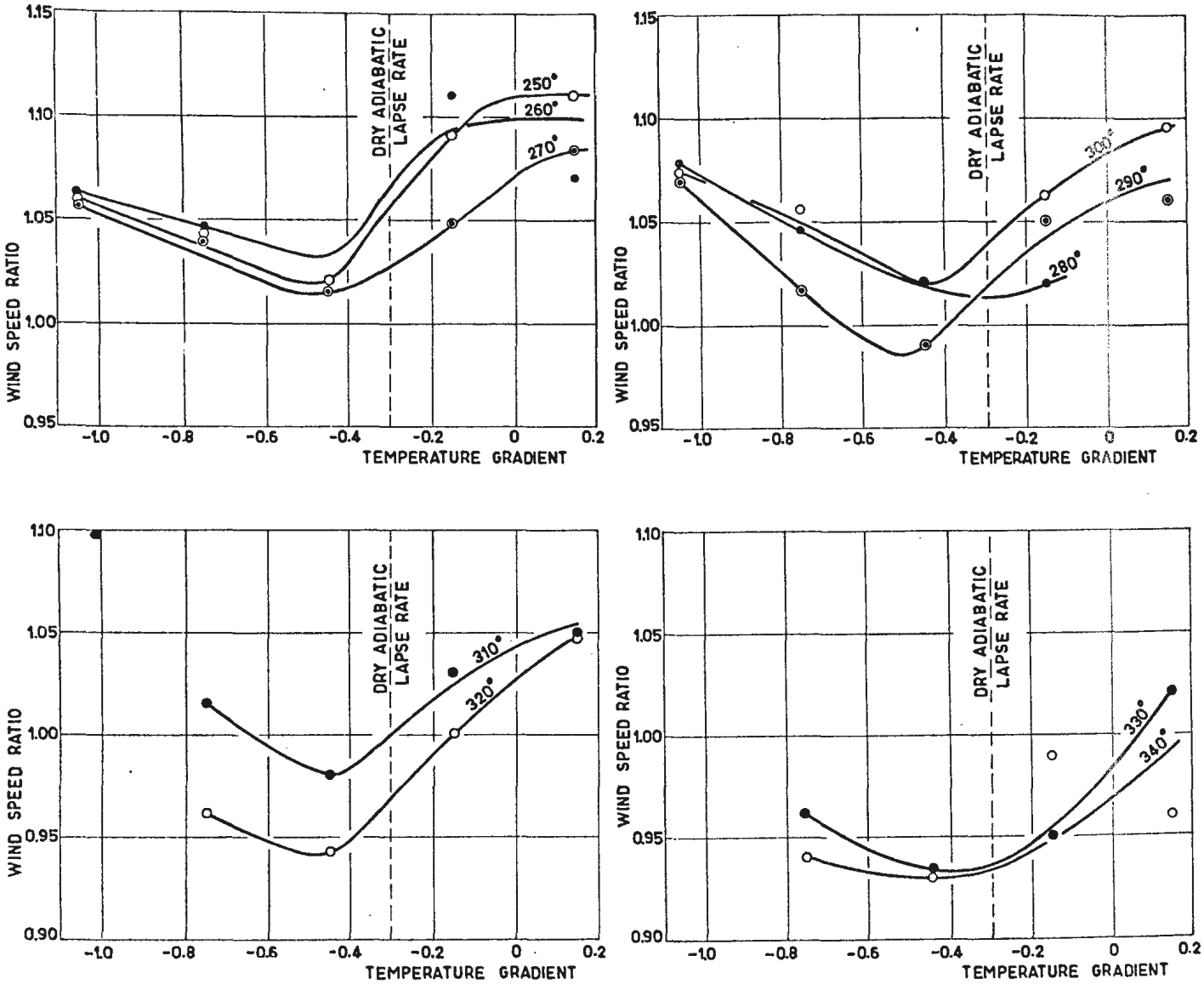

Figure 22. Directional wind ratio V_{40m}/V_{10m} *vs.* temperature gradient $T_{40m} - T_{10m}$ in Givat Hamore

To sum up, in order to have low wind ratios, the hill must have a small hill-top area; this condition cannot in general be fulfilled in a hill forming a part of a mountain ridge. Large flat hilltops produce wind ratios much in excess of those met over level country, and these must be avoided. The slope should be as uniform as possible in the last few hundred meters. The optimal slope is about 1 in 3½. If it reaches to within 20 to 30 m from the top, it will produce uniform flow conditions in the height interval from 10 to 40 m. A steeper slope will produce a pronounced inverse gradient and should again be avoided.

Conclusions

Before the measurements which form the subject of the present report began, it had been known from previous observations that Givat Hamore is a better wind power site than Hreiba. In the absence of proper criteria of "goodness of site", however, they were both considered good sites in their respective regions, and the advantage of Givat Hamore (higher mean and higher diurnal variation) was thought to result mainly from the regional channel effect of the plain of Esdraelon, which is felt particularly strongly during the summer season.

In the light of present measurements, this view can no longer be maintained. It has been established beyond reasonable doubt that the topographical features in the near approaches to the hilltop determine the structure of flow over it. This flow will, of course, be influenced by the general circulation of the region, but it is felt that within the region it is now possible to establish criteria for a good wind power site without referring to this general pattern.

What then are these criteria? It is the opinion of the author of the present report that a single criterion is sufficient, namely, the mean wind vertical gradient for the height interval from 10 to 40 m above ground. For optimal conditions for wind power utilization, this gradient must vanish within five per cent. Such flow conditions, as has been shown, exist

in most directions in Givat Hamore, and they are the result of regular slopes of about 1 in $3\frac{1}{2}$ (inclination 16°) in the nearest few hundred meters from the hilltop. Admittedly, such topographical features are not of a very frequent occurrence in nature. However, they are by no means exceptional, and a systematic search for them is bound to be successful in any hilly country. In the British wind survey, for instance, several sites have been located which should have flow characteristics approaching those of Givat Hamore. Foremost is Mynydd Anelog in North Wales where the wind vertical gradient was shown to be very small up to the height of 20 m above ground, and it vanishes in all probability altogether in the height interval from 20 to 40 m. Other such sites seem to be (from the inspection of cross-sectional views of the sites): Snaefell in the Isle of Man, Slieve Donard in Northern Ireland, Gorthack South and Croghan Kinshela in Eire (5).

In the second category, that of very good wind power sites, could come hills exhibiting a rise of wind speed in the interval from 10 to 40 m of between 5 and 10 per cent. Such conditions are the result of smooth regular slopes of about 1 in 6 (inclination 10°). The maximum flow, which in the first category would be located somewhere in the middle of the 10 to 40 m interval, would move upward, towards the upper boundary of the interval. The average power law index would then be less than 0.07.

The third category, that of good wind power sites, could be formed by hills with a rise in the mean wind speed in the 10 to 40 m interval of between 10 and 15 per cent. These would usually be hills of smooth regular shallow slopes (about 1 in 10), or fairly rough but regular slopes of about 1 in 6. The corresponding power law index would be less than 0.10.

Finally, the fourth category, that of fair wind power sites, could comprise the sites for which

$$1.15 < V_{40\ \mathrm{m}}/V_{10\ \mathrm{m}} < 1.21$$

These conditions could be occasioned by a great variety of topographical features, ranging from low-level coastal sites (23), through a smooth aerodynamically very shallow slope (1 in 20), and a very rough aerodynamically but regular steep (1 in 6) slope, to finally a very steep slope with gradual slope gradient within a radius of about 50 m from the hilltop. The corresponding mean power law index would be less than 0.14.

Any site characterized by $\alpha > 0.14$ should be avoided unless no other sites with smaller values of α can be found.

The above classification has been made on the assumption of the fixed height interval of wind flow utilization. This is in agreement with recent studies of optimal tower height by Vadot (11) and Gimpel and Stodhart (23).

To return to the original question of the "goodness of site", it is now evident that while Givat Hamore is an optimal site, Hreiba is certainly not. It is definitely inferior to what was classified as a "fair site", and is most certainly inferior to very many other sites in the Mount Carmel range, the profiles of which conform better to what has now been classified as a good site.

Acknowledgments

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The author wishes to thank Mr. E. W. Golding and Mr. J. R. Tagg of the Electrical Research Association, United Kingdom, for their valuable comments in the initial stages of the project. The latter's help in the matter of instrumentation is also gratefully acknowledged. His thanks are also due to the staff of the project, its engineering consultants, and those who contributed to the preparation of this paper.

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Summary

In view of the importance attached to the development of local energy resources in Israel, the possibility of wind energy utilization was also considered, in particular by means of wind-electric plants to be connected to the general supply network.

As a result of a wind survey, conducted in the years 1953-1956, several sites have been selected which appear suitable for large-scale generation of electricity by wind power. These sites can be roughly divided topographically into two broad categories:

(*a*) A mountain ridge athwart the prevailing wind direction with a steep leeward side;

(*b*) An isolated peak in a valley in the general direction of prevailing winds.

One site in each category — Hreiba and Givat Hamore — was chosen for a detailed investigation of wind behaviour with the purpose of correlating the topography of the site to the characteristics of the wind flow over it.

Measurements

At each site (both of which are of practically the same elevation 528 and 517 m above sea level and only 30 km distant from each other) a 40 m mast was erected, and wind measurements were made at the heights of 10, 25, and 40 m above ground, corresponding to the bottom, the hub-height and the top, respectively, of a 30 m diameter windmill. These measurements comprised continuous recording of wind direction and wind speed at the three heights, continuous recording of temperature gradient up to 40 m and occasional gust profile recordings. The measurements extended for over a year, terminating towards the end of 1960; the records of wind speed and direction and temperature gradient were evaluated in terms of mean hourly values and transferred to punch cards; those of gusts — in terms of mean wind speeds of each 2 sec (or 1 sec) interval of the records.

Wind régime and energy estimates

Comparison with previous observations from the sites has shown that the period of measurements gave average values, both in mean wind speeds and wind speed spectra; and consequently, the energy estimates derived from the measurements can be taken as representative of long-term means. These are (at 25 m above ground) approximately:

	Mean wind speed (km/hr)	*Energy in the wind (kWh p.a./sq.m.)*	*Specific output*		*Available energy for Danish 200 kW plant (kWh p.a/sq.m.)*
			(V_r = 32 km/hr) kWh p.a./kW	*(V_r = 40 km/hr) kWh p.a./kW*	
Hreiba	21.9	1 800	3 100	1 800	650
Givat Hamore . .	25.0	2 800	4 500	3 000	1 050

The relationship between specific outputs and mean wind speed on a monthly basis is shown to be linear but clearly distinct for the two sites.

Monthly mean hourly wind and temperature profiles

These are shown to be practically unrelated. The absence of a close relationship between the two quantities in both sites is readily explained by the influence of an additional factor, namely, that of hill geometry.

Effect of the shape of the hill on mean wind profile

This is examined by means of sorting the ratios according to wind direction at 10° intervals, and it is shown that there is hardly any influence of the wind speed on directional wind ratios. In general, it can be said that there is no need to analyze wind ratios for different wind speeds, and that ratios obtained from the continuous record of wind-run at different levels (provided the direction is constant) will apply with a good degree of approximation to

the operational range of wind speeds of any aerogenerator.

There is a definite variation, however, of the ratios with the direction. The range of this variation is as follows :

	V_{25m}/V_{10m}	V_{40m}/V_{10m}
Hreiba (ridge)	1.135-1.399	1.179-1.499
Givat Hamore (isolated hill)	0.988-1.075	0.969-1.096

These variations can be approximately accounted for by the hill profile, but for a quantitative relationship, account has to be taken of the thermal stratification.

Effect of thermal stratification on directional wind profile

This is shown to be important for all wind speeds. In Givat Hamore, the curves of wind ratio as a function of temperature gradient all exhibit a clear minimum for about $T_{40\,m} - T_{10\,m} = -0.5°C$, or a little more than one and a half the dry adiabatic lapse rate. This is explained by the fact that the low values of wind ratios at this site are below 1, which means that the differences between wind speeds at different levels are at their maxima, albeit secondary ones. More surprising is the fact that similar minima exist for Hreiba for wind ratio values well above 1, although in this case they are found in much higher lapse rates.

Effect of the hill profile on wind profile in neutral conditions

This is then analyzed, and it is shown that the wind profile is determined by : (*a*) hill profile in the immediate neighbourhood of the measurements site; (*b*) hill profile further up-wind in relation to that near the measurements site.

To have low wind ratios, the hill must have a small hill-top area; this condition cannot, in general, be fulfilled in a hill forming a part of a mountain ridge. A large flat hill-top area produces wind ratios well in excess of those met over level country and must be avoided. The slope should be as uniform as possible in the last few hundred meters. The optimal slope is about 1 in $3\frac{1}{2}$. If it reaches to within 20-30 meters from the top, it will produce uniform flow conditions in the height interval from 10 to 40 m. A steeper slope will produce a pronounced inverse gradient and should again be avoided.

Conclusions

To classify the relative worth of a wind power site, a single criterion is sufficient, namely, the mean wind vertical gradient for the height interval from 10 to 40 m above ground. For optimal conditions for wind power utilization, this gradient must vanish within 5 per cent. Such flow conditions are the result of regular slopes of about 1 in $3\frac{1}{2}$ (inclination 16°) in the nearest few hundred meters from the hilltop.

In the second category, that of very good wind power sites, could be hills exhibiting a rise of wind speed of 5-10 per cent between 10 and 40 m. Such conditions are the result of smooth regular slopes of about 1 in 6 (inclination 10°).

The third category, that of good wind power sites, could be formed by hills showing a rise in the mean wind speed of 10-15 per cent in the 10 to 40 m interval. These would usually be hills of smooth regular shallow slopes (about 1 in 10) or fairly rough but regular slopes of about 1 in 6.

Finally, the fourth category, that of fair wind power sites, could comprise the sites for which

$$1.15 < V_{40\,m}/V_{10\,m} < 1.21$$

These conditions could be occasioned by a great variety of topographical features ranging from low-level coastal sites, through a smooth aerodynamically very shallow slope and a very rough aerodynamically but regular steep slope, to finally a very steep slope with gradual slope gradient within the area of a radius of about 50 m from the hilltop. The corresponding mean power law index α would be less than 0.14.

Any site characterized by $\alpha > 0.14$ should be avoided, unless no other sites with smaller α can be found.

ÉCOULEMENT DU VENT SUR LES COLLINES PAR RAPPORT A L'UTILISATION DE L'ÉNERGIE ÉOLIENNE

Résumé

Compte tenu de l'importance que l'on prête au développement des ressources énergétiques nationales en Israël, on s'est attaché, entre autres, à la possibilité de mettre l'énergie éolienne en œuvre, particulièrement au moyen de centrales électriques entraînées par cette énergie, centrales dont la production pourrait être envoyée au réseau général de distribution.

A la suite d'études sur le régime des vents, menées entre 1953 et 1956, on a choisi plusieurs sites qui semblent appropriées pour la production d'électricité à grande échelle par l'énergie éolienne. Topographiquement, on peut répartir ces sites en deux grandes catégories :

a) Crête de montagne orientée sensiblement à angle droit avec la direction prédominante des vents avec versant sous le vent à pente raide,

b) Pic isolé situé dans une vallée dont l'orientation est la même que celle des vents prédominants.

On a choisi un site dans chacune de ces catégories — Hreiba et Givat Hamore — pour procéder à une étude détaillée du comportement du vent, en vue d'établir une corrélation entre la topographie du lieu et les caractéristiques de l'écoulement du vent en sa surface.

Mesures. On a dressé un mât de 40 mètres en chacun des sites en cause, lesquels se trouvent virtuellement à la même hauteur (528 m et 517 m au-dessus du niveau de la mer) et à 30 km seulement l'un de l'autre, et on a procédé à des mesures anémométriques aux cotes 10 m, 25 m et 40 m au-dessus du sol, correspondant au bas des pales, au moyeu et à la partie supérieure des pales d'une éolienne de 30 m de diamètre. Ces mesures ont comporté des enregistrements continus de la direction et de la vitesse du vent aux trois cotes, des enregistrements, également continus, des écarts de température jusqu'à 40 m et des tracés occasionnels des systèmes de rafales. Ces mesures se sont faites au cours d'une année, terminée vers la fin de 1960; les données sur la vitesse et la direction du vent, ainsi que l'écart ou gradient de température ont été exprimées en valeurs horaires moyennes et transcrites sur des cartes à perforations et celles des rafales — en fonction des vitesses de vent moyennes — sur chaque intervalle de deux secondes ou une seconde des enregistrements.

Évaluations du régime des vents et de l'énergie. Les comparaisons faites avec des observations antérieures des mêmes sites ont démontré que la période prise pour les mesures donnait des valeurs moyennes, tant pour l'intensité du vent que pour la répartition des vitesses, si bien que les évaluations relatives à l'énergie, faites à partir des mesures, pouvaient être prises comme caractéristiques de moyennes à long terme. A 25 m au-dessus du sol, ces évaluations sont :

	Vitesse moyenne du vent km/h	*Teneur du vent en énergie kWh p.a. par m²*	*Débit spécifique*		*Énergie disponible pour la centrale danoise de 200 kW kWh par an/m²*
			V_r = 32 km/h kWh par an par kW	*V_r = 40 km/h kWh par an par kW*	
Hreiba	21,9	1 800	3 100	1 800	650
Givat Hamore . .	25,0	2 800	4 500	3 000	1 050

Le rapport entre les débits spécifiques et la vitesse moyenne du vent sur une base mensuelle est linéaire mais nettement différent pour les deux sites.

Courbes moyennes mensuelles des vents et des températures. On observera que ces valeurs n'ont virtuellement pas de rapports entre elles. L'absence de rapports étroits entre les deux quantités pour les sites en cause s'explique facilement par un élément supplémentaire, la géométrie des collines.

Répercussions de la forme de la colline sur la courbe moyenne des vents. On l'examine en classant les proportions suivant la direction du vent tous les dix degrés et on démontre qu'il n'y a pour ainsi dire pas d'influence de la vitesse du vent sur les proportions en fonction de sa direction. Généralement parlant, on peut affirmer qu'il n'est pas besoin d'analyser les proportions applicables aux diverses vitesses et que celles que donnent les archives continues du vent tel qu'il souffle à divers niveaux (pourvu que sa direction soit constante), s'appliquent avec une bonne approximation sur la gamme des vitesses de vent acceptables pour un générateur à énergie éolienne quelconque.

On note, en revanche, une variation très nette des proportions en fonction de la direction. La gamme des variations est la suivante :

	V_{25m}/V_{10m}	V_{40m}/V_{10m}
Hreiba (crête)	1,135-1,399	1,179-1,499
Givat Hamore (colline isolée)	0,988-1,075	0,969-1,096

On peut expliquer ces variations en partie par le profil de la colline, mais, pour des rapports quantitatifs, il faut tenir compte de la stratification thermique.

Effet de la stratification thermique sur la variation du vent avec la direction. Son importance est marquée pour toutes les vitesses du vent. A Givat Hamore, les courbes qui donnent la proportion en fonction du gradient ou écart de température accusent un minimum net au voisinage de $T_{40\,m} - T_{10\,m} = -0{,}5$ °C, soit un peu plus d'une fois et demie le taux de décroissance adiabatique en milieu sec. Ceci s'explique par le fait que les faibles proportions que l'on trouve pour les vents en ce lieu sont inférieures à 1, ce qui veut dire que les différences entre les vitesses à divers niveaux sont à leur maxima, bien que ce soient là des maxima secondaires. Le plus étonnant, c'est que l'on trouve des minima du même ordre pour Hreiba, avec des valeurs de la proportion largement supérieures à 1, bien que, dans ce cas, on les trouve dans des zones où le taux de décroissance de la température est beaucoup plus fort.

Répercussions du profil de la colline sur la répartition du vent en situation neutre. On démontre que la répartition des vents est conditionnée par : *a*) Le profil des collines au voisinage immédiat du site des mesures; *b*) Le profil des collines plus loin au vent, par rapport à ce qu'il est près du site des mesures.

Pour que les proportions de vent soient basses, il faut que la surface de la crête de la colline soit

petite, condition qui ne peut pas habituellement être satisfaite là où la colline fait partie d'une crête montagneuse. Les surfaces de colline plates et étendues donnent des proportions nettement supérieures à celles que l'on trouve en pays plat et sont à éviter. La pente doit être aussi uniforme que possible sur les quelques dernières centaines de mètres, la pente idéale est de l'ordre de 1 par 3,5. Si elle se poursuit jusqu'à une distance de l'ordre de 20 à 30 m du sommet, on trouvera des conditions d'écoulement uniforme dans les hauteurs allant de 10 à 40 m. Toute pente plus marquée fera apparaître un renversement marqué du gradient : il faut l'éviter.

Conclusions. Pour classer la valeur relative d'un site d'installation à énergie éolienne, on peut se contenter d'un seul critère : le gradient vertical moyen du vent pour la gamme de hauteurs allant de 10 à 40 m à compter du sol. Pour les conditions idéales d'utilisation de l'énergie éolienne, ce gradient doit disparaître en moins de 5 p. 100. Ces conditions d'écoulement résultent de pentes régulières de l'ordre de 1 à 3,5 (inclinaison 16°) sur les dernières centaines de mètres à compter du sommet de la colline.

Dans la deuxième catégorie de sites encore très bons pour les installations d'énergie éolienne, on pourrait nommer des collines sur lesquelles la vitesse moyenne du vent augmente de 5 à 10 p. 100 dans l'intervalle allant de 10 à 40 m. Il s'agira le plus souvent de collines ayant des pentes douces bien égales de l'ordre de 1 sur 6 (inclinaison 10°).

La troisième catégorie, celle des bons emplacements, pourrait être composée de collines sur lesquelles la montée de la vitesse moyenne du vent est de 10 à 15 p. 100 sur l'intervalle allant de 10 à 40 m. Il s'agirait le plus souvent de collines ayant des pentes douces régulières (1 sur 10 environ) ou des pentes relativement brusques mais régulières, de 1 à 6 environ.

Finalement, la quatrième catégorie, ou celle des sites acceptables sans plus, pourrait comporter les sites pour lesquels

$$1{,}15 < V_{40\ \mathrm{m}}/V_{10\ \mathrm{m}} < 1{,}21$$

Ces conditions peuvent être créées par l'un d'une grande variété d'accidents topographiques allant des emplacements côtiers plats aux pentes aérodynamiquement égales et très douces et aux pentes aérodynamiquement brusques et très dures mais régulières jusqu'à, finalement, une pente très dure en progression régulière décroissante dans la zone d'un rayon d'une cinquantaine de mètres du sommet. L'indice applicable à la loi de la puissance moyenne ou α serait inférieur à 0,14.

Tout site pour lequel $\alpha > 0{,}14$ est à éviter, à moins que l'on ne puisse pas trouver d'emplacement ayant un α plus petit.

WIND MEASUREMENTS

Martin Jensen *

The Danish stations for the measurement of wind climate are located at Gedser, Torsminde and Tune, as shown in figure 1. The reasons for the selection of the three sites are given below.

At each station, a 25-m tower was erected to carry the apparatus. This height was chosen because it was the height to the level of the hub of the experimental windmill at Gedser.

The questions might be raised whether it would pay to use windmills of greater height and whether the energy obtained at the higher levels would justify the greater costs of the substructure for the mill. To elucidate these points, a 50-m tower with apparatus, in addition to the 25-m tower, was erected at Gedser.

* Wind Power Committee, Association of Danish Electricity Works, Copenhagen.

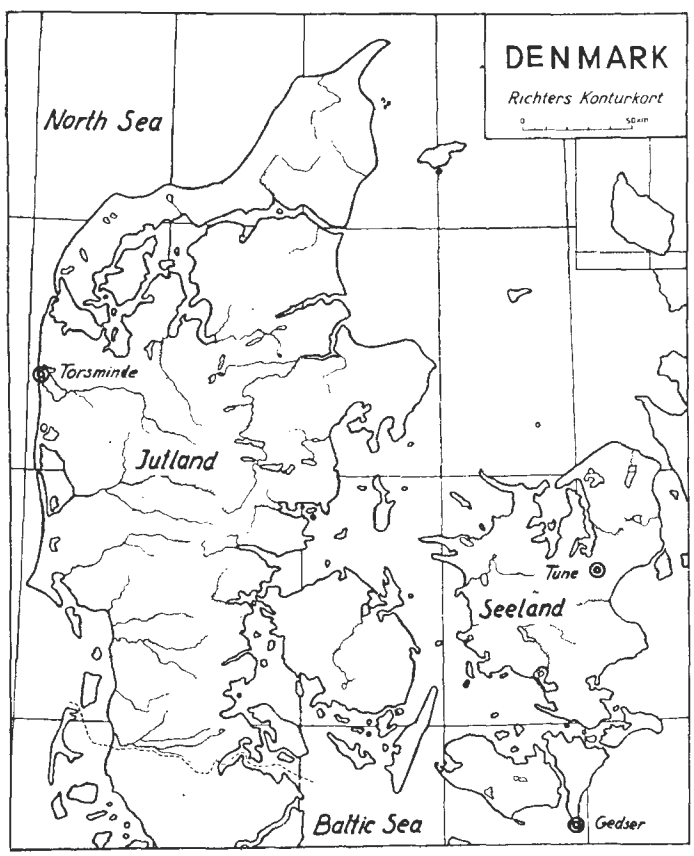

Figure 1. Map of Denmark, showing location of 25-m high wind measuring stations at Tune and Torsminde and of experimental mill at Gedser, a 25-m and 50-m wind measuring station

Figure 2. Land and water areas around Gedser. The islands of Lalandia and Falstria consist of low plains

(*a*) The town of Gedser is situated on the southernmost point of the island of Falstria. As shown in figure 2, this part of the island is a long, narrow isthmus projecting southward into the Baltic Sea.

The site is located 3 km north of Gedser in the western part of the isthmus. There the experimental mill, described in detail in paper W/17 under item II.B.2 below, has been erected. There are, in addition, two stations for wind measurements, one with a measuring level 50 m above ground and one at a height of 25 m. Figure 3 shows the arrangement of the plant.

The distance from the site to the west coast of Falstria is about 300 m. At this place, the isthmus is 3 km wide. The terrain slopes from the east up to the site, which is 10 m above sea level. Then the ground slopes down towards the west coast where the land is bounded by a 5-m high bank. Otherwise, the entire area consists of flat, agricultural country.

As shown in figure 2, Gedser is fully exposed to winds in the sector from west through south to north-north-east. The wind from these directions passes over 45 km of open sea. Also in the sector from west through north-west to north-north-west there are considerable distances of sea. Only in rather a small sector to the north will a landwind strike the plant. The country is, however, a low plain, the highest point of the islands of Lalandia and Falstria being only 35 m above sea level.

In Denmark, winds from the north are those of rarest occurrence, and the location of a wind power plant at Gedser must therefore be considered approximately the optimum as regards maximum energy.

(*b*) Torsminde is a hamlet at a lock with a harbour on the west coast of Jutland. The harbour faces the North Sea and is situated on a very narrow, low bay-bar extending in a north-south direction and separating the North Sea to the west from the Nissum Fjord to the east.

The measuring station is located south of the hamlet, right on the sea, in a terrain 2 m above sea level. Measurements are made at a height of 25 m above the ground.

The site at Torsminde was chosen because it is free from the tall row of sand dunes extending elsewhere along the west coast of Jutland.

The built-up area of Torsminde consists of houses between 3 and 5 m high, situated on the same level as that on which the tower was erected.

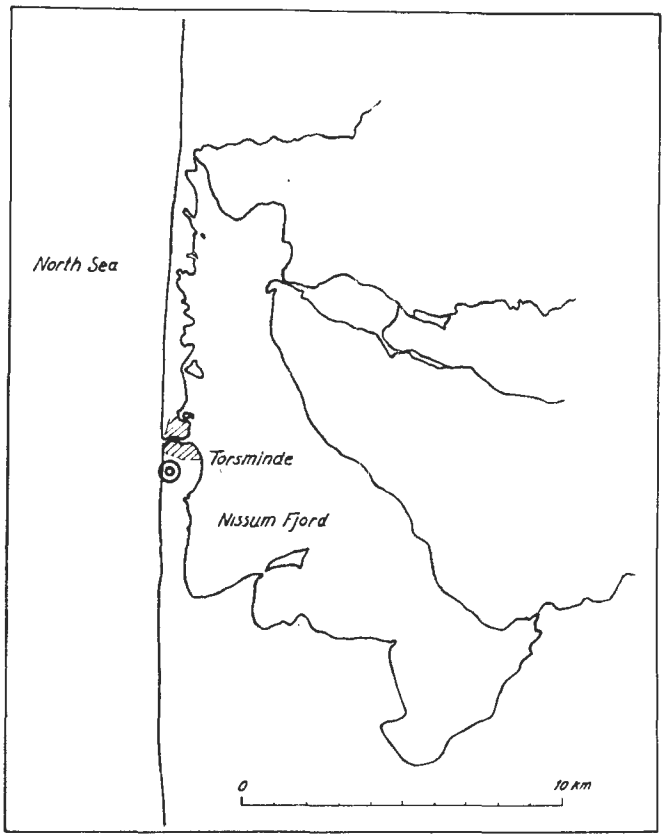

Figure 4. Land and water areas around Torsminde. All the country shown in the map is a plain, less than 40 m above sea level

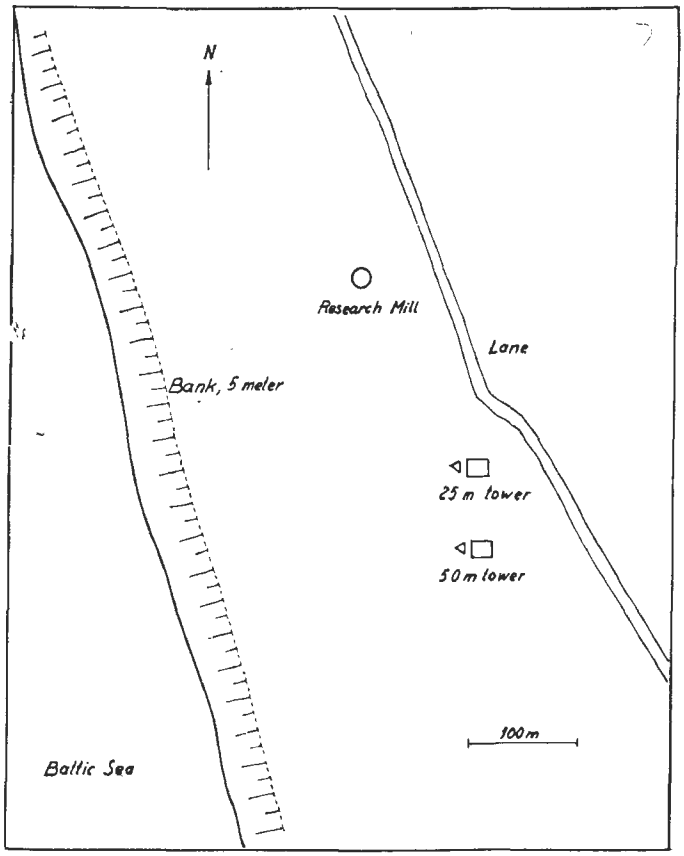

Figure 3. The plant of Gedser

As will be seen from figure 4, the site is completely exposed to sea winds from the sector from north by west through west to south by west. The site is also well exposed to easterly winds due to the fjord and to the fact that the country behind the fjord is a flat plain, within a radius of 15 km at any rate.

Only in a small sector to the north and a corresponding sector to the south will the wind be reduced in force by passing the bay-bar, a landscape of low dunes.

In view of the westerly winds prevailing in Denmark, the station at Torsminde must be presumed to represent the optimum to be found on the peninsula of Jutland.

(*c*) The station for the measurement of wind at Tune is located 25 km west of Copenhagen. Measurements are made at a height of 25 m above the ground.

The station is sited on a low ridge extending in a north-south direction and stands 62 m above sea level. Both to the east and west of the station, the terrain slopes slightly downwards (figure 5).

The area is rather open and slightly undulating agricultural country. Winds from all directions except the south-east pass over a considerable distance across country.

The station at Tune should represent the best obtainable site when a station in Denmark is to be placed inland.

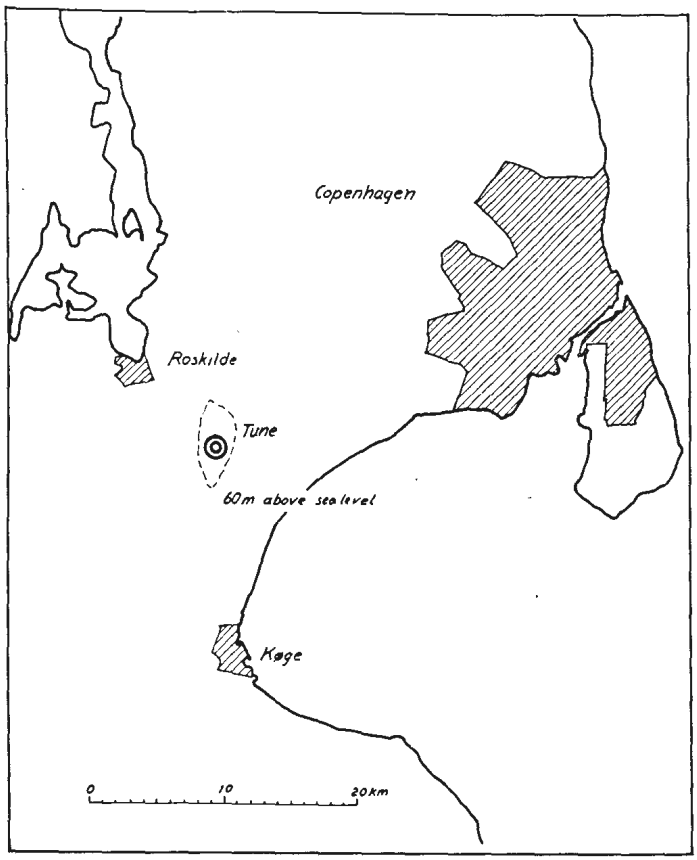

Figure 5. Land and water areas around Tune

Stations for the measurement of wind

The detectors of the measuring apparatus are placed on top of a guyed tower. The tower is a lattice construction, of triangular cross-section, and all members are solid steel rods. On top of the tower a small balcony is provided for the inspection of the apparatus. Recordings and readings take place in a hut at the foot of the tower (figure 6).

The wind power plant of the Danish Wind Power Committee, the so-called Gedser mill, described in detail in paper W/17, operates on the principle that the propeller through a constant gear-transmission drives a synchronous generator connected to the public supply network, the frequency of which is governed by the thermal power plants connected with it.

This construction implies that the revolutions of the propeller will vary only about 1 per cent between idling and full load. The propeller blades are not adjustable. It must be noted that the turnable tips serve solely as a brake to bring the working plant to a dead stop.

The efficiency of such a wind power plant will have its maximum value at a given speed of wind, depending on the degree of gearing between propeller and generator. If the speed of the wind increases beyond this optimum speed, the angle of incidence of the wind on the blades will become too great, with the result that the efficiency decreases. At even higher speeds, the blades will stall and the efficiency will decline sharply.

When a mill is constructed on this principle, it will be necessary to determine the range of wind speeds at which the mill will work with high efficiency. It will therefore be absolutely necessary to know the power distribution of the wind at the different wind speeds.

For this purpose, a new device, the power distribution meter (p.d.m.), was designed to integrate the wind power in terms of speed. The device integrates the wind intermittently, namely, in the following six ranges: 0-4 m/s, 0-6.5 m/s, 0-9 m/s, 0-11.5 m/s, 0-14 m/s, and 0-16.5 m/s.

The selection of just these ranges was made on the basis of a careful perusal of the data available with regard to the wind climate of Denmark. The measurements have confirmed that this selection was highly suitable for the purpose.

As mentioned, the Gedser mill has an upward variation in revolutions of only 1 per cent from idling to full load; it can therefore react to even very short gusts of wind. The p.d.m. was designed accordingly.

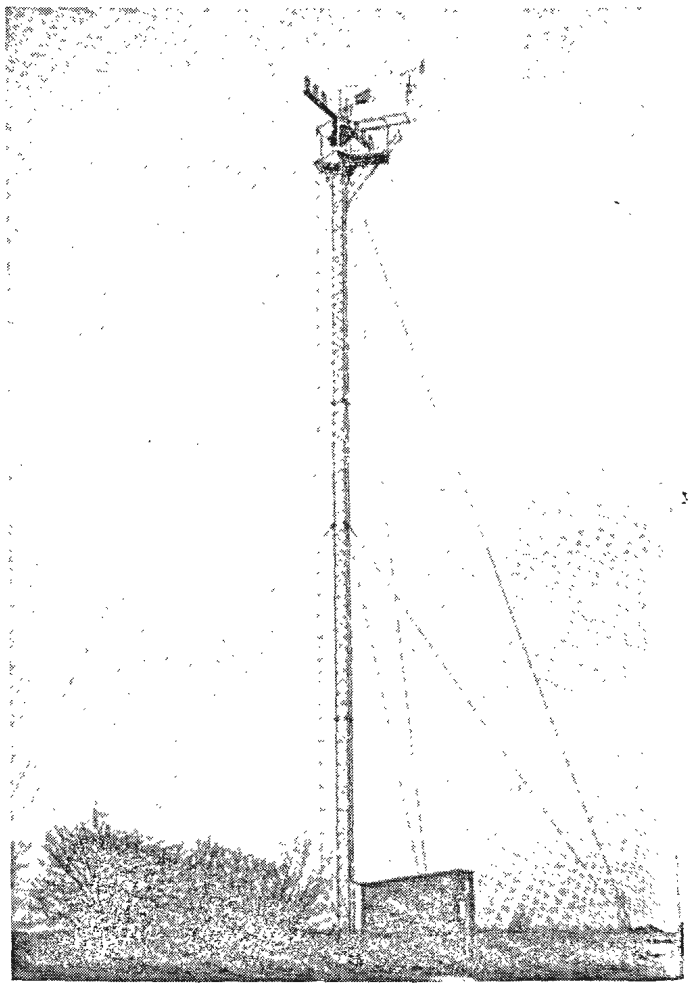

Figure 6. The wind measuring station at Tune. The tower is 25-m high

Like most wind power plants, the Gedser mill only turns slowly into the wind, and it cannot therefore register turns of the wind of short duration. The p.d.m. was designed accordingly.

The p.d.m. has six detectors placed on a horizontal beam mounted on the top of the tower. The beam is turned mechanically so that it will keep at right angles to the wind in the same manner as the Gedser mill. The detector has a movable plate at right angles to the wind. A spring forces the plate forward against the wind. If the speed of the wind exceeds the characteristic of the detector, the plate will be pushed slightly to the rear and close a contact in a circuit containing an electric counter.

Otherwise, the measuring method is statistical; a synchronous motor in the hut transmits an impulse to all the detectors every 15 seconds, and according to the speed of the wind, a greater or smaller number of the counters will make a recording. In addition to the six counters corresponding to the detectors, there is one more which counts all the impulses transmitted.

Each station is provided with a plant for the measurement of the maximum value of the velocity pressure of the wind, q_{max}-meter. The purpose of these measurements is to obtain statistical data for the velocity pressure of the wind, from which may be derived the wind load to be used in the calculations not only of windmills but also of structures in general.

The detector is a large Pitot-static tube which, by means of a windvane, is kept into the wind. From the detector, two pipelines lead down to the hut where the pressure causes a float to move vertically. Recording is made on a drum which is stationary except at midnight when it is turned slightly. The apparatus will thus give the maximum velocity pressure for each day.

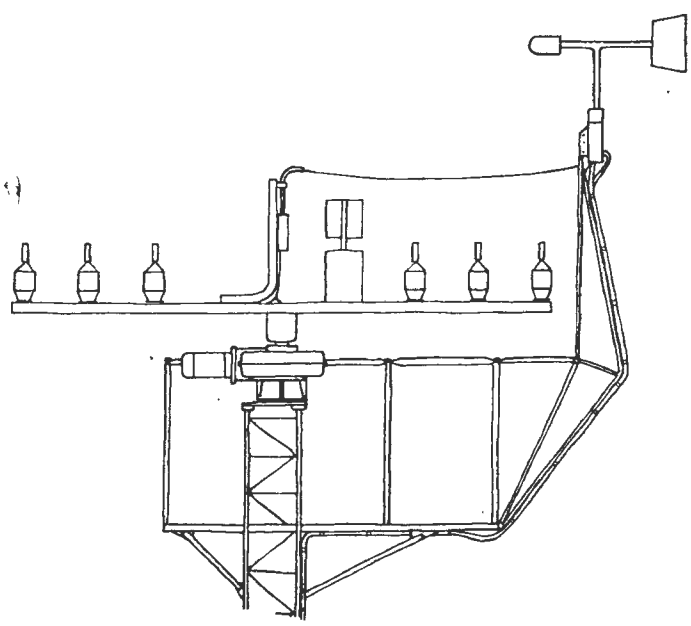

Figure 7. Top of a tower. To the right, the detector for the measurement of maximum velocity pressure. The 6 detectors for the power distribution meter are mounted on a horizontal beam which is automatically turned into the wind by a geared motor

Power distribution meter

The plant comprises six detectors mounted on a 4-m long, horizontal beam at the top of the tower. The beam turns on a vertical axis so that it will always be at right angles to the wind. The turning machinery is an electric motor geared to turn the beam one full revolution in 15 minutes, in the same way as at the Gedser mill. The geared motor is controlled by a wind-vane with contacts, the motion of the wind-vane being damped by two dash-pots (figure 7).

The detector is shown in figure 8. The plate's (*pl*) size is 15 × 15 cm, and is pivoted at its bottom

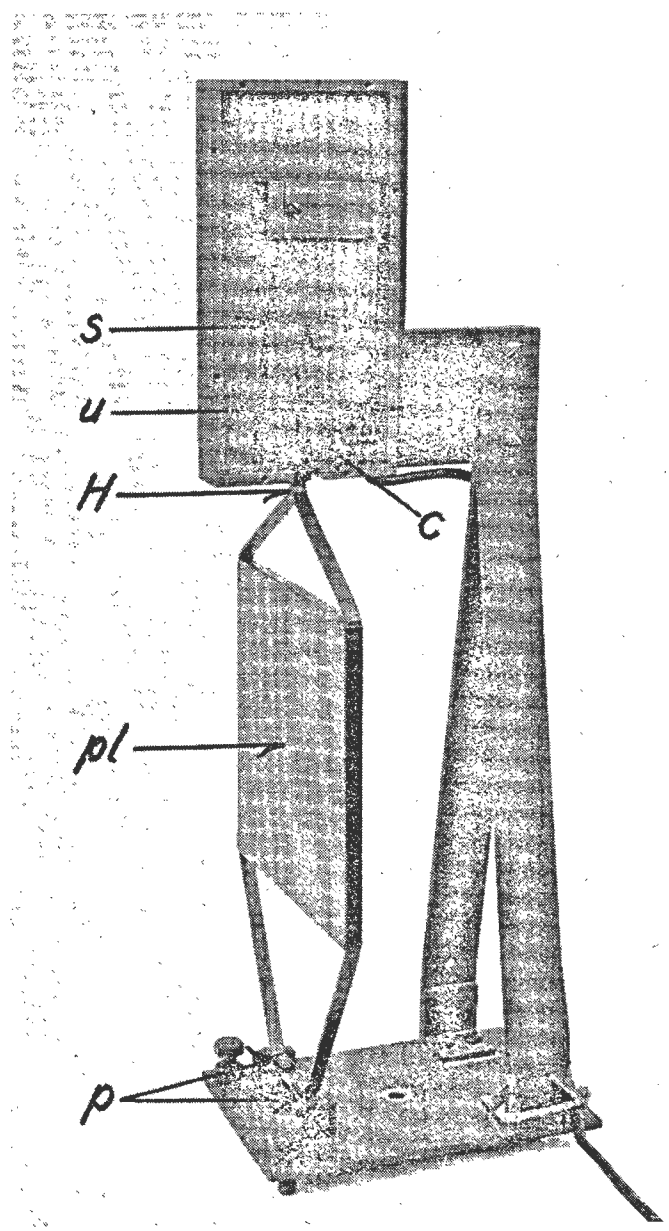

Figure 8. Detector for power distribution meter (*s*—main spring, *c*—contact point, *pl*—plate pivoted at *p*)

at *p*; the head, *H*, at the top, is pressed forward by a spring, *s*, with a force differing for each of the six detectors belonging to the set.

When the pressure of the wind against *pl* exceeds the characteristic of the detector, the head, *H*, will move to the rear, whereby unit *u* will be turned and close an electric circuit at contact *c*.

This is shown in detail in figure 9. At increasing wind pressure, *H* will first move 1 mm before the finger, *f*, is touched, and during the next 1 mm motion, the contact spring, *cs*, will move forward and close the contact at *c*. *H* will then move another 1 mm before impact and thereby bend the spring, *cs*, which is highly resilient. At decreasing pressure of the wind, *H* will first move 1 mm, *u* being held at rest by the trail spring, *ts*. During the next 1 mm motion of *H*, it will carry *f* with it; *cs* will straighten so that the contact will remain closed. Only when *H* has moved more than 2 mm will the contact be broken at *c*. *H* will now move its 3rd mm forward to impact and carry *f* with it, so that there will be a 1-mm gap at *c*.

This arrangement aims at preventing rapid contacts in succession due to the turbulence of a wind whose pressure against the plate just corresponds to that of the spring *s* of the detector.

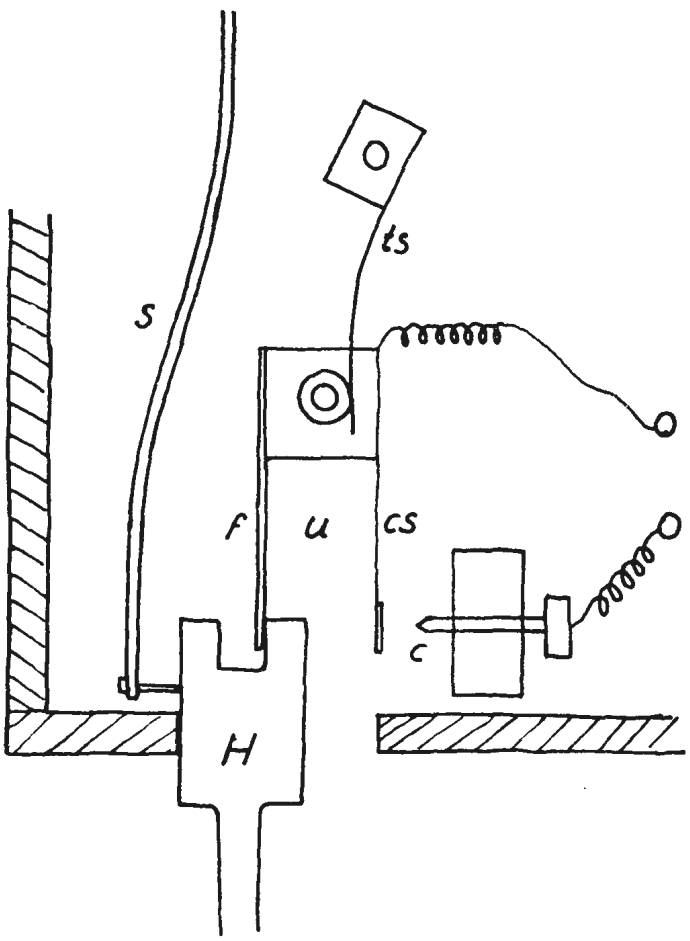

Figure 9. Contact in power distribution meter (*ts*—trail spring, *c*—platinum contacts, *cs*—contact spring, *H*—top of movable plate)

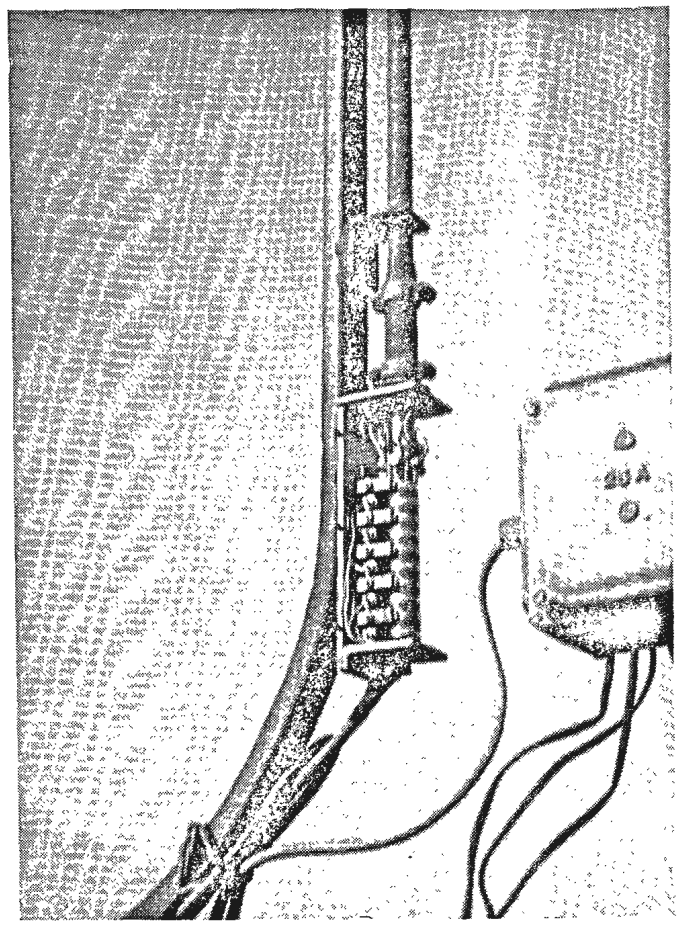

Figure 10. Slip-ring contacts for power distribution metre

The plate, *pl*, is a 0.4-mm aluminium plate mounted in a frame of duraluminium. The spring, *s*, is of phosphor-bronze. The contact, *c*, is provided with contact faces of platinum. Otherwise the apparatus is made of brass. In figure 8 the case of the apparatus is shown in open condition. While in operation, it is closed by a cover.

The six detectors belonging to a set will close the contacts when the speed of the wind exceeds the following values:

Detector No.	*m/s*
1	4.0
2	6.5
3	9.0
4	11.5
5	14.0
6	16.5

The detectors were adjusted in a 60·60 cm wind tunnel of NPL type. Adjustments were repeated at intervals of about one year. Changes in the apparatus have proved to be insignificant.

From the terminals of the detectors, wires are taken to a system of slip-rings mounted on an upright at the centre of the beam. There the motions of the beam are overcome, so that a fixed cable may extend upwards and over to the upright for the q_{max}-meter and thence down to the hut (figure 10).

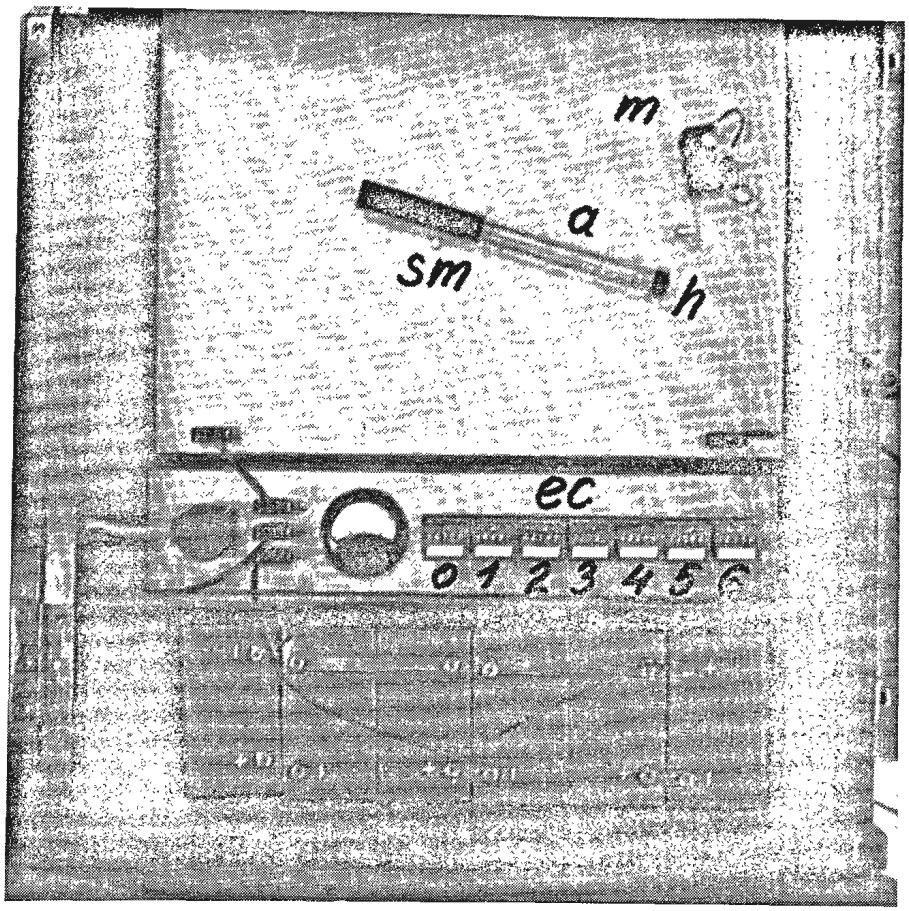

Figure 11. Pulse timer and recorder for power distribution meter. The head, *h*, is rotated by the synchronous motor, *sm*, and emits an impulse every 15 seconds. The impulses are counted by counters (*ec*) Nos. 0 - 6

Slip-rings and contacts are of hard-chromed brass.

From the panel in the hut, a pulse timer transmits a momentary current every 15 seconds to all the detectors; *sm* in figure 11 is a self-starting synchronous motor which through a gear makes the arm, *a*, rotate once every 15 seconds. At each rotation, the head, *h*, presses in the micro-switch, *m*, whereby the 27 v of the battery will pass to all the detectors.

Each detector is connected with an electric counter (see figure 11). Counter No. 0 has no detector but counts all the impulses given by the pulse timer. Counter No. 1 will count if the speed of the wind is higher than 4.0 m/s, counter No. 2 when it is 6.5 m/s or upwards, and so on.

The counters are 5-digit counters for 24 v; the resistance is 500 ohms.

We introduce the following designations: i is the pulse time, i.e. the time during which the head, *h*, keeps *m* depressed; t is the impulse interval, i.e. the time from the beginning of an impulse to the beginning of the succeeding one; r is the time of reaction of the counter, i.e. the time in which current will have to pass through a counter in order that a recording may just be made; and c is the contact time, i.e. the time during which the contact of the detector is closed.

In figure 12, time is taken to the right (x). A contact in the detector like $c1$ will give no count, but $c2$ will give a count; $c4$ gives a count, but $c5$ gives no count. There will thus be counts from $x = r$ to

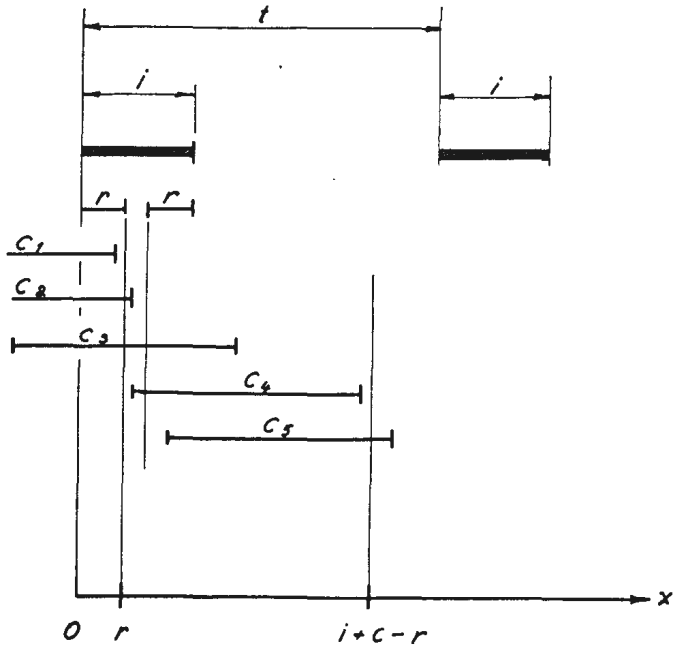

Figure 12. Legend: i = the pulse time, t is the impulse interval, r is the time of reaction of the counter, c is the contact time, c_1-c_5 is the same contact time in five different cases

$x = i + c - r$, i.e. over a period of $i + c - r - r = i + c - 2r$. The period giving the count $i + c - 2r$ is to be equal to c; hence $i = 2r$.

When $i = 2r$, it will just be impossible to have two counts during one impulse.

Let us consider how closely the requirement $i = 2r$ must be fulfilled. The apparatus should count $\frac{c}{t}$, but actually counts $\frac{c + i - 2r}{t}$;

the error is

$$\frac{c}{t} - \frac{c + i - 2r}{t} = \frac{2r - i}{t}$$

If $i = \alpha 2r$, the error of the apparatus will be

$$\frac{2r - i}{t} = \frac{2r}{t}(1 - \alpha).$$

Since r is about 0.035 s and $t = 15$ s, the error will be

$$\frac{2 \cdot 0.035}{15}(1 - \alpha) = 0.005\,(1 - \alpha).$$

As α in the plant ranges between 0.7 and 1.4, the maximum error will be 0.002.

Meter for measurement of the maximum value of the velocity pressure of the wind

The detector is shown in figure 13. The upper part, with the head h, wind-vane wv and cylinder cy, is turnable. The wind-vane sees to it that the head, h, is at all times kept into the wind. The front part of the head has a 25-mm bore in which the total pressure, i.e. the sum of the velocity pressure and the static pressure, will be obtained. This pressure is taken by a pipeline through the apparatus to the terminal 1.

The cylinder, cy, has slits in the two generators, where the pressure is just equal to 0. In the cylinder, the static pressure will thus be obtained, and this pressure is taken on to terminal $t2$.

From $t1$ and $t2$, rubber hoses lead to the middle of the tower where there is a pipeline to the hut. The pipes are $\frac{3}{4}$-in pipes in the 25-m tower, whereas 1-in pipes have been used in the 50-m tower. As a result, the damping of the apparatus due to resistance in the pipes will be uniform in the two types of tower.

In the hut, the two pipes are taken to pipe-connections on a water tank, as shown in figure 14.

A recording device is affixed to the rod, r. The point of the writer, pw, is a small steel ball resting on the recording drum with a very light pressure.

The float, fl, is actuated on its lower surface in an upwards direction by the velocity pressure of the wind plus the static pressure, while its upper surface is actuated in a downward direction by the static pressure. The resulting energy will thus be the velocity pressure of the wind, so that the level of the point recorded will give a measure of the velocity pressure.

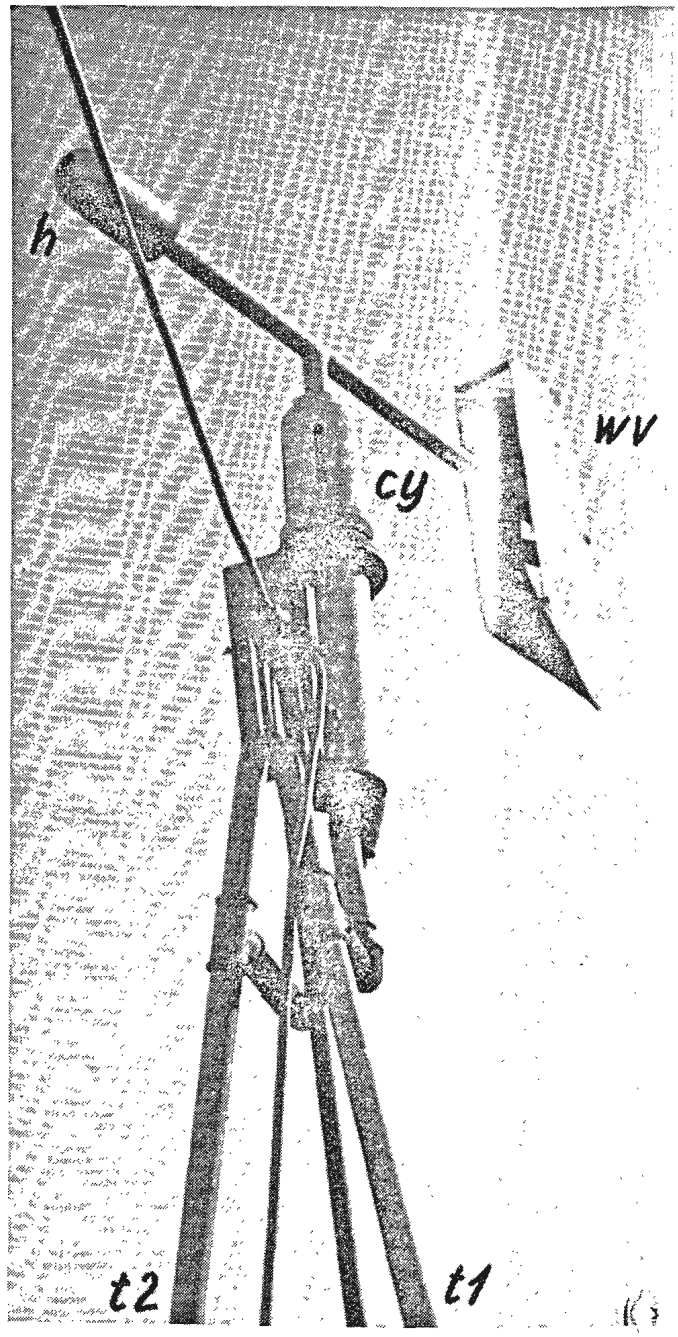

Figure 13. Detector for maximum velocity pressure. The total pressure is obtained in the bore at h. The static pressure is obtained in the slits at cy; wv is the wind vane. The pressures are taken to the terminals t_1 and t_2

Figure 15 shows the drum, d, which is a piece of smooth brass tube sooted on the surface; cl is a self-starting synchronous motor with gear. Its axle makes one rotation per 24 hours. Through a pawl arrangement, the synchronous motor causes the drum to be turned 3 mm forward every day at 00 hours GMT.

Thus, every day a vertical line will be drawn on the drum. The top of this line represents the maximum velocity pressure for the 24 hours. The drum is

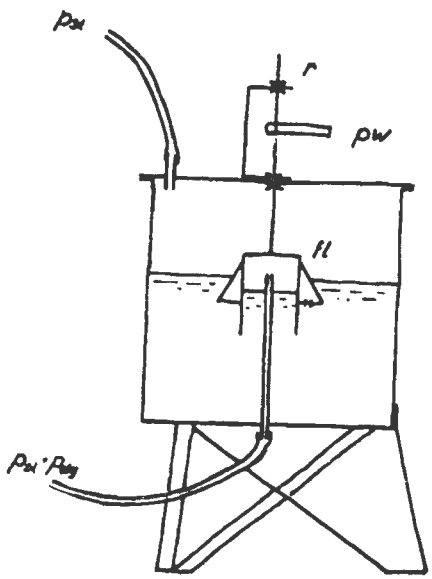

Figure 14. Recorder for maximum velocity pressure. The float, *fl*, is lifted by the velocity pressure and the movement is recorded by the point *wp* on a drum; *r* is a rod guiding the float

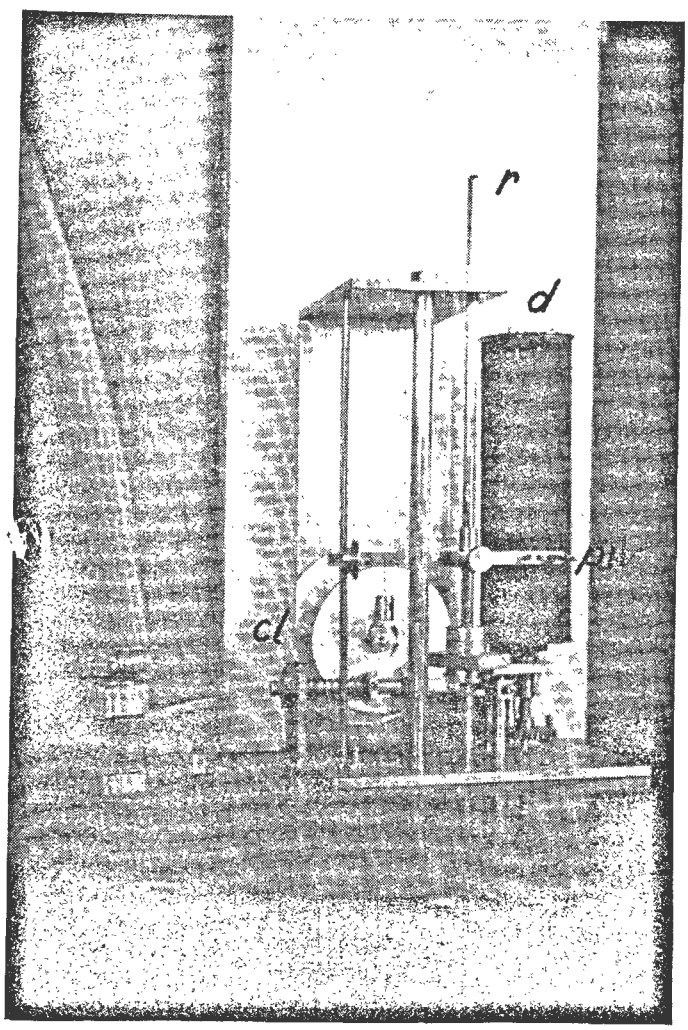

Figure 15. Recorder for maximum velocity pressure. Every night the drum, *d*, is turned slightly forward by the clockwork, *cl*. At other times it remains stationary

capable of holding recordings for 50 days. When it is filled with recordings, the graphs are fixed by submersion in cellulose lacquer.

Adjustment of the plant is made by means of a Fuess manometer at each replacement of the drum.

The plant is dimensioned to record a velocity pressure of maximum 156 kg/m², corresponding to a wind speed of 50 m/s.

For wind speeds of less than 6 m/s, the sensitivity of the apparatus is rather low. This is, of course, without significance, the object of the plant being to record high velocities of the wind.

The wind power

The method used for working up the readings of the p.d.m. may be explained most easily by an example.

During the period from 24 December 1959 to 11 February 1960, the following counts were recorded by the station at Tune:

Counter No.	*Counts*	*Relative number*	*Speed of wind exceeding*
0	283 689	1.000	0 m/s
1	240 649	0.850	4.0 m/s
2	134 342	0.475	6.5 m/s
3	64 665	0.228	9.0 m/s
4	26 617	0.094	11.5 m s
5	7 658	0.027	14.0 m/s
6	1 398	0.005	16.5 m/s

Counter 0 counted all the impulses transmitted; counter No. 1 counted impulses when the speed of the wind was higher than 4.0 m/s, which, as will appear from the table, was the case in 0.850 of the entire period.

With the relative values given in the table as the ordinate and the speed of the wind as abcissa, the curve shown in figure 16 was obtained, representing the accumulated frequency.

This curve is graphically differentiated once, whereby the distribution as to time of the speeds of wind shown in figure 17 was obtained. The ordinate in s/m, the abscissa the speed of wind in m/s. The area below the curve is 1.

From the distribution of wind speeds given in figure 17 the curve for power distribution shown in figure 18 was calculated. The ordinate is kg/m² and the abscissa the speed of the wind in m/s. For $v = 7$ m/s, figure 17 gives an ordinate of 0.12 s/m, the velocity pressure at this speed of wind is:

$$q = \frac{1}{16} 7^2 = 3.06 \text{ kg/m}^2$$

and the power of the wind:

$$qv = 3.06 \cdot 7 = 21.42 \frac{\text{kg}}{\text{m}^2} \frac{\text{m}}{\text{s}}$$

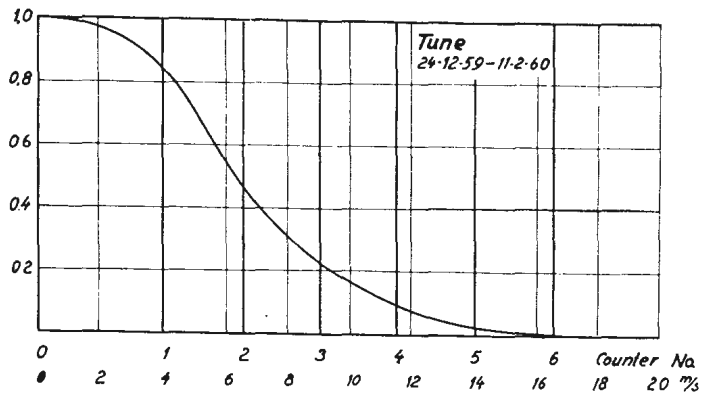

Figure 16. Accumulated frequency of the wind during the period from 24 December 1959 to 11 February 1960 at Tune

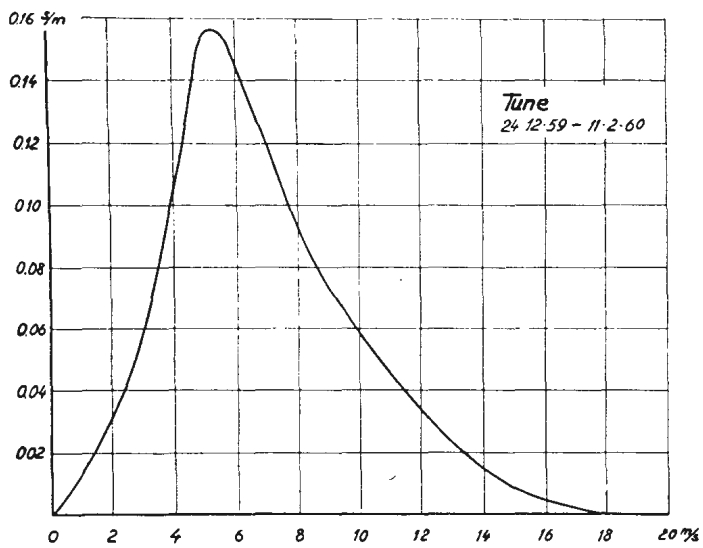

Figure 17. Frequency of wind during the period from 24 December 1959 to 11 February 1960 at Tune

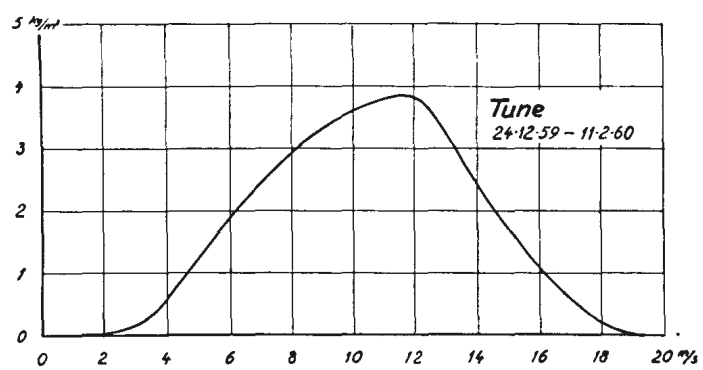

Figure 18. Power distribution during the period from 24 December 1959 to 11 February 1960 at Tune

Thus, the ordinate of the curve for power-distribution will be $0.12 \cdot 21.42 = 2.57$, and the dimension is:

$$\frac{\text{kg}}{\text{m}^2}\,\frac{\text{m}}{\text{s}}\,\frac{\text{s}}{\text{m}} = \frac{\text{kg}}{\text{m}^2}$$

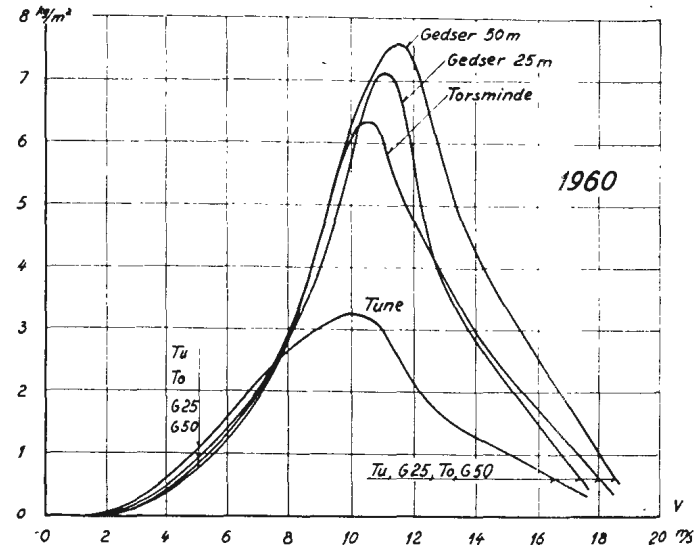

Figure 19. The distribution of power for 1960 at the four stations. The abscissa is the speed of the wind in m/s; the ordinate, the mean energy in $\frac{\text{kg}}{\text{m}_2}$

The area below the curve in figure 18 represents the average power through the period, or 33.2, and the dimension is:

$$\frac{\text{kg}}{\text{m}^2}\,\frac{\text{m}}{\text{s}}$$

The measuring stations were started at the end of 1957, and, with some interruptions, results are available until the beginning of March 1961. The stations have worked without interruption since the autumn of 1959.

In the calendar year 1960, the measurements gave the results shown in table 1. The power is the mean value for the period concerned in $\frac{\text{kg}}{\text{m}^2}\,\frac{\text{m}}{\text{s}}$.

The distribution of power on wind speeds for 1960 is shown in figure 19.

The average ratio between the power at the 50-m level and at the 25-m level is 1.21.

Maximum velocity pressures

The measurements of the daily maximum values of the velocity pressure were started at all four stations at the end of 1957 and were carried through with a few interruptions. The measurements must be continued for some years to come in order that sufficient data may be provided for a statistical computation resulting in the fixing of the maximum value for a given term of years.

Only a few results will be mentioned in this paper.

The maximum values at the four stations were:

Tune (25 m) 21 Feb. 1959 . .	$q_{max} = 51$ kg/m² ($v_{max} = 28.5$ m/s)
Gedser (25 m) 19 Jan. 1958 .	$q_{max} = 73$ kg/m² ($v_{max} = 34$ m/s)
Gedser (50 m) 19 Jan. 1958 .	$q_{max} = 81$ kg/m² ($v_{max} = 36$ m/s)
Torsminde (25 m) 6 Feb. 1961	$q_{max} = 86$ kg/m² ($v_{max} = 37$ m/s)

It may further be mentioned that, at Gedser, the ratio between the velocity pressures at the 50-m level and the 25-m level is 1.13, which corresponds to a ratio in power of 1.20, in agreement with the result of the direct measurements of the power.

Table 1

Tune		*Torsminde*		*Gedser*		
Date	*Mean power*	*Date*	*Mean power*	*Date*	*25 m Mean power*	*50 m Mean power*
1960		*1960*		*1960*		
1/1	33.2	1/1	69.8	1/1	48.4	61.2
		25/1	48.2	12/1	51.6	69.4
11/2	21.4	20/2	41.5	18/2	49.7	60.0
2/4	35.3	2/4	53.6	2/4	45.7	52.7
14/5	19.9	14/5	38.2	14/5	39.6	40.6
3/7	15.8	2/7	28.0	2/7	24.8	30.1
13/8	18.0	13/8	29.1	13/8	32.2	40.1
19/9	21.1	17/9	28.1	17/9	28.8	36.7
22/10	34.1	22/10	53.0	22/10	51.3	64.4
3/12	26.8	3/12	45.4	3/12	56.1	62.2
31/12		31/12		31/12		
1960	25.2	1960	42.0	1960	41.8	50.8

Summary

The wind-power plant of the Danish Wind Power Committee, the so-called Gedser mill, is described in detail in paper W/17 under item II.B.2 below. The mill operates on the principle that the propeller, through a constant gear-transmission, drives a synchronous generator connected to the public supply network, the frequency of which is governed by the thermal plants connected with it.

This construction implies that the revolutions of the propeller will vary only about 1 per cent between idling and full load. The propeller blades are not adjustable. It must be noted that the turnable tips serve solely as a brake to bring the working plant to a dead stop.

The efficiency will have its maximum value at a given speed of wind, depending on the degree of gearing between propeller and generator. If the speed of the wind increases beyond this optimum speed, the angle of incidence of the wind on the blades will become too great, with the result that the efficiency will decrease. At even higher speeds, the blades will stall and the efficiency will decline very markedly.

When a mill is constructed on this principle, it is necessary to determine the range of wind speeds at which the mill will work with high efficiency. It is therefore absolutely necessary to know the power distribution of the wind at the different speeds.

For this purpose, a new device, the power-distribution meter (p.d.m.), was designed to integrate the wind power in terms of speed.

A p.d.m. was mounted close to the experimental wind power plant at Gedser, at a height above ground of 25 m, i.e. on a level with the hub of the propeller. To find out whether it would pay to build higher mills, a p.d.m. was mounted at a height of 50 m.

A 25-m high measuring station with a p.d.m. was erected on the west coast of Jutland, directly facing the North Sea. A similar station was established west of Copenhagen in an open agricultural area.

From these four stations, p.d.m. measurements covering a period of about two years are available.

In addition, apparatus for measuring the maximum velocity pressure of the wind is mounted in each station.

MESURES EFFECTUÉES SUR LE VENT

Résumé

La centrale éolienne de la commission danoise de l'énergie éolienne connue sous le nom de « Centrale de Gedser » fait l'objet d'une description détaillée dans le mémoire W/17, se rapportant au point II.B.2 *a* de l'ordre du jour. Son hélice entraîne une transmission à engrenages en prise constante et,

par son entremise, un alternateur asynchrone branché sur le réseau public de distribution d'électricité, dont la fréquence est définie par ses centrales thermiques.

Ce mode de construction présuppose que la vitesse de rotation de l'hélice ne variera que de 1 p. 100 environ entre le ralenti et la marche à pleine charge. Elle est à pas fixe. On observera que l'on ne fait tourner les bouts de pale que pour freiner le système et en assurer l'arrêt absolu.

Le rendement est maximum pour une vitesse de vent donnée, qui dépend du train réducteur interposé entre l'hélice et l'alternateur. Si la vitesse du vent dépasse ce régime idéal, l'angle d'incidence du vent sur les pales devient trop grand et le rendement tombe. A des vitesses encore plus élevées, il y a décrochage aérodynamique et ce rendement s'effondre.

Une fois l'éolienne construite en conformité avec ce principe, il est nécessaire de déterminer la gamme de vitesses sur laquelle son rendement sera bon. Il sera donc absolument nécessaire d'établir la courbe donnant la puissance en fonction de la vitesse du vent.

On a réalisé dans ce but un nouveau dispositif servant à intégrer l'énergie que débite le vent en prenant la vitesse comme variable, appelé compteur totalisateur de la répartition de puissance.

On a installé un tel instrument près de la centrale expérimentale de Gedser, à une hauteur de 25 m au-dessus du niveau du sol, soit à celui du moyeu de l'hélice. On en a placé un autre à 50 m pour juger de l'opportunité de construire des aéromoteurs d'une plus grande hauteur.

On a prévu un poste de mesure de 25 m doté d'un tel compteur, sur la côte ouest du Jutland, face à la mer du Nord. On en trouve un autre à l'ouest de Copenhague, dans une région agricole découverte.

Ces quatre postes ont donné des mesures au compteur totalisateur s'échelonnant sur une période de deux ans environ.

Chaque poste est également doté d'un appareil servant à mesurer la pression dynamique maximum que donne le vent.

SOME ASPECTS OF SITE SELECTION FOR WIND POWER PLANTS ON MOUNTAINOUS TERRAIN

Karl O. Lange *

Information on the general wind régime of a geographical region is a prerequisite for considering the utilization of wind power in the region. Such information may consist of long-term anemometry, at characteristic ground stations, of upper-air wind measurements or of gradient winds computed from the pressure fields of synoptic maps covering the region. In either case, the problem is then to find suitable local sites in the region, matching their specific winds to the performance characteristics of specific wind power plants or *vice versa*, with due regard to economy and required power.

The selection of suitable local sites depends much on knowledge of the shape of the "wind profile" — the variation of wind velocity with height from the surface to gradient wind level — because the wind profile permits, first, the tying in of the existing long-term wind measurements with wind conditions at different levels and localities and, secondly, the computation of power inputs over various turbine diameters and heights; the wind profile also enters into the structural requirements of the wind power plant.

Much information is available about free-air wind profiles over level terrain, for example in the paper presented by Professor Petterssen (W/26). However, in regard to wind velocities and wind profiles over topography with sizable elevation differentials, our knowledge is inadequate.

It is probably generally true that the average wind and the most frequent wind increase with the elevation of prospective sites on mountain tops in somewhat the same fashion as the free-air wind increases with height. Available wind power, being essentially proportional to the cube of wind velocity, therefore, should increase rapidly with elevation, calling for the location of wind power plants of greatest capacity as high up as possible. Construction and maintenance costs, on the other hand, are also functions of elevation. Moreover, in many locations, the occurrence and severity of icing increase with elevation, which in turn calls for structural requirements which tend to increase costs. Thus, an optimum should be determined in each case on the basis of meteorological factors at the various elevations, on the one hand, and local costs and power needs, on the other.

Obviously, a favorable site in that respect would be one which produces relatively high winds at a given elevation due to compression of stream lines. From the results of investigations in aerodynamics, one would expect to find such sites on terrestrial obstacles, such as mountains and, particularly, ridges athwart the main wind direction.

Existing aerodynamic knowledge has been gained principally at comparatively low Reynolds numbers, or else at high Mach numbers. The flow on terrestrial obstacles, however, takes place at high Reynolds numbers, due to the large geometric dimensions of the terrain, and, at common wind speeds, it certainly represents incompressible fluid flow. In wind tunnels, every effort is made to produce laminar air-streams, but the air in nature is usually turbulent and beset with motions introduced by prior history of mechanical and thermodynamic mixing. Most of the aerodynamic knowledge, both theoretical and experimental, has been obtained on the basis of homogeneous free-stream velocity and homogeneous free-stream density, but atmospheric flow on mountains is usually by air containing vertical velocity gradients of various magnitudes, and vertical dimensions in nature are usually too large to permit neglect of the variations of pressure, temperature and humidity in the vertical.

Notwithstanding these discrepancies in flow parameters, many attempts have been made to extend flow similarities to atmospheric flow, for example by applying the "speed-up factor", found on the side of air foils, to the ridge of mountains of similar geometric shape. Time and again, models of landscapes have been subjected to wind tunnel tests. Results so obtained have been used in estimating the wind and the resultant available power on mountain sites, sometimes with very disappointing and costly consequences.

It is difficult to verify or deny the validity and accuracy of "speed-up factors" because in each case it is necessary to have not only accurate measurements of wind speed and direction on the mountain itself, but also simultaneous measurements of the wind velocity in the free atmosphere. Present techniques of anemometry on the ground and in the free air are quite different from one another and not strictly comparable with each other. Moreover, pilot balloon data computed on the basis of known rates of climb (which constitute the bulk of long-term, free-air wind measurements) are quite unreliable over terrain with vertical air currents. On the mountain itself, there exists an unknown boundary layer, making it questionable at just

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what height above ground or above tree tops the significant wind should be measured. This last mentioned difficulty makes it even hard to compare mountain sites with each other by anemometry.

In an investigation on the respective merits of a number of mountains in New England in connection with the Smith-Putnam aero-electric turbine project, the following data were carefully determined:

Mountain	*Speed-up factor*		*Power factor*	
	Model test	*Anemometry*	*Model test*	*Anemometry*
Pond (1 500 ft)	1.29	0.84	2.15	0.60
Glastenburg (3 900 ft)	1.44	1.04	3.00	1.13
Mt. Washington (6 430 ft) . . .	1.30	1.47	2.20	3.18

It may be seen that the model tests were utterly misleading.

The following considerations will perhaps suffice to show why wind tunnel data should not be expected to simulate atmospheric flow over terrestrial obstacles. Out of the infinite variety of possible conditions, three simple examples are selected in which a parcel of air is supposed to flow over a ridge, z meters high. Although the ascending air might absorb heat on the way up when the slope is exposed to the sun, or lose heat, the equally adequate assumption is made that it should move adiabatically. For simplicity's sake, the atmosphere is assumed to have a linear lapse rate β, in one case to be dry adiabatic, in the second case to be the "standard atmosphere" lapse rate and in the third case to be isothermal. All three cases are well within possible everyday conditions. The pressure distribution along the path of the parcel is assumed to be that of the free atmosphere. This is an oversimplification, as it would leave no incentive for the parcel to move, but the order of magnitude of the results is not disturbed.

Assuming the air parcel to be sufficiently dry, it will follow the equation of state of an ideal gas:

$$pdv + vdp = RdT$$

where p = air pressure; v = volume per unit mass; T = absolute temperature; R = the gas constant of air per unit mass.

The adiabatic expansion of an ideal gas is expressed by:

$$O = C_p \frac{dT}{T} - R \frac{dp}{p}$$

where C_p = specific heat of air at constant pressure; C_v = specific heat of air at constant volume; $R = C_p - C_v$.

The atmospheric pressure height relationship is:

$$dz = -\frac{v}{g} dp$$

where g = acceleration of gravity, considered constant, and z = height.

From these stipulations results the well-known fact that the temperature of the adiabatically rising parcel of air drops with height at the rate of

$$\left(\frac{dT}{dz}\right)_{ad} = \gamma = -\frac{g}{Cp} = -0.98°\text{C}/100\,\text{m}$$
$$= \sim -1°\text{C}/100\,\text{m}$$

At the foot of the mountain, the parcel has the same density as the surrounding air. The dynamics of what causes the existing wind having been eliminated from consideration, the net force on the parcel is zero, its weight being equal to the buoyancy of the surrounding air. Such is not the case any more, however, as soon as the parcel starts up in an atmosphere of a lapse rate β other than dry adiabatic.

Observing the air parcel anywhere along its path up the mountain, its weight is:

$$W = \frac{g}{v} \text{Vol} = \frac{p}{RT'} g \text{ Vol}$$

where T' = temperature of the air parcel.

The buoyant force B exerted by the surrounding air on the air parcel is:

$$B = \frac{p}{RT} g \text{ Vol}$$

where T = temperature of the ambient air.

The net downward force on the parcel then is

$$W - B = \frac{p}{R} \text{Vol} \left(\frac{1}{T'} - \frac{1}{T}\right) = \frac{T - T'}{T} W =$$
$$\frac{(\beta - \gamma)\, z}{T_o (1 + \beta z)} = \sim \frac{\beta - \gamma}{T_o} Z\, W$$

where T_o = initial temperature at $z = 0$.

Depending on the lapse rate of the ascending air (which need not be adiabatic, because heat might be lost or gained during the ascent), and depending on the stability of the atmosphere, forces come into play which do not exist in the wind tunnel. The moving air is subjected to vertical accelerations of the order of

$$\frac{dv_z}{dt} = \frac{T - T'}{T} g$$

which, while not ordinarily large, become important to the flow characteristics because of the length of time during which they are active. The ascent of air at 30 kilometers per hour over a 3-kilometer long slope, for example, takes 360 seconds, and an

average vertical acceleration of only 0.01 g should cause a vertical velocity component of about 35 meters per second, or 116 feet per second, not considering drag and resultant mixing.

The thermodynamic effects in atmospheric flow are perhaps best exemplified by energy considerations of the three selected cases. If the air parcel rose to z, it would have to overcome successively larger downward forces. The energy required to lift W weight units of air of temperature T_o to an elevation z is, from the foregoing,

$$E = \int_{z_o}^{z} (W - B)\, dz = W \int_{z_o}^{z} \frac{\beta - \gamma}{T_o} z dz$$

$$= \frac{1}{2} \frac{\beta - \gamma}{T_o} z^2 W$$

This energy must be supplied to make the upward flow possible and an available source of energy is the original kinetic energy of the wind. Thus the original wind velocity V is reduced to V_z by the time elevation z is reached:

$$\frac{1}{2} \frac{\beta - \gamma}{T_o} Z^2 = \frac{1}{2g} (V^2 - V_z^2)$$

The wind velocity $V_{\min}$, which would be required to just push air to an elevation z, arriving there with wind velocity zero, is

$$V_{\min} = \left(g \frac{\beta - \gamma}{T_o} \right)^{\frac{1}{2}} z$$

Note that the required initial wind is directly proportional to the height of the obstacle.

For the purpose of survey, the wind velocities $V_{\min}$ which would be required under the three stability conditions to push air of 288° to an elevation of 1 000 meters, arriving there with no velocity, are presented below:

Lapse rate	*Adiabatic*	*"Standard"*	*Isothermal*
$V_{\min}$, meters per second . .	0	11	19
$V_{\min}$, feet per second. . . .	0	35	60

This shows, then, that atmospheric flow over natural topography might conceivably be similar to model flow only when neutral stability exists in the atmosphere or if the elevations are quite small. In any stable atmosphere, much wind energy is consumed in moving the air vertically, and one would have to conclude that any "speed-up factor" found in homogeneous fluid flow would be counteracted and overshadowed by these energy losses in the "standard atmosphere", the more so, the higher the mountain.

One might argue that whenever there exist wind speeds high enough to be of interest for wind power, then there should also exist an adiabatic lapse rate due to prior turbulent mixing. In that case, another complication arises. The turbulent layer will almost invariably be topped by a turbulence inversion, which acts as a baffle, non-existent in the wind tunnel. The height of the inversion is likely to vary and so will its unpredictable effect on the flow, particularly if the inversion vacillates above and below summit height.

If the humidity of the air is high, other thermodynamic processes enter into the picture. Liquid water in the air must affect the fluid flow. Heat transfer during the flow must produce effects. It would seem to be a rather severe task to fully analyze all these conditions, and even then it would probably be impractical for power site selection to undertake the measurement of all the parameters likely to be involved.

Perhaps one conclusion may be drawn: whenever the atmosphere is stable, energy of the order of magnitude outlined above is required for vertical motion. To conserve this energy, the wind will want to go around the obstacle rather than over it. This should result in increased wind speeds along the edges and in gaps of mountain ranges. Some anemometric measurements and such commonplace names as "wind gap" seem to bear this out.

Until further knowledge on velocity distributions and wind profiles in mountainous regions becomes available, the meteorological suitability of wind power plant sites has to be prejudged by the crude means of collecting subjective experiences of inhabitants of the region and by ecological means, if proper vegetative growth exists.

In the author's opinion, only comparative anemometry on a number of such preselected sites can then furnish reliable data on the respective meteorological merits of the sites.

Summary

In general, the selection of specific sites for wind power plants in a mountain region involves a compromise between the desired maximum output and the economy at which the power can be made available.

Within the design limitations of a specific wind power plant, the output is higher the higher the average — or the most frequent — wind is. Ordinarily, available wind power increases with elevation. But so do erection and maintenance costs. Moreover, in many locations, the possibility and the severity of icing increase with elevation, which in turn calls for structural requirements which tend to increase costs. Thus, an optimum should be determined in each case on the basis of local construction costs, on the one hand, and the meteorological factors at various prospective sites, on the other.

As an alternative to high elevations, one would look for terrestrial obstacles to the wind, where compression of stream lines causes a wind speed

higher than that of the undisturbed atmosphere at the same height. It is, however, not possible to obtain reliable quantitative values for such "speed-up factors" by similarity with the results of ordinary aerodynamic research. Contrary to the conditions of theoretical and experimental aerodynamic investigations, atmospheric flow on mountains and mountain ranges takes place at very high Reynolds numbers and low Mach numbers, and the free stream is not only turbulent, but has pronounced velocity and density gradients in the vertical. Moreover, because of the length of time required for air to flow over terrestrial distances, heat transfer to or from the air-stream is likely to take place.

An example is given of air adiabatically ascending over a 1 000-meter high obstacle when the stability of the atmosphere is that of the " standard " atmosphere. By equating the energy required to overcome this stability of the atmosphere to the kinetic energy of the wind, it is found that a wind of 11 meters per second would reduce to zero due to the climb.

At the present time, there are no reliable criteria by which the power input into a wind power plant on a mountain site can be predicted accurately from the general wind régime of the region. Until such information is available, the meteorological suitability of wind power plant sites has to be prejudged by the crude means of collecting subjective experiences of inhabitants of the region and by ecological means, if proper vegetative growth exists.

In the author's opinion, only comparative anemometry on a number of such preselected sites can then furnish reliable data on the respective meteorological merits of the sites.

CERTAINS ASPECTS DU CHOIX DE L'EMPLACEMENT DES CENTRALES ÉOLIENNES EN MONTAGNE

Résumé

En général, le choix d'un emplacement pour les centrales éoliennes dans une région montagneuse comporte la nécessité d'un compromis entre le débit maximum recherché et l'économie du dispositif de mise en œuvre de l'énergie. Dans le cadre des limitations imposées à la conception d'une centrale éolienne spécifique, le débit est d'autant plus grand, que l'intensité moyenne du vent ou sa fréquence est plus élevée. Normalement, l'énergie éolienne disponible augmente avec l'altitude. Il en va de même, en revanche, pour les frais d'installation et d'entretien. Au surplus, en nombre de lieux, la possibilité et la gravité du givrage augmentent avec cette altitude, ce qui soulève des exigences quant au mode de construction des centrales, qui tendent à faire monter les frais. En conséquence il faut trouver une solution idéale, dans chaque cas, sur la base des frais de construction sur place d'une part et les facteurs météorologiques en divers lieux possibles de l'autre.

Au lieu de s'en remettre aux grandes altitudes, on pourrait chercher des obstacles terrestres au vent, avec lesquels la compression des lignes d'écoulement crée une intensité de vent plus grande que celle de l'atmosphère non dérangée à la même hauteur. Cependant, il n'est pas possible d'obtenir des valeurs quantitatives dignes de foi pour ces facteurs d'accélération en tentant des analogies ou des rapprochements entre les résultats de ces travaux et ceux des recherches aérodynamiques ordinaires. A l'inverse de ce qui se passe pour ces recherches aérodynamiques théoriques et expérimentales, l'écoulement atmosphérique sur les montagnes et les chaînes s'effectue dans des conditions telles que les nombres de Reynolds sont très élevés et les nombres de Mach faibles, si bien que le courant d'air libre n'est pas seulement turbulent mais, au surplus, présente des pentes de vitesse et de densité prononcées sur la tranche verticale. Étant donné le temps qu'il faut à l'air pour s'écouler sur des distances terrestres, il faut s'attendre à des échanges de chaleur vers le courant d'air ou à partir de lui.

On donne un exemple d'air montant adiabatiquement pour franchir un obstacle de 1 000 m de haut avec une stabilité d'atmosphère dite « standard ». En écrivant que l'énergie nécessaire pour surmonter cette stabilité et l'énergie cinétique du vent sont égales, on trouve qu'un vent de 11 m/sec serait ramené à 0 en raison de sa montée.

A l'époque actuelle, on ne dispose pas d'étalons dignes de foi dont on puisse se servir pour prévoir exactement la quantité d'énergie fournie à une centrale éolienne en un site montagneux sur la base du régime général des vents dans la région. Jusqu'à ce que l'on dispose de semblables données, les qualités météorologiques des sites de centrales éoliennes doivent être prévues au moyen des systèmes actuels assez grossiers qui consistent à recueillir les observations subjectives des habitants de la région, ainsi que de la mise en œuvre de méthodes écologiques si on dispose de la végétation voulue.

De l'avis de l'auteur, ce n'est que l'anémométrie comparée en un grand nombre de sites ainsi choisis d'avance qui pourra fournir des données dignes de confiance sur les mérites météorologiques respectifs des emplacements.

LA MESURE DU VENT EN MÉTÉOROLOGIE

A. Perlat *

Les données météorologiques sur les vents en surface constituent souvent la seule documentation existante pour obtenir des indications générales sur le régime des vents au voisinage du sol.

Bien que certains sites soient particulièrement favorables pour utiliser l'énergie éolienne, les indications des anémomètres permettent d'avoir une première idée des disponibilités en énergie, pour des gammes de vitesse déterminées, dans diverses régions.

Le présent mémoire indique comment est effectuée la mesure du vent dans les stations météorologiques. Afin de rendre comparables ces mesures, des recommandations concernant les techniques à utiliser sont éditées par l'Organisation météorologique mondiale (OMM) et publiées dans un *Guide des méthodes d'observation et d'instrumentation météorologiques.*

Par définition, la mesure du vent est celle de la composante horizontale du mouvement de l'air, quantité vectorielle caractérisée par deux nombres représentant la direction et la vitesse. L'absence de mouvement appréciable de l'air est appelée « calme » et il est admis (Guide) qu'aucune tentative ne doit être faite pour déterminer la direction du vent à l'aide d'instruments quand la vitesse est inférieure à 2 nœuds (environ 1 m/s).

Mais l'écoulement de l'air est souvent irrégulier; la vitesse présente de rapides fluctuations ou rafales. Suivant le but poursuivi, la mesure doit indiquer une vitesse moyenne prise sur un certain intervalle de temps, de manière par exemple à rendre comparables les données des différentes stations pointées sur les cartes servant aux études de la situation météorologique synoptique, ou bien donner une indication de la variabilité du vent à une certaine échelle, en définissant les caractéristiques d'une rafale.

Des études menées dans plusieurs pays, en utilisant les données recueillies par des anémomètres possédant les caractéristiques convenables, ont montré que la valeur indiquée pour la vitesse du vent varie dans le temps, et ce, d'une façon d'autant plus grande que la période choisie pour calculer la vitesse moyenne du vent au cours de cette période est plus courte. On constate une croissance rapide de ces variations lorsque la moyenne est prise sur des intervalles de temps inférieurs à 5 mn et l'écart des valeurs moyennes prises sur 5 ou 10 mn n'est pas considérable.

La valeur moyenne du vent sur 10 mn donne donc une valeur relativement stable, et cette échelle de temps permet, en minimisant les variations de vitesse dues à la turbulence provoquée par la surface, de rendre comparables les observations. Aussi en météorologie, dans les messages synoptiques, la vitesse moyenne du vent en surface est définie comme correspondant à une période de 10 mn. Il n'existe pas de règle analogue pour caractériser la direction moyenne du vent.

Le degré de turbulence du vent est une donnée importante, tant pour certains usagers que dans l'étude des mécanismes d'échanges entre le sol et l'atmosphère. Mais la définition d'une rafale, variable suivant les cas, reste un problème posé mais non résolu.

La finesse avec laquelle peut être appréciée la turbulence dépend des caractéristiques de l'anémomètre et de son enregistreur.

La vitesse du vent peut être estimée d'après les effets qu'elle produit et caractérisée alors par un nombre, suivant une échelle conventionnelle comme celle de Beaufort, ou mesurée, la vitesse étant donnée en mètres par seconde, nœuds ou kilomètres par heure.

Une mesure de la direction, de la vitesse et de l'intensité des rafales ne peut être obtenue qu'à l'aide d'instruments dont l'emplacement dans le cas des mesures synoptiques doit être à l'abri des influences locales qui, en déviant les filets d'air, peuvent amener une déviation systématique de sa direction, une oscillation ou un freinage de sa vitesse et créer une turbulence particulière. Par ailleurs, la vitesse du vent croît, en moyenne, avec la hauteur d'une façon sensible dans les basses couches. Les règles suivantes sont préconisées :

« La hauteur normale des instruments anémométriques utilisés en terrain plat et découvert est de 10 m au-dessus du sol. Un « terrain découvert » est défini comme un terrain où la distance entre l'anémomètre et tout obstacle est au moins égale à 10 fois la hauteur de cet obstacle » (Guide CIMO).

Toutefois ces règles ne sont pas encore appliquées universellement et on note encore aujourd'hui dans les diverses installations de mesure des hauteurs allant de 5 à 25 mètres. Il y a donc lieu, dans les études des diagrammes d'un anémomètre, de tenir compte du niveau auquel est placé l'appareil.

Les anémomètres, comme les girouettes auxquelles ils sont souvent accouplés, sont donc de préférence installés à assez grande distance du local d'observation et nécessitent un système de télémesure.

* Météorologie nationale, Paris.

Nous n'insisterons pas sur les girouettes, la direction du vent étant généralement de peu d'importance dans le problème de la captation de l'énergie éolienne.

Différents types d'anémomètres ont été et sont encore en service; les capteurs de la plupart d'entre eux sont basés sur l'action du vent sur les hélices et les moulinets, ou encore sur la pression dynamique exercée par le vent.

Une hélice, à axe horizontal maintenu face au vent par une girouette, prend un mouvement de rotation sous l'action de la pression exercée sur les pales par le vent. Si l'on étalonne le moulinet, on obtient une relation de la forme $V = KN + v_0$, où N représente le nombre de tours et v_0 le seuil de démarrage. On montre que le meilleur rendement est obtenu en utilisant des pales hélicoïdales.

Les moulinets utilisés pour la mesure du vent sont généralement composés de trois ou quatre coupes, hémisphériques ou coniques, fixées chacune à un bras, solidaire d'une embase centrale fixée sur l'axe vertical de rotation. L'ouverture des coupes se trouve dans des plans verticaux passant par l'axe de rotation et formant entre eux des angles égaux.

Si l'on considère deux coupes diamétralement opposées, l'une présente au vent la partie concave, l'autre la partie convexe. La résistance offerte au vent étant en gros quatre fois plus forte pour la première coupe que pour la seconde, sous l'action du vent le moulinet prend un mouvement de rotation dont la rapidité est fonction de la vitesse v du vent.

De nombreux auteurs (Robinson, Brazier, Patterson, Spilhaus et d'autres) ont étudié la théorie du moulinet, pour trouver la loi $N = f(v)$ et la disposition des coupes donnant les meilleures performances (couple et sensibilité).

Si D est le diamètre du cercle décrit par le centre des coupes de diamètre d, Spilhaus a montré qu'on obtient une relation de la forme $v = a + bN$ pour un rapport $\frac{d}{D}$ qui dépend de la dimension et de la forme des coupes.

La loi de rotation est, d'après certains, plus régulière lorsque le bord des coupes est terminé par un bourrelet.

Il a été avancé que les moulinets à trois coupes possédaient un couple de démarrage plus indépendant de la direction du vent que ceux à quatre coupes, mais des expériences faites en France contredisent cette assertion, et il a été montré récemment que c'est un moulinet à cinq coupes qui permet de mieux minimiser l'effet de la direction du vent sur le couple de démarrage.

Dans tous les cas, le poids total doit être faible pour minimiser les effets d'inertie; il atteint par exemple 145 g dans le modèle à quatre coupes hémisphériques (d = 61 mm, D = 165 mm) adopté en France.

L'inertie des hélices et moulinets présente la particularité d'être dissymétrique, bien plus grande pour l'arrêt du moulinet en air calme que pour son démarrage dans un vent donné. On peut déterminer ainsi deux constantes de temps, l'une de démarrage correspondant souvent à une constante de temps d'une seconde, l'autre d'arrêt qui peut être de 10 à 50 fois plus grande que la première, suivant l'inertie du système, et qui varie d'ailleurs avec la vitesse de rotation.

Cette dissymétrie s'explique aisément. Au démarrage, l'air à vitesse v, constamment renouvelé, impose aux pales un couple qui ne dépend que des vitesses relatives. Si la ventilation devient nulle, les pales communiquent, au prix d'une faible perte d'énergie cinétique, leur mouvement à l'air environnant, et l'arrêt n'est plus causé que par les très faibles renouvellements de cet air et par sa viscosité. D'où une inertie apparente beaucoup plus grande.

La correction d'inertie des enregistrements anémométriques est donc difficile; les lois de correction sur les moyennes doivent être appliquées avec précaution.

Un anémomètre doit permettre d'obtenir directement, sur un cadran ou sur un enregistreur, la vitesse du vent; plusieurs méthodes sont utilisées pour mesurer la vitesse de rotation des hélices et des moulinets.

Dans de nombreux anémomètres actuels, l'hélice ou le moulinet entraînent l'aimant permanent d'une petite magnéto, constituant un générateur de courant alternatif dans un circuit comportant un redresseur de courant et un galvanomètre gradué en vitesse du vent.

La force électromotrice efficace U engendrée par la magnéto est proportionnelle à la vitesse de rotation de la magnéto, c'est-à-dire au nombre de tours par seconde N du moulinet :

$$U = KN.$$

La loi $N = f(v)$ étant linéaire, un voltmètre donne donc la vitesse du vent sur une échelle linéaire.

Si au contraire on effectue une mesure de courant en utilisant un récepteur de faible résistance par rapport à l'impédance du circuit, cette dernière augmentant avec la fréquence, donc avec la vitesse de rotation du moulinet, on obtient alors une loi $I = f(v)$ telle que la précision de lecture, grande aux faibles vitesses, diminue lorsque la vitesse du vent augmente.

Le vent à échelle fine est donné à distance en dirigeant le courant sur un galvanomètre enregistreur par une ligne à deux fils.

La vitesse moyenne sur 10 mn est obtenue en totalisant pendant cette durée le nombre de contacts établis, grâce à une démultiplication mécanique convenable, placée dans le transmetteur, chaque fois que le moulinet a effectué un certain nombre de rotations.

Un enregistrement discontinu de la vitesse moyenne est facilement obtenu. Dans un modèle, l'enregistreur, relié par une ligne au transmetteur, est alimenté par une pile basse tension qui, à chaque fermeture de contact, débite dans un électro-aimant actionnant alors le cliquet d'une roue à rochets dont l'axe porte une vis sans fin attaquant une roue dentée. Un style muni d'une plume solidaire de l'axe portant cette dernière roue par l'intermédiaire d'un méca-

nisme en permettant le débrayage, donne l'enregistrement de la vitesse moyenne sur un diagramme entraîné par un tambour. Le mouvement d'horlogerie ferme un contact toutes les 10 mn pour commander la remise à zéro du style par débrayage.

Les anémomètres à magnéto tendent à remplacer les dispositifs plus anciens dans lequels l'hélice ou le moulinet commandent la fermeture d'un contact chaque fois qu'un certain nombre de tours était effectué. La cadence des signaux émis (proportionnelle à la vitesse du vent) fut d'abord mesurée par un fréquencemètre mécanique, tel l'anémocinémographe Richard qui équipa de nombreuses stations météorologiques.

Dans certains anémomètres modernes, la fréquence de rotation de l'hélice ou du moulinet est mesurée par un fréquencemètre électrique.

L'anémomètre à moulinet bridé est un moulinet à grand nombre de coupes, mobile autour d'un axe vertical dont la rotation est limitée, le couple de rotation, dû à la pression du vent (proportionnelle à v^2), étant équilibré par la force d'un ressort qui s'exerce d'une manière proportionnelle au carré de la rotation. On obtient ainsi une loi de rotation linéaire en fonction de la vitesse du vent, et la rotation de l'arbre est transmise à un appareil de lecture à cadran ou enregistreur, par un système genre selsyn. Un amortisseur magnétique permet d'obtenir une position d'équilibre stable.

Un autre type d'anémomètre utilise la différence de pressions aérodynamiques sur les deux embouchures d'un tube manométrique dirigé par une girouette et dont une ouverture est disposée face au vent, l'autre horizontale, parallèle au courant.

La différence des pressions dynamiques (P_D) et statique (P_s) est égale à $\rho\, v^2/2$. La vitesse s'exprime donc en valeur absolue par

$$v = \sqrt{\frac{2\,(P_D - P_s)}{\rho}}$$

ρ, masse spécifique de l'air, est connue par la pression atmosphérique et la température de l'air, $P_D - P_s$ est indiqué directement par le manomètre. Sous réserve d'une correction de densité, celui-ci peut donc être étalonné directement en v.

La forme des prises de pression doit être soigneusement étudiée pour que le filet fluide reste aussi parfaitement laminaire que possible. Une turbulence s'installe aisément au voisinage de la prise statique, dont l'effet est de rendre P_s inférieure à la pression théorique. La valeur de $P_D - P_s$ est alors excessive et v est un peu inférieur à la valeur calculée par la formule théorique.

Le tube de Pitot est utilisé comme élément sensible dans l'anémomètre de Dines (1892), sur le principe duquel de nombreux appareils ont été réalisés et sont en service. La différence de pression agit sur la chambre d'un manomètre à flotteur dont le réservoir est rempli d'eau ou, au cas du danger de congélation, d'un liquide spécial incongelable du même poids. On raccorde les conduites de pression à l'appareil de manière que la pression totale provenant de la pointe de la girouette agisse sous le flotteur, et la pression statique au-dessus de lui. Ainsi la pression statique se trouve éliminée, et la position du flotteur ne dépend que de la pression dynamique due à la vitesse du vent. Dans certains modèles, la forme parabolique du flotteur assure la proportionnalité des indications à la vitesse. Le flotteur commande mécaniquement le style de l'enregistreur.

La principale difficulté d'emploi du tube de Pitot est l'obligation de le monter en girouette pour l'orientation de la prise de pression dynamique face au vent. La transmission anémométrique est, de ce fait, peu aisée.

On a réalisé des appareils non orientables avec quatre prises de pression dynamique face aux quatre points cardinaux. L'appareil peut indiquer ainsi à la fois la force et la direction du vent.

Résumé

Les données météorologiques sur les vents en surface constituent souvent la seule documentation existante pour obtenir des indications générales sur le régime des vents au voisinage du sol.

Bien que certains sites soient particulièrement favorables pour utiliser l'énergie éolienne, les indications des anémomètres permettent d'avoir une première idée des disponibilités en énergie, pour des gammes de vitesse déterminées, dans diverses régions.

Le présent mémoire indique comment est effectuée la mesure du vent dans les stations météorologiques. Afin de rendre comparables ces mesures, des recommandations concernant les techniques à utiliser sont éditées par l'Organisation météorologique mondiale (OMM) et publiées dans un *Guide des méthodes d'observation et d'instrumentation météorologiques*.

Toutefois, ces règles ne sont pas encore appliquées universellement, et par exemple on note encore aujourd'hui dans les diverses installations de mesure des hauteurs allant de 5 à 25 mètres. Il y a donc lieu, dans les études des diagrammes d'un anémomètre, de tenir compte du niveau auquel est placé l'appareil.

Différents types d'anémomètres ont été et sont encore en service; les capteurs de la plupart d'entre eux sont basés sur l'action du vent sur les hélices et les moulinets, ou encore sur la pression dynamique exercée par le vent.

Une hélice, à axe horizontal maintenu face au vent par une girouette, prend un mouvement de rotation sous l'action de la pression exercée sur les pales par le vent. Si l'on étalonne le moulinet, on obtient une relation de la forme $V = KN + v_0$, (où N est le nombre de tours et v_0 le seuil de démarrage. On

montre que le meilleur rendement est obtenu en utilisant des pales hélicoïdales.

Les moulinets utilisés pour la mesure du vent sont généralement composés de trois ou quatre coupes, hémisphériques ou coniques, fixées chacune à un bras, solidaire d'une embase centrale fixée sur l'axe vertical de rotation. L'ouverture des coupes se trouve dans des plans verticaux passant par l'axe de rotation formant entre eux des angles égaux.

L'inertie de ces organes présente la particularité d'être dissymétrique, bien plus grande pour l'arrêt du moulinet en air calme que pour son démarrage dans un vent donné. On peut déterminer ainsi deux constantes de temps, l'une de démarrage correspondant souvent à une constante de temps d'une seconde, l'autre d'arrêt qui peut être de 10 à 50 fois plus grande que la première, suivant l'inertie du système, et qui varie d'ailleurs avec la vitesse de rotation.

Un autre type d'anémomètre utilise la différence de pressions aérodynamiques sur les deux embouchures d'un tube manométrique dirigé par une girouette et dont une ouverture est disposée face au vent, l'autre horizontale, parallèle au courant.

La différence des pressions dynamiques (P_D) et statique (P_s) est égale à $\rho\, v^2/2$. La vitesse s'exprime donc en valeur absolue par

$$v = \sqrt{\frac{2\,(P_D - P_s)}{\rho}}$$

ρ, masse spécifique de l'air, est connue par la pression atmosphérique et la température de l'air, $P_D - P_s$ est indiqué directement par le manomètre. Sous réserve d'une correction de densité, celui-ci peut donc être étalonné directement en v.

WIND MEASUREMENT IN METEOROLOGY

Summary

The meteorological data on the winds at the ground are often the only existing means of obtaining general indications about the wind régime near the ground.

Although certain sites are particularly favourable for harnessing the wind energy, the anemometer readings give a provisional idea of the available energy resources for definite ranges of wind speed in various regions.

This paper indicates the way in which the wind is measured at meteorological stations. To make these measurements comparable, recommendations on the techniques to be employed have been issued by the World Meteorological Organization (WMO), and published in a *Guide to Methods of Meteorological Observation and Instrumentation*.

These rules, however, are not yet universally applied. For instance, even today, various measuring instruments are placed at heights ranging from 5 to 25 m. The height of the instrument above the ground must therefore be taken into account when studying anemometer graphs.

Various anemometer types have been used in the past and are still in service. In most cases, their collectors are based on the action of the wind on airscrews or windmills, or on the dynamic pressure exerted by the wind.

An airscrew with a horizontal axis, held by a vane to face the wind, undergoes a motion of rotation under the action of the wind pressure against its blades. If the windmill is calibrated, one gets a relation of the form $V = KN + v_0$, where N is the number of turns, and v_0 is the threshold at which the mill starts. It is shown that the best power output is obtained by the use of helicoidal blades.

The windmills used for wind measurement generally consist of three or four cups, hemispherical or conical, each attached to an arm which is integral with a central base fixed on the vertical axis of rotation. The openings of the cups lie in vertical planes passing through the axis of rotation and forming equal angles between one another.

The inertia of these elements has the peculiarity of being asymmetric, since it is considerably greater for the stoppage of the mill in calm air than for its starting in a given wind. Two time constants may thus be determined, one of starting, often corresponding to a time constant of 1 sec, the other of stopping, which may be from ten to fifty times as great at the former constant, depending on the inertia of the system. This also varies with the rotational speed.

Another anemometer type makes use of the difference in the aerodynamic pressure on the two openings of a vane-controlled manometer tube, one of these openings being located facing the wind, and the other horizontally, parallel to the airflow.

The difference between the dynamic pressures P_D and the static pressure (P_S) is equal to $\rho v^2/2$. The speed is thus expressed in absolute value by

$$v = \sqrt{\frac{2\,(P_D - P_S)}{\rho}}$$

ρ, the specific mass of the air, is known from the atmospheric pressure and the air temperature, while $P_D - P_S$ is indicated directly by the manometer. Subject to a density correction, this may be calibrated directly in terms of v.

SOME ASPECTS OF WIND PROFILES

Sverre Petterssen *

Since the power of the wind is proportional to the cube of the wind speed, knowledge of the normal wind profile over potential turbine sites is essential for efficient exploitation of the energy of the wind. The purpose of this paper is to summarize present knowledge of the wind profiles near the ground, particularly with a view to identifying gaps in our knowledge which we may hope to eliminate within the relatively near future. For much valuable information on wind structures in relation to engineering, reference is made to recent papers by Biggs, Vincent, Blackadar, Cramer, Segner and Cohen, published by the American Meteorological Society as Meteorological Monographs Vol. 4, No. 22, 1960, entitled *Topics in Engineering Meteorology*.

Profiles above level ground

Prandtl's profile

Under neutral stability the formula

$$u = k^{-1} u_* \, ln \, (z \, z_0^{-1}) \tag{1}$$

has been found to be completely satisfactory up to at least 10 m above level ground. In this formula k is the von Kármán constant ($= 0.4$), u_* is the friction velocity (Schubspannungsgeschwindigkeit), u is the wind speed at the height z, and z_0 is the roughness parameter with dimension of length. Also,

$$u_*^2 = \alpha \, \tau_0 \tag{2}$$

where α is specific volume, and τ_0 is the drag of the wind per unit area of the surface.

The roughness parameter (z_0) has been determined for a variety of land surfaces, and our knowledge of it is generally satisfactory, provided that the roughness elements are reasonably small. For large obstacles, such as buildings, trees, etc., an improvement may be introduced by subtracting a height (say z_1) from all measured heights, thus replacing z by $z - z_1$ The length z_1, which is called the zero level displacement, must be determined from local observations.

The Prandtl profile is satisfactory only when the stratification of the surface layer is in a state of neutral equilibrium. In the case of stability (e.g., by night) the wind increases more rapidly with elevation, and in the case of instability (e.g., on sunny days) the increase is slower than indicated by the formula.

The height above the ground to which formula (1) may be applied has not been determined satisfactorily. In the case of neutral equilibrium the formula may be expected to apply up to about 15 m (50 ft). In the case of highly stable or unstable stratifications, the deviation of the wind from the Prandtl profile may be appreciable above about 2 m above the ground.

The profiles of Deacon and Palm

Deacon (3) proposed an empirical formula which was intended to encompass neutral as well as non-neutral stratifications. From observations, Deacon derived the expression

$$u = k^{-1} u_* \, (1 - \beta)^{-1} \, [(z/z_0)^{1-\beta} - 1] \tag{3}$$

where $\beta \lesseqgtr 1$ according as the stratification is stable, neutral, or unstable. If Deacon's formula is expanded into a power series, Prandtl's formula is obtained as a first approximation. Though Deacon's formula may be useful for interpolation, its extrapolative ability is rather limited, since β appears to be variable with height or with the wind profile itself.

The shortcomings of the foregoing formula have been clarified in principle by Palm (9) who, after an elegant analysis of the Reynolds stresses, extended his arguments to eddy diffusion and derived the following expression for the wind shear

$$\frac{\partial u}{\partial z} = C \, z^{-1 + \sigma \varepsilon} \tag{4}$$

Here, C is a constant, while ε is a slowly varying parameter, and σ is a measure of the static stability, such that

$$\sigma = - g \frac{1}{\theta} \frac{\partial \theta}{\partial z}$$

where g is the acceleration of gravity and θ is potential temperature.

If ε is taken as a constant, Palm's expression is essentially the same as Deacon's formula.

Essentially, ε represents a statement concerning the kinematics of the turbulent flow, and in the absence of such knowledge ε must be determined from observations. Palm presented no observational data and the success of his formula in predicting wind profiles remains to be determined.

The profiles of Monin, Obukhov, Ellison and Swinbank (8, 4, 13)

An imaginative approach to the problem has been presented by Monin and Obukhov (8) who, from

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similarity considerations, suggested the relationship

$$\frac{\partial u}{\partial (ln z)} = k^{-1} u_* S \tag{5}$$

Here S is a universal function of the nondimensional ratio z/L where L is defined by

$$L = \rho u_*^3 c_p T (kgH)^{-1} \tag{6}$$

The symbols have the following meanings:

c_p = specific heat of air at constant pressure
ρ = density
T = temperature in °K
H = the upward eddy flux of heat.

For small values of the ratio z/L, S can be replaced by

$$S = 1 - m\, z/L \tag{7}$$

where m is to be determined from observations. The corresponding velocity profile is

$$u = k^{-1} u_* [ln\ (z z_0^{-1}) - mz\, L^{-1}] \tag{8}$$

This representation has the advantage that the profile is not limited to the Prandtl layer (below 10 to 15 m) but may be extended to such heights as are of interest to wind turbines. Monin and Obukhov suggested that $m = 0.6$ would give satisfactory results from small negative values of H (downward flux) to very large positive values with large super-adiabatic lapse rates in the surface layer.

The Monin-Obukhov representation has the distinct disadvantage that L is difficult to determine since the heat flux is not directly observed. This difficulty was circumvented by Ellison (4), who derived the following equation for

$$S^4 + \gamma \frac{z}{L} S^3 = 1 \tag{9}$$

Here γ is a universal constant which must be determined from observations. The ratio γ/L is now replaced by an equivalent ratio γ'/L' such that

$$L' = - u_* \theta \frac{\partial u}{\partial z} \Big/ kg \frac{\partial \theta}{\partial z} \tag{10}$$

and γ' has to be determined empirically. Panofsky, Blackadar and McVehil (10) produced some evidence to show that γ' is about 18, but accurate determination is still lacking.

The height to which the Ellison profile may be extended has not been determined, but there is some indication (1) that it may be valid up to, and possibly beyond, 100 m (300 ft).

Swinbank (13) introduced an hypothesis which permitted him to represent in one term the contributions from the mean motion and from buoyancy. By measuring the wind at four levels, he eliminated $u_* k^{-1}$ and determined L (and H) from the measured wind. He found remarkably consistent results below 15 m for a large range of stabilities.

The Power-Law profile

The wind distribution above the Prandtl layer and below about 150 m (500 ft) has been found to obey the relation

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p \tag{11}$$

where u_1, is the velocity at height z_1, and p is a factor that varies with the stability of the air. With neutral equilibrium $p = 0.14$ (or 1/7), and with such stable stratification as occurs toward the end of a radiative night p may be about twice as large. The value of p varies also with the roughness of the ground.

Profiles over ridges

The profiles discussed in the foregoing section have one feature in common, namely, that they all give a monotonic increase of wind speed with height, with the result that the problem of selecting a turbine site on level land is relatively simple. On the other hand, when the wind blows across a ridge, a variety of wind profiles may occur, depending upon the angle of incidence of the wind relative to the axis of the ridge, the geometry of the cross section of the ridge, the roughness of the surface, etc. About 25 years ago, the writer had occasion to measure the winds in the vicinity of some anemometer sites along the west coast of Norway and found that for relatively small islands the wind about 7 m above the crest was stronger than the undisturbed wind at the same height at some distance from the island. In one case the speed-up ratio of 1.35 was found. Though the wind profile could not be determined, it was concluded that a wind maximum existed a short distance above the crest. These early measurements led the writer to believe that a speed-up factor of, say, 1.2 would be a relatively common occurrence. Later, work in connection with the Smith-Putnam wind turbine proved disappointing in the sense that speed-up factors in excess of unity appeared a relatively rare occurrence over large mountain ridges in New England.

The mechanism of the speed-up process is well understood, but the natural phenomenon is far more complex than any theoretical model. Some insight into the mechanism was first provided by Blasius (2) who considered the flow over a cylindrical body placed in a stream perpendicular to its axis. Blasius' analysis, with later extensions, notably by Hiemenz (5) and Howarth (6), is well known and need not be recapitulated here. The essential features over the crest of the semicylinder are as follows. Within the boundary layer the velocity (u) varies from zero to U as the nondimensional height

$$h = \frac{y}{R} \sqrt{\frac{U_\infty R}{\nu}}$$

varies from zero to about 2.5. Here y is the height above the crest, R is the radius of the cylinder, U_∞ is the undisturbed velocity, and ν is the kinematic viscosity. Above the boundary layer the velocity

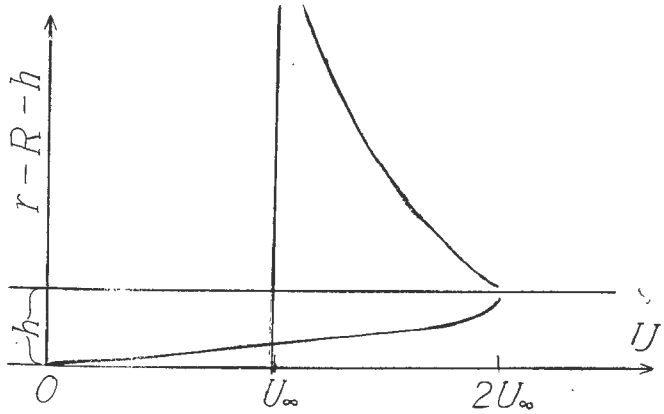

Figure 1. Sketch showing the variation of the wind within and above the boundary layer over the crest of semi-cylinder with radius R (not to scale)

distribution along the vertical above the crest is approximated by

$$U = 2\,U_\infty \left[1 + \left(\frac{R}{r}\right)^2\right]$$

where $r - R$ is the height above the crest. The essential features of the velocity profile are shown in figure 1.

In 1941 von Kármán (7) provided numerical estimates of the speed-up factor over smooth ridges as a function of their height-width ratio and found the values indicated in table 1. According to these figures it would be reasonable to expect the speed-up factor to approach 2.0 as the height-width ratio approaches that of a semicylinder.

Another set of interesting data was obtained from wind tunnel tests of models of certain mountains in New England. In all cases a speed-up factor in excess of unity was found, though the values varied somewhat with the wind direction. Some typical values are given in table 2, which also shows some measured speed-up factors for mountain ridges in New England.

Recalling that the power is proportional to the cube of the wind speed, the deviations between the observed speed-up factors and those determined through model tests are very large; for example, at Pond the cube of the speed-up factors is 0.59 and 2.15, respectively.

Table 1. Effect of the geometry of the ridge upon the speed-up factor (after Putnam, 1948)

Height of ridge as a percentage of the width of the base	*Speed-up factor*
4.5	1.15
7.5	1.23
12.0	1.37
17.5	1.6

Table 2. Speed-up factors at various sites on mountain ridges in New England (after Putnam, 1948)

Station	*Height above sea level (ft)*	*Speed-up factor*	
		Observed	*Wind-tunnel*
Pond	1 500	0.84	1.29
Biddie I	2 070	0.90	
Grandpa's	2 130	0.88	
Biddie Proper	2 150	0.84	
Seward	2 220	0.94	
Chittenden	2 490	0.89	
Herrick	2 700	0.92	
Glastenbury	3 900	1.04	1.44
Pico Peak	4 110	1.10	
Mt. Washington	6 430	1.47	1.30

In retrospect it appears that the observed speed-up factors shown in table 2 are much in doubt, the uncertainties being due to difficulties in determining the undisturbed wind at the level concerned. The apparent increase in the speed-up factor with elevation above about 3 000 ft should be accepted *cum grano saldo*, for at the time when these estimates and measurements were made, our knowledge of the normal increase with height of the free-air wind was inadequate. In the opinion of the writer there is really no firm observation to show that speed-up factors in excess of unity are obtainable over large mountain ridges. On the other hand, there appears to be some evidence in support of the view that the wind over relatively small ridges tends to exhibit a wind maximum of the general type shown in figure 1, though speed-up factors in excess of 1.3 might be relatively infrequent.

Conclusions

The foregoing discussion seems to justify the conclusion that our knowledge of the wind profiles over ridges and other terrain features is very meagre and that much research must be completed before one can hope to provide models which will predict wind profiles with satisfactory results.

Over relatively level land, studies of profiles of the Monin-Obukhov-Ellison type seem to offer good chances of results, particularly since they are based upon sound physical arguments and seem to be capable of spanning the layer of air to be swept even by large turbines.

Over ridges and other obstacles the wind profiles are largely unknown and a first objective might be to determine the dimensions of simple ridges below which speed-up factors in excess of unity will be found. The ultimate goal would be to develop criteria for selecting sites without costly and time-consuming field observations.

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Summary

A review of present knowledge of the shape of wind profiles near the earth's surface is presented. In connection with selection of wind turbine sites over level land, it is maintained that the models proposed by Monin, Obukhov and Ellison, and also that outlined by Palm, deserve particular attention since they are well rooted in physical principles and appear to be able to span the layer swept even by large turbines. In regard to selection of turbine sites on ridges, it is maintained that present knowledge is quite inadequate. Some evidence is presented in support of the view that a speed-up factor in excess of unity will normally be found over relatively small ridges, but there is little evidence to indicate that such factors are associated with mountains of the size investigated in New England in connection with the Smith-Putnam Wind Turbine. A summary of the analyses of the wind observations made in New England for the Smith-Putnam Wind Turbine Project will be presented in a separate paper by Professor Karl O. Lange.

QUELQUES ASPECTS DES SONDAGES ANÉMOMÉTRIQUES

Résumé

On donne, dans le présent mémoire, une revue de nos connaissances actuelles sur la forme des profils anémométriques à la surface de la terre. En liaison avec le choix d'emplacements pour les turbines éoliennes dans des régions plates, on avancera le point de vue que les modèles proposés par Monin, Obukhov et Ellison, ainsi que celui qu'a décrit Palm, méritent de recevoir une attention particulière, car ils reposent sur des principes physiques bien établis et semblent de nature à satisfaire les exigences des modèles de turbines même les plus gros. En ce qui concerne le choix d'emplacement de turbines sur des crêtes, on soutient que les connaissances actuelles dont on dispose sur la question sont tout à fait insuffisantes. On présente certaines indications à l'appui du point de vue suivant lequel un facteur d'accélération supérieur à l'unité est normalement trouvé pour des crêtes relativement petites. En revanche, on dispose de bien peu de preuves indiquant que de tels facteurs s'appliquent à des montagnes des dimensions étudiées en Nouvelle-Angleterre en liaison avec la turbine éolienne de Smith-Putnam. Un résumé des analyses des observations anémométriques faites en Nouvelle-Angleterre dans le cadre du projet de turbine de Smith-Putnam sera présenté dans un autre mémoire par le Professeur Karl O. Lange.

WIND POWER RESOURCES OF INDIA WITH PARTICULAR REFERENCE TO WIND DISTRIBUTION

K. P. Ramakrishnan and S. P. Venkiteshwaran *

When one undertakes to assess the total power that can be developed in any geographical region by utilizing the wind which is blowing over the country, one would like to know the wind prevailing at every point over the whole country where a windmill could be installed. Such extensive observations are obviously not feasible. As a matter of fact, many comparatively windier spots may at the same time be difficult of access and therefore observations at such spots may be well nigh impossible. Even when such difficult sites are left out of consideration, there can still be too large a number of sites where wind observations could be made.

In the initial stages of assessing the wind power potentialities, most countries have, therefore, depended mainly on the wind data that have been collected by their respective Meteorological Services. India has been no exception to the above rule and although

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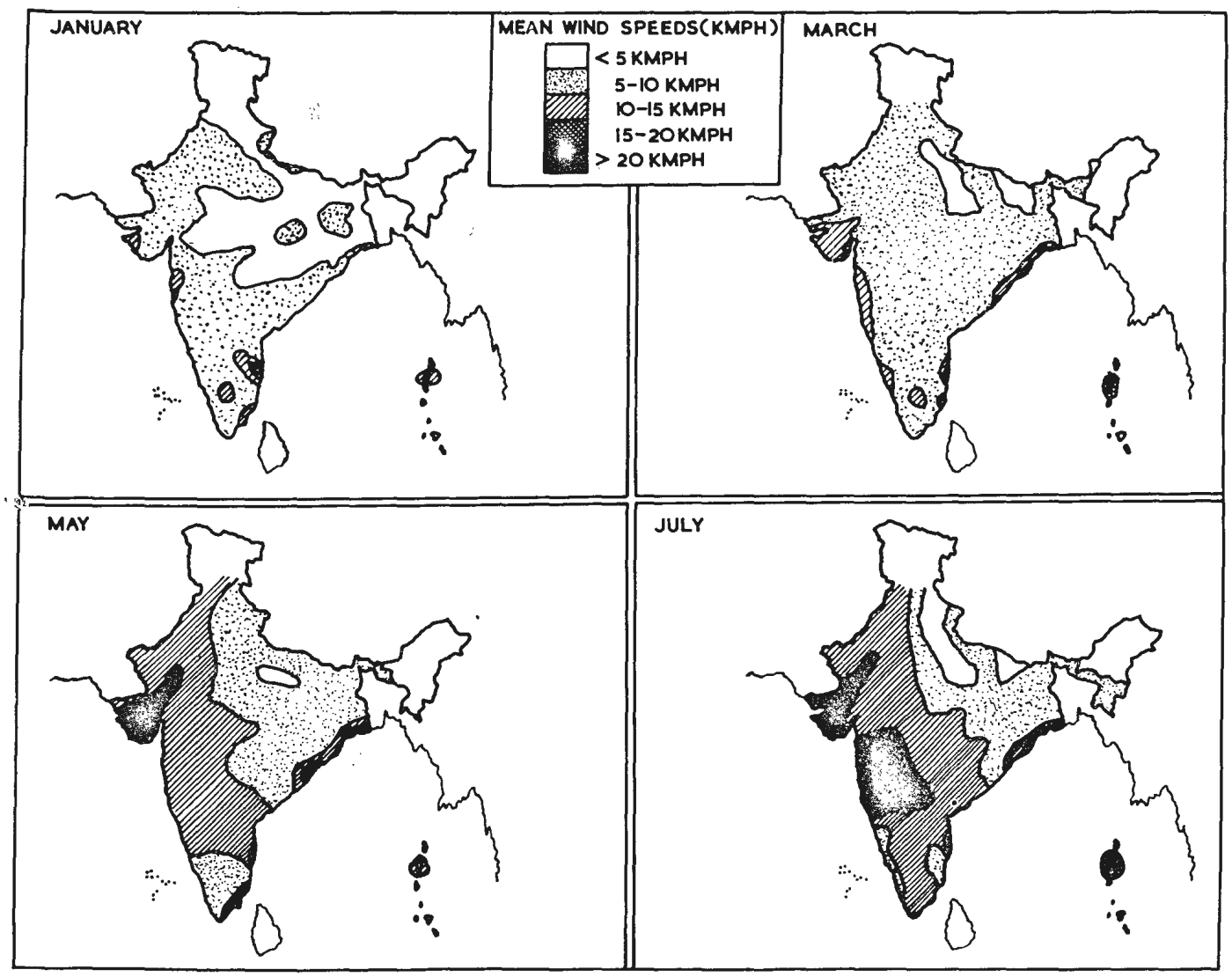

Figure 1

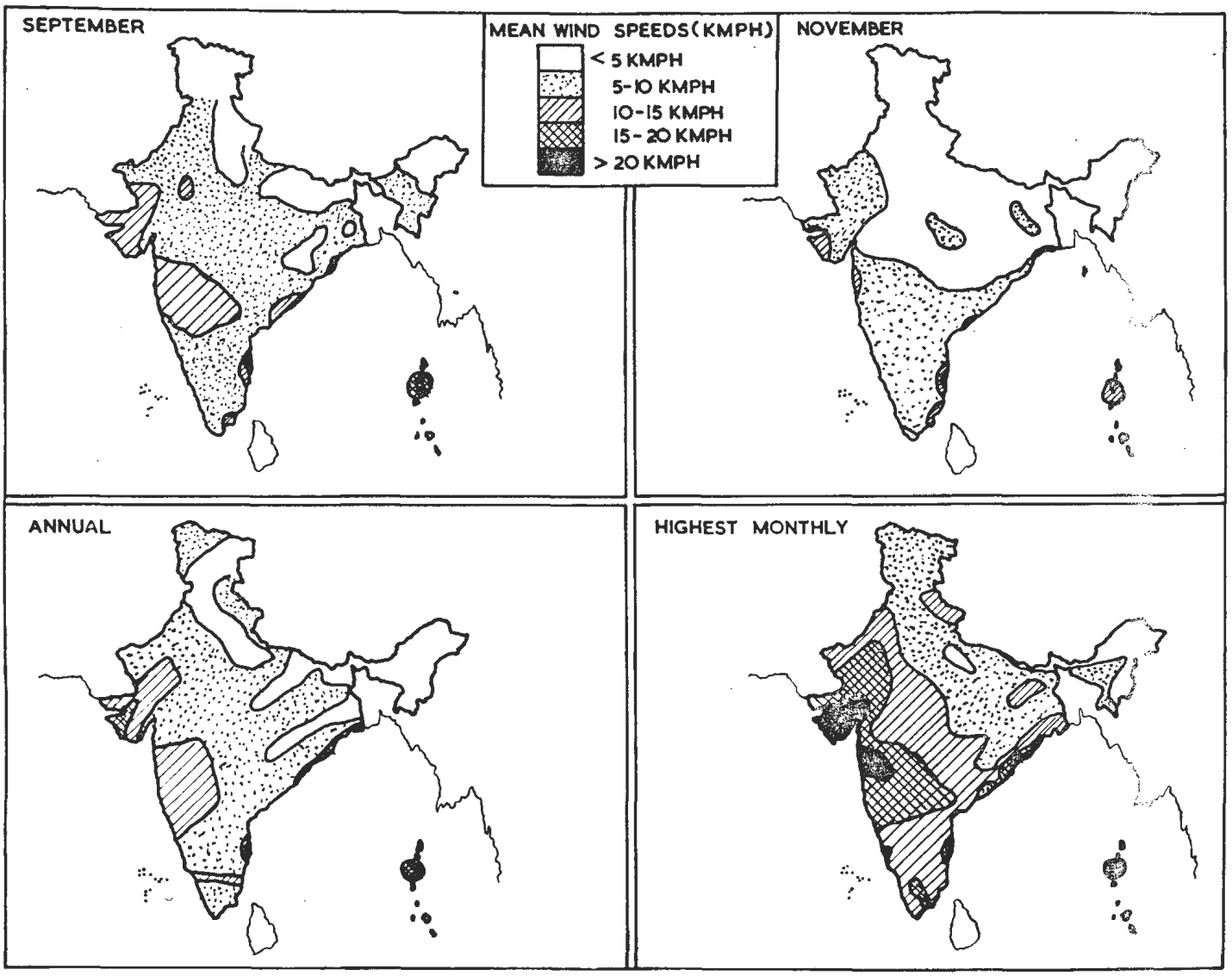

Figure 2

it is realised that meteorological observation stations have not been chosen from the point of view of their " wind-worthiness ", it has been accepted that the first step is to make the best use of all information on winds that has been collected over extended periods by the Meteorological Department. As wind power utilization schemes make headway, it is hoped that wind data for sites specially selected on account of their favourable wind characteristics will also be accumulated. The wind data used in the present paper are entirely those collected by the India Meteorological Department and kindly made available to the National Aeronautical Laboratory by them.

Indian wind data had been studied earlier from the point of view of the possibilities of their utilization as a source of power in several papers. Special mention must be made of those by V. D. Iyer (1), Bhatia (2), Nilakantan and Varadarajan (3) and Ramdas and Ramakrishnan (4). In the preparation of the present paper, considerable use has been made of two reports by Golding (5, 6) on the generation of electricity by wind power.

Wind data from non-recording anemometers

Robinson cup counter type anemometers have been functioning at meteorological observatories in India for more than 50 years. Besides being used for giving instantaneous speeds at intervals of 3 minutes at the standard synoptic hours, the total runs in 24-hour periods from 0 800 hrs (0 830 in recent years) of one day to 0 800 hours of the next have also been recorded. Long-term average values of speeds, based on these total runs for the different months as well as the whole year, based on all available data up to the end of 1940 have been published in the Climatological Tables of the India Meteorological Department. Using values of the stations in India, about 150 in all, from this publication, maps of isovents for the ranges 0-5, 5-10, 10-15, 15-20 and > 20 kmph were

drawn for each of the 12 months and the whole year. In addition, a composite map based on the highest monthly mean speed for each station, irrespective of the month in which the highest speed occurred, has also been prepared.[1] The maps for alternate months, year and highest monthly mean are shown in figures 1 and 2. For windmill installation programmes of India in the immediate future, first preference is being given to localities which according to the isovent maps have an annual mean speed of at least 10 kmph.

It is realised that there may be many individual sites outside the broad regions which these figures show to be windy enough for the exploitation of wind power. However, such sites will have to be surveyed by obtaining hourly values of wind speeds for a minimum period of two years before installation of wind power plants could be decided upon. For instance, the detailed analysis of hourly wind speeds of Bhopal has shown that it has a wind power potentiality much greater than that indicated in figures 1 and 2.

Wind data from recording anemographs

About 25 stations of the India Meteorological Department are currently equipped with Dines type pressure tube anemographs. Figure 3 shows these stations.[2] The hourly values of wind speed from the records of these instruments are tabulated by the Meteorological Department as a matter of routine. The hourly values for selected stations for periods

[1] The month of highest speed was generally April, May, June or July except in a small portion in the south-east of India where the highest speed occurred in November-December.

[2] Where two instruments function at different sites of same town, only one has been shown in figure 3.

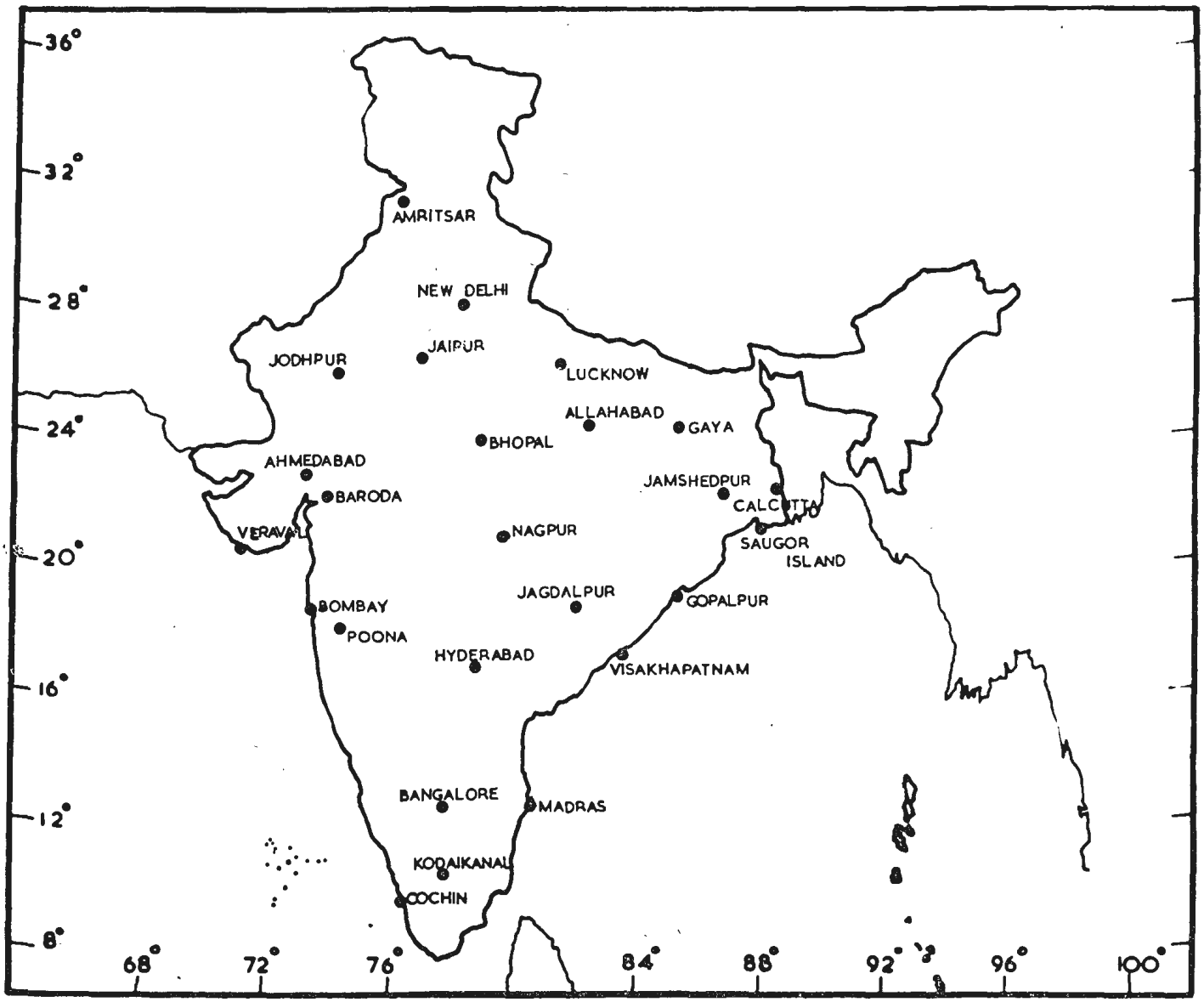

Figure 3. Anemograph stations of the India Meteorological Department

of 3 to 4 years have been obtained from them and have been analysed from the point of view of wind power utilization. The period 1951-53 has been generally chosen. Other periods have been used only in cases where records for the period 1951-53 were either non-existent or discontinuous. The results of analysis of the data for a dozen stations have been incorporated into this paper. These stations are: Allahabad, Bangalore, Bhopal, Bombay, Cochin, Jaipur, Jodhpur, Madras, Nagpur, New Delhi, Veraval, Visakhapatnam.

In particular sections, similar data for three more stations, i.e., Saugor Island, Belgaum and Deesa, extracted from V. D. Iyer's paper (1), have also been used.

Using average frequencies of occurrence of different speeds for the 3-year period, annual velocity-duration curves, giving the number of hours in the whole year when speeds exceeding different values are reached were drawn. In order to make the data of different months comparable, the frequency values for each month were reduced to a common duration of 720 hours and so the total number of hours for the whole year is taken as 8 640 only. The annual velocity-duration curves of selected stations are shown in figures 4 and 5.

Usable energy of the wind

Using the frequencies of occurrence of different speeds in the average year, values of the maximum usable energy, i.e. 59.3 per cent of the energy in the wind in kilowatt-hours for a swept area of 30 sq metres have been calculated for the 15 stations. In these calculations, an allowance has been made for the lower air density prevailing in India near the ground which is about 94 per cent of the corresponding value over England/Europe. The energy in the wind in watt-hours for these conditions works out to

$$\frac{\Sigma V^3 N}{2.59}$$

where V is expressed in kmph and N is the number of hours in which each speed value occurs. The maximum usable energy is 59.3 per cent of this.

The maximum usable energy values in different speed ranges 8-16 kmph, 17-24 kmph, 25-32 kmph, 33-40 kmph, 41-48 kmph and the total for the speed

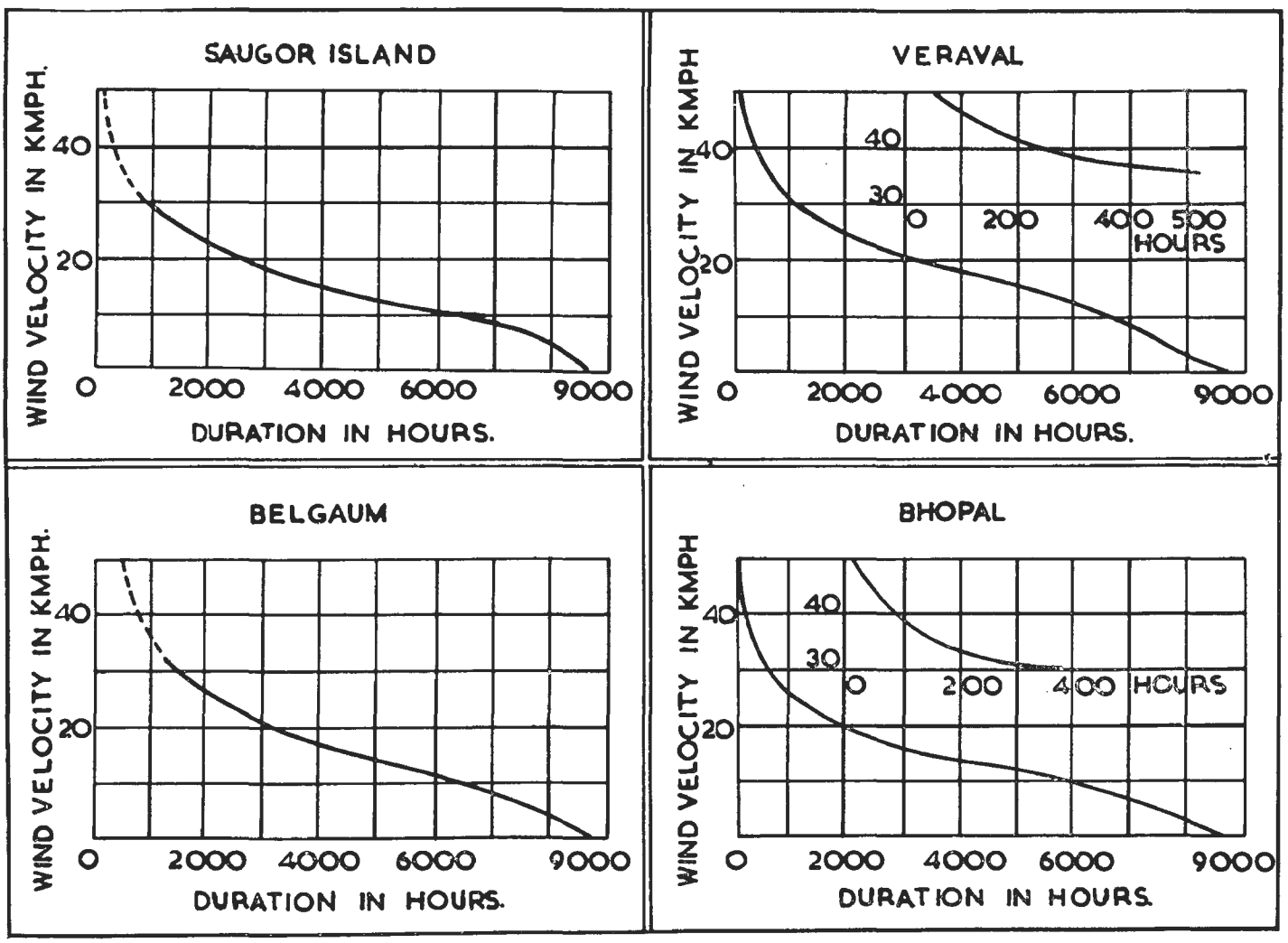

Figure 4. Annual velocity-duration curves

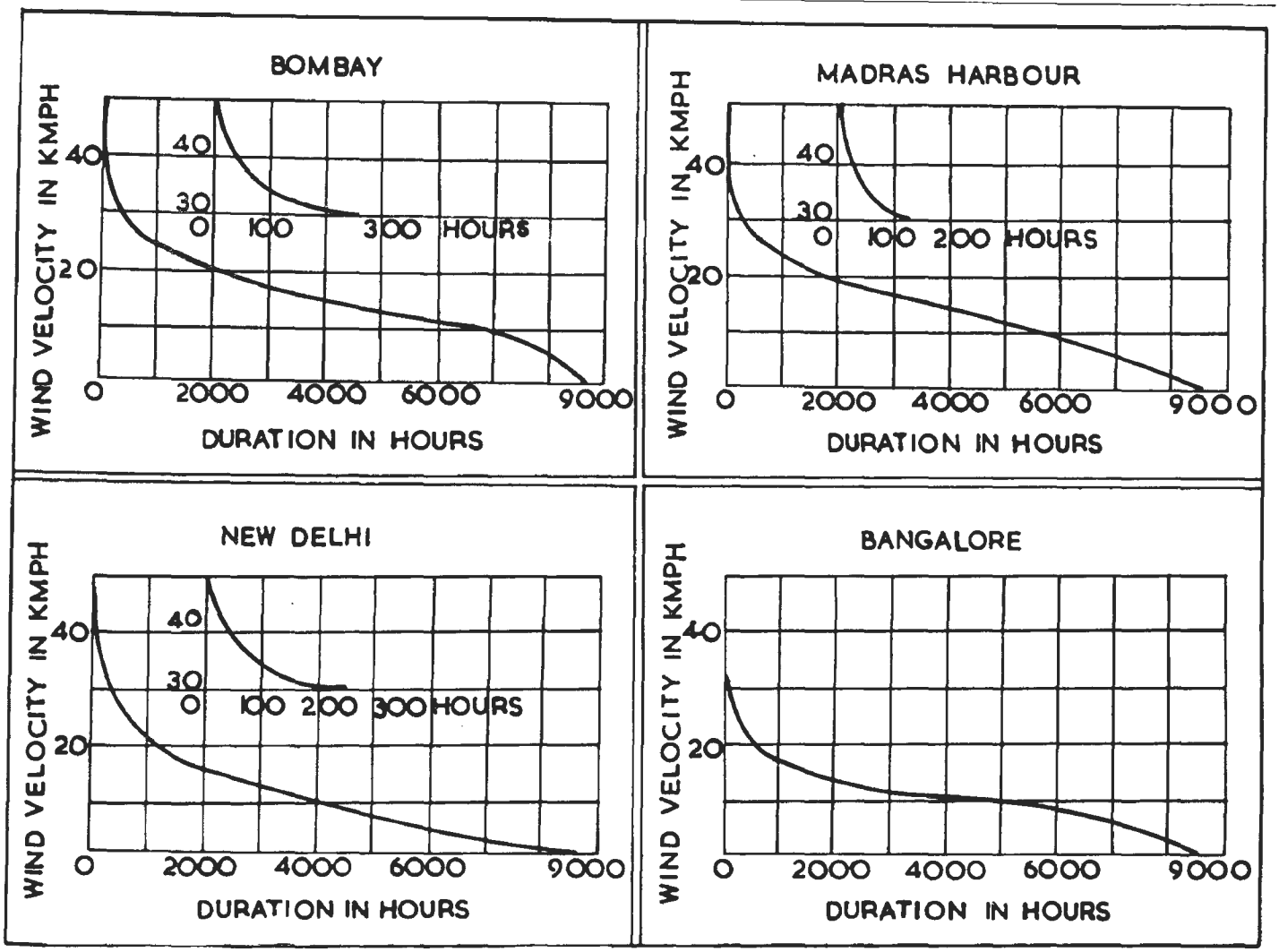

Figure 5. Annual velocity-duration curves

Table 1. Maximum usable energy (59.3 per cent) in wind in kilowatt hours per year for swept area of 30 sq metres in different speed ranges

Station	*8-16 kmph*	*17-24 kmph*	*25-32 kmph*	*33-40 kmph*	*41-48 kmph*	*8-48 kmph*	*Annual mean vel., kmph*
1. Saugor Island [a]	1 131	4 051	17 020	—	—	22 202	15.3
2. Veraval	1 389	4 421	61 177	5 146	3 078	20 246	16.6
3. Belgaum [a]	1 044	3 868	13 260	—	—	18 172	12.0
4. Bhopal	1 783	3 153	3 377	1 483	811	10 607	12.9
5. Bombay	2 114	3 998	2 660	886	249	9 907	14.1
6. Madras Harbour	1 925	3 951	2 193	348	222	8 639	12.7
7. Deesa [a]	1 107	2 496	3 618	—	—	7 221	12.0
8. New Delhi	1 272	1 807	2 021	718	275	6 093	9.2
9. Jodhpur	1 604	1 828	1 308	190	64	4 994	9.5
10. Visakhapatnam	1 067	1 630	1 000	53	—	4 220	7.1
11. Cochin	1 496	1 656	720	82	—	3 954	9.0
12. Nagpur	1 010	1 278	943	183	—	3 414	7.6
13. Bangalore	1 886	1 041	318	—	—	3 245	9.5
14. Allahabad	977	669	652	57	40	2 395	6.6
15. Jaipur	1 224	850	238	31	—	2 343	8.9

[a] The data for these stations have been taken from V. D. Iyer's paper in which all cases above 32 kmph have been given as a single group. The figures in the last two columns are therefore underestimates for these stations. Also a part of the energy indicated under speed groups 25-32 actually relates to higher speed groups.

range 8-48 kmph have been given in table 1. They are also shown diagrammatically in figure 6. An actual machine, of course, will be able to generate only about 1/5 to 1/4 of these values. It is assumed that a wind-driven machine will not be effective at wind speeds below 8 kmph. The annual average wind speeds, worked out at the same hourly values, are given in the last column.

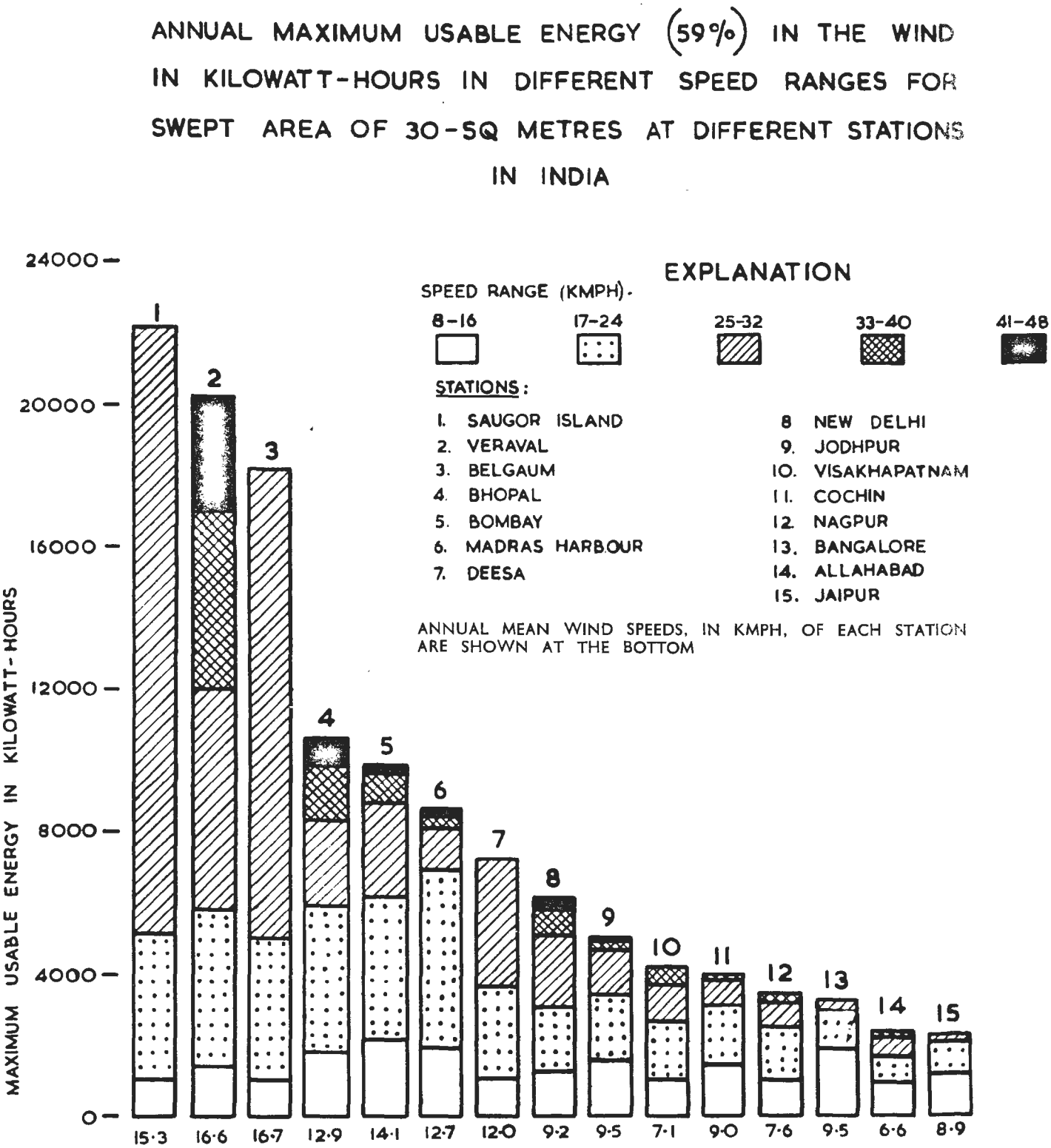

Figure 6

The stations are arranged in the descending order of total energy yield. It will be observed that the annual average wind speed does not strictly follow the same order.

It may be mentioned that in the case of three stations, data for which have been taken from V. D. Iyer's paper (1), all speeds above 32 kmph are grouped together and therefore the total energies and annual average wind speeds for these three stations are rather under-estimates. Further, a part of the energy shown in the speed group 25-32 kmph actually relates to higher speed groups.

The distribution of the values of maximum usable energy over different speed ranges will in due course

be of use to decide the most suitable speed ranges within which wind-driven machines may be adapted for the different stations.

Energy pattern factor

The energy pattern factors, defined by Golding and others as the ratio:

$$\frac{\text{actual energy available}}{\text{energy from steady wind of average velocity}}$$

for the average year, have also been worked out for the above-mentioned 15 stations and they are given in table 2. The main utility of the energy pattern factor is that if it is found that the energy pattern factors at different stations in a region do not vary much, then for that region the annual average wind speeds may be used as a good enough index of the annual energy derivable, thus saving elaborate analysis of wind data. The variations in energy pattern factors for the stations worked out are quite significant, particularly at the stations having less energy potentiality.

Spells of low wind

It has been well recognised by all workers on the subject of wind power utilization that the wind is an inexhaustible but undependable source of energy. Some provision for alternative arrangements when there is insufficient wind to work a machine has therefore to be made, whenever a continuous output of power is expected from the machine. Where a wind-driven machine is made to pump water, the water may be stored for use at times when there is insufficient wind and where it is made to generate electricity, the electricity has to be stored in storage batteries. When the wind data of a station are therefore studied from the point of view of utilization of wind power, it is necessary to consider its dependability also.

Table 2. Annual energy pattern factors

Station	*E.P.F.*
1. Saugor Island	3.1
2. Veraval	2.2
3. Belgaum	2.0
4. Bhopal	2.5
5. Bombay	1.8
6. Madras Harbour	2.2
7. Deesa	2.2
8. New Delhi	4.1
9. Jodhpur	3.1
10. Visakhapatnam	5.5
11. Cochin	2.7
12. Nagpur	4.2
13. Bangalore	2.0
14. Allahabad	4.3
15. Jaipur	1.8

From this point of view, in the tables of hourly wind speeds of the different stations, the periods when wind speed was below 8 kmph were marked out. A speed of 8 kmph has been arbitrarily chosen as a critical speed below which a wind-driven machine cannot produce much useful work. Frequencies of occurrence of such spells (or continuous stretches) lasting for one hour, two hours, three hours, etc. respectively, were prepared for each month and year. These frequencies, grouped into spells of 1-5 hours, 6-10 hours etc., up to 46-50 hours and over, taking the year as a whole and averaged over a three-year period, are given in table 3. It will be observed from the meteorological data available that Veraval and Bombay are the most dependable stations. At these two stations, the numbers of occasions per year when a windmill will remain idle for more than 10 hours at a time are 11 and 5 respectively, while the longest periods for which a windmill will remain idle at a time are 17 and 16 hours respectively. These two stations stand high from the point of total yield of

Table 3. Average number of spells of low wind (< 8 kmph) of different durations during the whole year

Duration of spell (hours)	*Station number (names below)*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
1- 5	421	509	370	380	514	536	318	711	548	600	407	596
6-10	49	73	37	73	102	105	65	129	113	106	93	140
11-15	10	33	4	31	68	38	100	64	77	33	74	80
16-20	1	21	1	12	31	21	97	11	39	10	80	37
21-25	—	3	—	—	9	6	10	1	21	1	28	6
26-30	—	—	—	—	1	1	—	1	—	—	—	—
31-35	—	—	—	1	4	8	3	—	4	3	6	8
36-40	—	—	—	1	3	4	4	—	7	3	2	7
41-45	—	2	—	1	15	5	6	—	7	—	17	6
46-50	—	—	—	1	5	5	1	—	5	1	10	1
> 50	—	1	—	2	8	10	8	—	16	3	7	2
Duration of longest spell in hours	17	69	16	68	83	155	148	29	188	85	91	60

Station names : 1, Veraval; 2, Bhopal; 3, Bombay; 4, Madras; 5, New Delhi; 6, Jodhpur; 7, Visakhapatnam; 8, Cochin; 9, Nagpur; 10, Bangalore; 11, Allahabad; 12, Jaipur.

Table 4. Theoretically calculated quantities of water (in kilolitres) that can be pumped daily by a windmill of swept area 30 sq metres from a depth of 10 metres at Veraval (India) (based on hourly wind speeds of 1958). Output of windmill assumed to be 20 per cent of maximum usable energy in wind

Dates	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
1 . .	6	40	143	271	196	136	323	294	344	6	108	40
2 . .	22	107	122	182	188	78	199	218	458	15	49	118
3 . .	10	116	199	168	165	190	576	167	359	25	22	212
4 . .	50	74	138	332	60	343	1 059	291	45	103	58	164
5 . .	193	107	112	300	208	584	613	588	116	199	260	76
6 . .	175	84	102	344	83	382	477	920	416	236	84	102
7 . .	98	99	74	367	121	129	324	587	967	210	30	37
8 . .	9	199	137	226	110	78	1 280	18	798	103	63	14
9 . .	23	147	287	201	124	223	2 424	23	424	356	223	19
10 . .	149	157	159	172	157	430	1 489	30	500	635	476	45
11 . .	197	85	109	104	178	452	1 982	31	203	476	327	43
12 . .	82	145	176	151	161	459	2 428	183	252	1 087	252	71
13 . .	134	116	450	68	140	334	1 318	305	837	380	191	85
14 . .	163	156	412	199	301	142	896	182	617	215	132	150
15 . .	145	106	271	317	13	168	1 282	222	379	352	114	151
16 . .	35	109	17	360	103	82	1 670	197	185	180	27	182
17 . .	39	73	44	612	194	33	1 328	169	191	47	43	29
18 . .	137	164	234	521	147	428	525	154	117	216	80	46
19 . .	73	256	329	134	190	1 085	203	189	64	216	46	96
20 . .	8	167	396	98	168	1 663	485	84	18	256	141	163
21 . .	61	48	278	225	229	1 201	398	94	51	130	87	52
22 . .	16	56	137	356	641	1 382	755	17	26	304	58	227
23 . .	104	43	59	351	748	1 079	1 407	38	116	241	30	139
24 . .	27	90	64	395	672	1 753	1 750	87	99	162	13	86
25 . .	65	69	78	404	294	762	1 203	190	53	121	82	593
26 . .	41	255	224	119	118	779	1 125	526	86	92	142	203
27 . .	81	85	97	123	69	597	851	169	77	73	73	162
28 . .	253	105	181	267	116	377	598	114	168	27	69	237
29 . .	132	—	90	121	98	247	439	4	25	83	134	163
30 . .	66	—	87	245	259	55	303	155	19	48	55	274
31 . .	92	—	327	—	227	—	329	316	—	107	—	47
Mean .	87	116	178	258	209	522	969	213	267	216	116	130

Average daily output for whole year = 273 kilolitres

energy also. Among the stations which have rather low energy yields, Cochin is very dependable. There, the longest spell with wind speed less than 8 kmph was only 29 hours.

Estimates of daily output at Veraval

Since the output of a wind-driven machine in terms of quantity of water pumped or electrical energy produced is a function of the cube of the wind speed, in order to get an estimate of either quantity for a particular station, the monthly or annual mean wind speed is not a good enough index. In order to have an idea of the average output and its variations from day to day, from the hourly wind speeds of the windiest station (for which hourly speeds were available), Veraval, the quantities of water in kilolitres that can be pumped from a depth of 10 metres by a windmill of 30 sq metres swept area and an output 20 per cent of the maximum extractable energy in the wind were calculated for each hour. This choice of 20 per cent is based on the conclusion in the paper by Nilakantan and Varadarajan (3) where they say: " The existing types actually do not measure up to even this and a power ratio of 0.2 is the practical limit that may be achieved. " The daily totals of one year, 1958, are given in table 4. The daily values are given so as to bring out the variations from day to day and month to month also. The average daily outputs for each month and the whole year, along with the corresponding values of electrical energy inkilowatt-hours are given in table 5.

Table 5. Average daily water lifted through 10 metres or equivalent electrical energy generated in different months and year at Veraval (1958)

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Water, kilolitres . .	*87*	*116*	*178*	*258*	*209*	*522*	*969*	*213*	*267*	*216*	*116*	*130*	*273*
Electrical energy, kWh	2.4	3.1	4.9	6.7	5.6	14.1	25.8	5.8	7.2	5.8	3.1	3.5	7.3

It will be seen that the output is largest in July and quite high from April to October.

The actual quantities of water pumped from day to day are seen to vary from 4 kilolitres to 2 428 kilolitres. If one half of the water is assumed to be used as it is being pumped, still, if it is considered necessary to store the rest on the day of highest output, the storage tank will have to be of the capacity of 1 200 kilolitres, i.e., 20 m × 10 m × 6 m.

Highest gust speeds at the different stations

The maximum gust speeds met with at certain stations in each month and year were given in a paper by Ramdas and Ramakrishnan (4). The maximum gust speeds for the whole year taken from the above for the stations analysed in this paper are given in table 6.

These values are of interest from the point of view of the possible damages to the structures due to strong winds and adequate precautions will have to be taken in the design of windmills to safeguard against such occasional high gusts.

Table 6. Maximum gust speed in kmph, V_x, at different stations

(Based on data up to end of 1952)

Station	V_x
Allahabad	159
Bangalore	97
Bombay	129
Cochin	113
Jodhpur	151
Madras	117
Nagpur	132
New Delhi	113
Visakhapatnam	95

Acknowledgement

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Summary

The wind data used in this paper are those already collected by the India Meteorological Department. These are of two categories. The first consists of values of total run of wind on each day measured by non-recording types of anemometers. Long period averages for nearly 150 stations in India are available and using these, maps of isovents for alternate months, the year and the highest monthly mean are shown. The second category consists of hourly values of wind speed tabulated from the records of Dines anemographs. This type of data exist for nearly 25 stations in India. The data of 12 such stations for 3 to 4 years have been analysed from the point of view of wind power utilization. Annual velocity-duration curves of 8 selected stations are given in the paper. The maximum usable energy for different stations and its distribution over various speed ranges have been worked out, which will be of help in adapting wind-driven machines for particular stations to particular speed ranges. The dependability of the wind as a source of power at the various stations has been assessed by preparing frequencies of occurrence of low wind, chosen arbitrarily as below 8 kmph, of various durations at a stretch.

At the most favourable stations, the maximum usable energy in the wind for a 30 sq metre swept area is of the order of 20 000 kilowatt hours. A machine with a power ratio of 0.2 could yield about 4 000 kilowatt hours in the year.

The quantities of water that a windmill of 30 sq metre swept area and a power ratio of 0.2 can lift through a depth of 10 metres from day to day in a typical year at Veraval in the most windy area have been worked out. The average daily output taking the whole year works out to 273 kilolitres, i.e., 60 000 gallons. On an individual day, the quantity can be as high as 2 428 kilolitres or 534 000 gallons.

RESSOURCES INDIENNES EN ÉNERGIE ÉOLIENNE, ÉTABLIES EN TENANT SPÉCIALEMENT COMPTE DE LA RÉPARTITION DU VENT

Résumé

Les données anémométriques que l'on trouvera dans le présent mémoire sont celles qui ont déjà été recueillies par le service météorologique de l'Inde. Elles sont de deux catégories. La première est constituée par les valeurs de l'activité totale de la brise chaque jour, mesurée par des anémomètres dépourvus de tout dispositif d'enregistrement. On dispose de moyennes prises sur de longues périodes pour près de 150 postes et, en se servant de ces valeurs, on a établi des cartes des isovents bimensuels, avec indication de l'année et de la plus grosse moyenne annuelle. La seconde catégorie est constituée par les valeurs horaires de la vitesse du vent, extraites des enregistrements faits à l'anémographe de Dines. Ce genre de données existe pour près de 25 postes en Inde. Les renseignements que fournissent 12 d'entre eux sur 3 ou 4 ans ont été analysés du point de vue de l'utilisation de l'énergie éolienne. On donne, dans le mémoire, des courbes annuelles vitesse-durée pour 8 stations spécialement choisies. L'énergie utilisable maximum, pour divers postes, ainsi que sa répartition suivant diverses gammes de vitesses ont été déterminées, ce qui facilitera l'adaptation de machines entraînées par le vent à des vitesses appropriées pour leur emplacement. On a évalué la stabilité du vent en tant que source d'énergie aux divers postes en préparant des tables de fréquence de l'apparition de vents peu intenses, arbitrairement choisis comme étant de moins de 8 km/h et se prolongeant sur diverses durées.

Aux postes les mieux situés, l'énergie utilisable maximum que recèle le vent pour une surface balayée de 30 mètres carrés est de l'ordre de 20 000 kW/h. Une machine ayant un coefficient d'utilisation de 0,2 pourrait donc débiter 4 000 kW/h sur l'année entière.

On a calculé les quantités d'eau qu'un aéromoteur ayant une surface balayée de 30 m² et un facteur d'utilisation de 0,2 peut élever d'une profondeur de 10 m tous les jours au cours d'une année-type à Veraval, dans la région la plus exposée au vent. Il ressort que le débit quotidien moyen, en prenant l'année entière, s'élève à 273 mètres cubes ou 60 000 gallons. Pour une journée donnée, ce volume d'eau peut atteindre 2 428 m³ ou 534 000 gallons.

WIND MEASUREMENT TECHNIQUES

M. Sanuki *

Shortcomings of cup anemometers

Ordinary cup anemometers have, first of all, two main shortcomings.

(*a*) Non-linearity of the indication, and

(*b*) Influence of the atmospheric turbulence on the indication.

The first shortcoming is not serious, as the non-linearity exists only in the low speed region, say, below about 15 m/s wind speed (figure 1, the curve labelled as "without network"), and can be remedied by some compensation, or basically, by proper selection of cup diameter to arm-length ratio. Figure 1 applies to the former Japanese standard four-cup anemometer with cup diameter of 8 cm and arm length of 14 cm, tested in the low turbulence [1] wind tunnel of the Japan Meteorological Agency (JMA), Tokyo.

The second shortcoming on the contrary, is quite serious as can be seen from figure 1. The curve labelled "with network" is obtained by introducing artificial turbulence by means of a wire network of ca. 9 × 15 mm mesh spread across the tunnel jet. The influence of turbulence is remarkable, shifting the indication, or the cup-wheel rotating speed, almost parallel to that in low turbulence for wind speeds over 20 m/s, where the amount of shift is more than 10 per cent of the indication. The result was first pointed out by R. Kuraishi, JMA, and will only be obtained in a low turbulence wind tunnel. In ordinary wind tunnels it can probably never be observed, since they always contain a reasonably high turbulence comparable to that caused by a wire network.

The influence of turbulence will be quite all right if the atmosphere were always turbulent. Then the calibration curve of an anemometer prepared in a turbulent tunnel wind is valid in actual use. The degree of turbulence, once it is beyond a certain threshold value, has very little to do with the calibration curve. However, we have no guarantee that it really is, and we must be very careful as to whether the actual atmospheric turbulence is high or low.

The best way is to employ an anemometer which is free from the influence of turbulence, and this can be realized by any one of the following two designs.

(i) Cup anemometer with bead, or

(ii) Windmill anemometer with sharp leading edge.

The first design has hitherto been employed in several countries not necessarily for the above mentioned reason. In this country K. Kano and S. Kawano in their unpublished work carried out

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[1] The intensity of turbulence is less than 0.2 per cent compared with more than 1 per cent for ordinary wind tunnels.

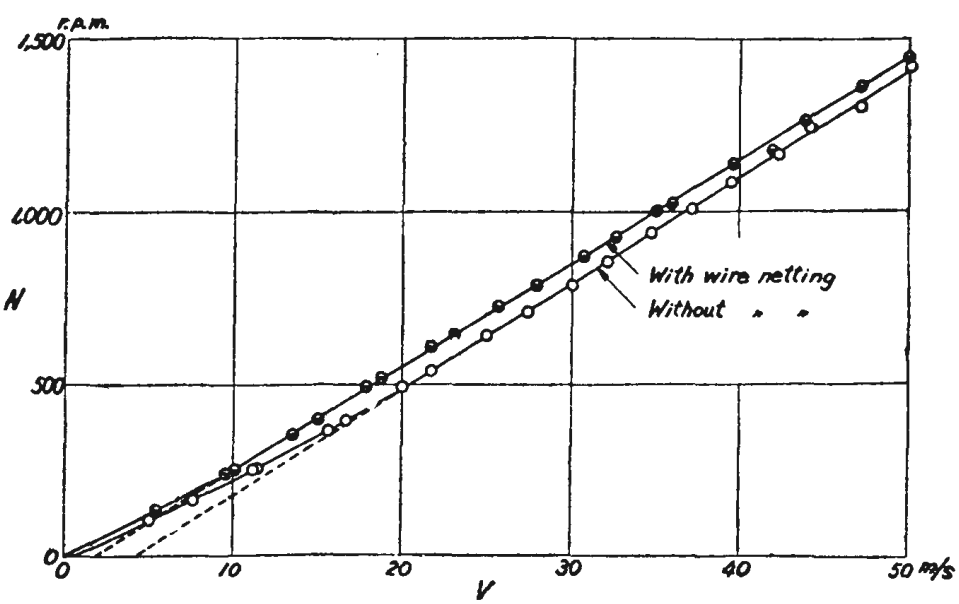

Figure 1. Influence of wire netting upon the rotational speed of standard four-cup anemometer, C. M. O. wind tunnel. (By courtesy of R. Kuraishi)

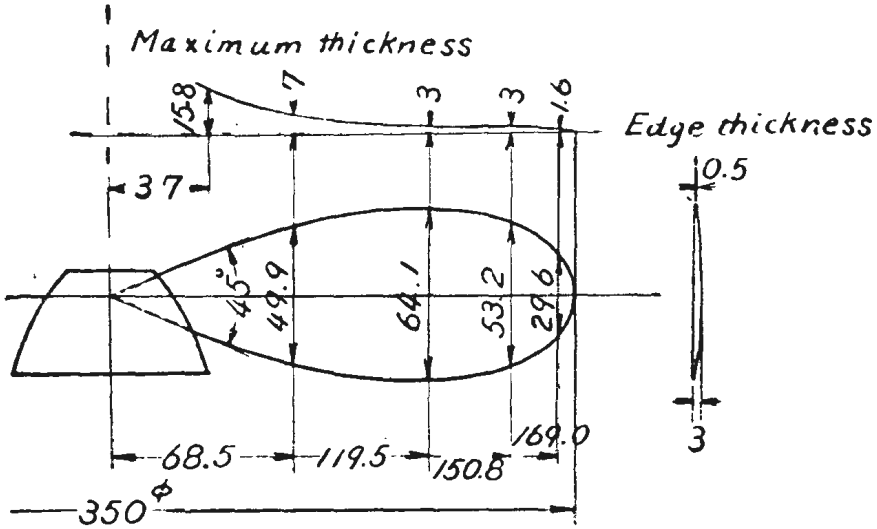

Figure 2. Developed plan of solid four-blader. (Uniform pitch distribution when set at 60° at 75 per cent radius)

several experiments to improve the conventional cup anemometers, and reached the final goal in this respect with a beaded three-cup anemometer of 10 cm cup diameter and 10 cm arm length, which is now adopted as a new standard at the JMA. According to their opinion, freedom from the turbulence can be obtained not solely with the attachment of cup bead but with combined effect of it and cup diameter to arm-length ratio, which also results in a practical linearity of the indication.

Concerning the second design, i.e., the sharp edged windmill anemometer, the next paragraph will be referred to.

Windmill anemometers

At times windmill anemometers are used as a combination anemometer and wind vane, favoured for unmanned wind measuring equipments or sites where space is comparatively limited for installing independent instruments for wind speed and direction.

In this respect, the writer made a systematic study (1) of windmill anemometers, as a counterpart of cup one. It was found that the linearity of indication and the freedom from turbulence can only be effected by the use of a windmill blade profile with a sharp leading edge (figure 2). Other seemingly aerodynamic blade profiles with round sharp leading edge were detrimental in both respects. The thickness to blade chord ratio has little effect up to 10 per cent or so, which was employed in an anti-freezing windmill anemometer to be described later.

The next demand of the windmill anemometer as combined with a wind vane is the possibly quick response to the fluctuations of wind direction. The writer designed a streamlined fuselage, at the nose of which the windmill anemometer is attached, and at the tail a vertical fin. To effect the high response, a small moment of inertia around the vertical rotating shaft and a large tail-fin arm length therefrom are imperative. The representative value of the response may be expressed by the characteristic time, which, under a step change of the wind direction, is the time needed for the amplitude envelope of the performed damped oscillation of the whole system to decrease to 1/e of the initial value. The characteristic time is inversely proportional to the wind speed. The characteristic time multiplied with the wind speed is therefore a constant, and a value of the order of 10 m is obtainable with a well designed combination windmill anemometer and wind vane. In this case, the equipment damps to 1/e initial amplitude under 10 m/s wind speed in a time of 1 sec.

The number of blades has been determined from the possible insensitiveness of indication in a yaw. The four-blader showed underrunning of only 3 per cent for a yaw angle of 15° to the left or right, whereas the three-blader gave more than 10 per cent for the same amount of yaw. Thus a combination windmill anemometer and wind vane with four blades is employed as a standard equipment at airfields, automatic weather stations and for other specified purposes, while the three-cup anemometer is for ordinary weather station use in Japan.

Over-estimation of wind speed

Anemometers, whether they are cup or windmill type, are subject to over-estimation. Under-estimation is possible at the start or accelerated running stage, but the overrunning at the stop or decelerated stage always overshadows the underrunning, resulting in an over-estimation in total. This problem was first studied by O. Schrenk (2) for cup anemometers and extended to windmill anemometers by the present writer (3). The over-estimation factor, or the amount of overrunning above the mean wind speed is a function of aerodynamic torque and moment of inertia of the cup-wheel or windmill system for

given mean speed, amplitude and period of fluctuating wind. The over-estimation factor is larger for smaller aerodynamic torque, larger moment of inertia, lower mean speed, larger amplitude and shorter period of fluctuating wind. It is larger for smaller air density, i.e., smaller aerodynamic torque, and therefore, at higher altitude, more overrunning must be expected.

In this respect a cup anemometer is a less favourable choice than a windmill type because the mass of the former is inevitably concentrated at cup-arm tip resulting in larger moment of inertia compared to its effective aerodynamic torque. A numerical estimate shows the over-estimation factor of the former Japanese standard four-cup anemometer to be about 0.07, i.e., it overruns at 7 per cent excess of the mean wind speed. In this calculation, a mean wind speed of 10 m/s and a period of fluctuating wind of 10 sec were assumed together with a sinusoidal fluctuation of half the mean wind speed. Under the same condition, the Japanese standard combination anemometer and wind vane gives practically zero over-estimation factor. The estimate is confirmed by the wind tunnel experiments conducted by the writer. The new Japanese standard three-cup anemometer cuts the overrunning remarkably (4) owing to its low moment of inertia, i.e,, to about one-third of that for the four-cup, but is appreciably inferior to the windmill type, despite nearly the same moment of inertia.

Pressure-tube anemometers

A pressure-tube anemometer such as Dines or Pitot-static type has long been considered as an instantaneous wind speed indicator. Had it not been for the always inevitable long pipings, this might be true, but in actual cases each type possesses an over-estimation just in the same sense as that of cup or windmill type. Even with a favourable plumbing, i.e., reasonably short pipe length of large bore, a pressure-tube anemometer lags from the wind fluctuations less than a cup anemometer does but more than a windmill type, in the latter case, except in low speed and slowly fluctuating winds (5). The over-estimation factor of the pressure tube is a function only of piping characteristics, amplitude and period of wind fluctuation, and is independent of the mean wind speed air density.

Anti-freezing anemometers

It is often demanded that wind data be collected in winter and on mountain tops, when and where snow and ice should be expected. Especially for moderate and severe icing the electric heating is the sole remedy, other chemical anti-freezing agents almost always failing. According to the writer's tests (6) conducted on the summit of Mt. Fuji (the weather station height, 3 773 m above sea level), a moderate wattage of about 800 or less was enough to prevent heavy icing encountered. The heater windings are imbedded within the fuselage, tail, supporting strut, its rotating skirt, and windmill blades. In such situations a faithful reproduction of wind data is still essential and the windmill anemometer serves well. To this end, several anti-freezing cup anemometers were designed and used in Japan and elsewhere, but their inherent low aerodynamic torque seems to make them less suitable for such a heavy duty.

However, the operation of the windmill itself in such a condition is doubtful, as much more electricity than generated might be necessary to prevent icing.

Wind measuring sites

The present writer confirmed by means of a water-tank test (7) that the wind speed measurement on top of a cylindrical tower should be carefully done concerning the anemometer installation. The wind passing the tower top is accelerated and bent upward, especially at windward position. Most favourable installation will be effected at a position not higher than half a tower diameter and possibly at the center of tower roof area. If possible, another flat roof of sizeable area should be provided with the instrument at a height equal to half a tower diameter, where the anemometer indication is found to be equal to the general wind speed.

In this connection, a two-direction wind vane indicating the vertical and horizontal wind components is useful to survey the flow pattern (8). The vane has a tail unit of cruciform, or vee-form, and can be used as a platform to mount an anemometer, or alternatively a tail windmill realizes a combination set. The problem is that they all show a tendency to perform a spiral motion of the tail due to independent stallings of the horizontal and vertical portions of the tail plane or planes at a large angle of attack. This can be avoided by employing a cylindrical tail unit.

The interference of near-by obstacles upon the anemometer indication in case of a pole or girder-framed tower installation, which is often adopted in field observation, is studied (9). According to a wind tunnel experiment for a cup and a windmill anemometer in presence of cylindrical poles of various sizes and in different positions, a most essential thing is to use a thin pole, say, less than one-fifth or one-sixth of the cup center to center diameter or windmill diameter, which installation affords, in the leeward wake at a distance more than four or ten times the pole diameter, an indication less than 10 per cent of unobstructed reading. If the installation can be considered to be always in the windward side, or, at least, sideways of the pole, far less stringent restrictions will be enough. Similar considerations might apply to the case of a girder member.

Unmanned wind measuring and reporting station

Often wind data are needed from the sites not yet populated at all. For such purpose, several unmanned

and automatic wind measuring and reporting stations are already established and operated (10). As the original purpose was the gale warning, all of them are equipped with UHF (414 Mc/s) transmitters, which send hourly in Morse-code the mean wind speed over five minutes before the transmission and the prevailing wind direction over the same period. Concerning the wind speed, no difficulty exists, but for the prevailing wind direction in the said period, some form of memory must be employed. To this end, a series of 17 equally-spaced electric pulses is generated mechanically during the period by means of a cam switch. The pulses are allocated to sixteen wind direction pre-selector switches according to the relative position of a contactor (rotating with the combination wind vane) and sixteen fixed segments. The allocated pulses in a pre-selector switch (the maximum number would be 17) insert in steps a corresponding number of parallel resistances of a determined amount in the coil circuit of the switch. Now it is clear that the predominant wind direction builds up the largest number of parallel resistances. After five minutes a rotatable permanent-magnet disc searches out from the sixteen coils arranged around the disc the one which has the largest parallel resistance or magnetic flux, and aligns itself with it. This position of the disc magnet selects a brush to sweep the Morse-code drum. The transmission signals are an alphabetical abbreviation of one of sixteen wind directions.

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Summary

The present writer, during his service with the Japan Meteorological Agency, was for years confronted with the problem of standardization of wind measuring instruments. The climatologists, among others, are extremely prudent and conservative regarding the change of instruments because their statistical data might suddenly be altered thereby, even if they are frequently well aware of the proposed merits of new instruments. For their benefit, a lot of realistic experiments and tests were needed. The situation is quite the same also in the wind measurement for the utilization of wind energy. A worldwide standardization of anemometer and wind vane seems somewhat difficult and it is essential that each data reduction should reflect the characteristics and behaviour of each instrument, for which the present paper will be of some use.

The conclusions deduced from the work of the writer are summarized as follows.

(1) A three-cup anemometer with bead and possibly low moment of inertia guarantees a faithful reproduction of wind speed owing to its linearity of indication and freedom from atmospheric turbulence.

(2) A four-blade windmill type combination anemometer and wind vane, with sharp leading edges, is a better alternate from the standpoint of the above-mentioned demands and quicker response.

(3) In any case, the over-estimation factor should be taken into consideration.

(4) A pressure-tube anemometer is trustworthy only with good plumbing. Even so its response is of the same order as those of windmill anemometer and excellent cup anemometer. Only in low speed and slowly fluctuating winds is it superior to the other two types.

(5) An anti-freezing anemometer, possibly of windmill type with its larger aerodynamic torque, are realized with electric heating for the purpose of a faithful reproduction of wind data.

(6) The selection of wind measuring sites needs a keen concern as elevated locations such as a tower top and a pole or girder-frame installation often seriously interfere with the indication. Suitable locations for representative installations are given.

(7) An unmanned wind measuring and reporting station is realized and reported.

TECHNIQUES DE MESURE DE LA VITESSE DU VENT

Résumé

L'auteur de ce mémoire, au cours de ses travaux au service de l'agence météorologique du Japon, se trouva face à face, pendant plusieurs années, avec le problème de la standardisation des instruments servant à mesurer la vitesse du vent. Les climatologistes, en particulier, se montrent très prudents, voire méfiants, en présence d'un changement d'instruments éventuel parce que les données statistiques avec lesquelles ils travaillent risquent alors d'être modifiées, dès à présent et pour l'avenir et, bien qu'ils sachent souvent que les nouveaux instruments présentent d'indiscutables mérites, ils s'opposent à leur adoption. Il faut des quantités d'expériences réalistes et de nombreux essais pour les convaincre. La situation est tout à fait analogue dans le domaine de l'utilisation de l'énergie éolienne. Il semble assez difficile de réaliser une standardisation mondiale des anémomètres et des girouettes et il est essentiel que l'exploitation mathématique des données exprime bien les caractéristiques et le comportement de chaque instrument. C'est sur ce plan que l'on espère voir le présent mémoire présenter quelque utilité.

Les conclusions auxquelles les travaux de ses auteurs permettent d'aboutir sont les suivantes :

1. L'anémomètre à trois coquilles, avec un renflement et dans certains cas un moment d'inertie réduit, assure une reproduction fidèle de la vitesse du vent en raison du caractère linéaire de sa caractéristique et du fait qu'il est à l'abri des effets de la turbulence atmosphérique.

2. La combinaison anémomètre-girouette, du genre aéromoteur à quatre pales, à bords d'attaque minces, constitue un meilleur instrument de remplacement pour celui qui vient d'être décrit ci-dessus, compte tenu des exigences déjà signalées et de l'accroissement de ses réactions plus rapides aux fluctuations.

3. En tout état de cause, il faudra tenir compte des exagérations dans les lectures.

4. L'anémomètre à tube manométrique n'est sûr que si les tuyauteries sont en bon état. Même quand c'est le cas, sa vitesse de réaction est du même ordre que celle de l'anémomètre à pales et de l'excellent anémomètre à coquilles. Ce n'est que dans les vents à faible vitesse et à fluctuations lentes qu'il est supérieur aux instruments des deux autres types.

5. L'anémomètre antigel, le cas échéant du type « moulin à vent », avec son couple aérodynamique plus grand, peut se réaliser avec chauffage électrique pour la reproduction fidèle des données relatives au vent.

6. Le choix des postes anémométriques exige beaucoup de soin car les emplacements au sommet d'une tour ou d'une structure constituée par un mât ou un pylône avec charpente à croisillons nuisent souvent beaucoup à l'exactitude des données. On indique des emplacements appropriés pour des installations types.

7. On décrit l'établissement d'un poste de mesure de la vitesse du vent et de signalisation de sa direction qui fonctionne sans personnel.

STUDY OF WIND BEHAVIOR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

K. H. Soliman *

Windmills have long been in use in both regions of the United Arab Republic. Most of those now in use are water pumping windmills installed directly over a well for irrigation purposes in the semi-arid zones, away from regular sources of water (such as rivers) and where rainfall alone is insufficient. These windmills are commonly seen along the Mediterranean coast of the Egyptian region, and also in the area of Homs in the Syrian region.

Although irrigation was the main aim of installing windmills in the Egyptian region, yet a fair number were used for supplying isolated houses of farm owners with water for domestic use. In this case, subsoil water is pumped to reservoirs. There were also few electric generating wind-driven machines used by private owners for lighting purposes in isolated places.

The Ministry of Municipal and Rural Affairs in Egypt (before the country merged with Syria to form the U.A.R.) had been carrying out trials to supply villages with water pumped by windmills for domestic use as an alternative to the filtration and purification of the Nile water. This subsoil water, only a few metres below ground surface, is safer to use than the direct river water, since the latter contains the parasites of the endemic diseases of the region as well as mud. The trials were carried out in a village (Hallaba) some 15 kilometres north of Cairo. The preliminary results were encouraging and a study is being made to generalize the use of such windmills and to see how far they compete economically with diesel engines in each district.

The Desert Institute in Cairo (and later the General Desert Development Authority) have made great efforts for the development of the deserts in recent years. The Ministry of War started to manufacture water-pumping windmills to satisfy the rapidly increasing demand for such machines, which will be mainly utilized on the north coast of the Egyptian region.

In 1957, the Meteorological Department at Cairo felt the urgent need for an expert to organize the efforts and give advice on the problem of utilization of wind power in Egypt.

The Meteorological Department invited E. W. Golding, as a United Nations expert on this subject, through the World Meteorological Organization.

Mr. Golding spent five weeks in the Egyptian region towards the end of 1959, during and after which time the problem of wind power utilization took a new phase. The major change in the new phase lies in the use of an electric generating windmill to drive a group of water pumps, instead of the present system of having a multi-blade water pumping windmill over each well. The big advantage in this new system is a reduction in the cost as well as a gain of more wind energy by the installation of the electric windmill on the top of a suitable hill, whereas most of the present windmills are located on the low ground of valleys shielded by high ground.

Since Mr. Golding's mission and these studies were confined to the Egyptian region of the U.A.R., this paper will deal only with the experience in that region, especially on the Mediterranean coast where pilot studies were made.

It is planned to extend the results gained to all areas in both regions of U.A.R. wherever it would be profitable.

The successful utilization of wind power involves several important factors, but this paper will deal only with the two following aspects :

(*a*) Wind measurement;

(*b*) Selection of favourable sites.

Wind measurement

General information

In the wind survey, advantage should be taken of data already obtainable from Meteorological Services, but it is essential to know the extent to which such data could be used for the purpose.

In the United Arab Republic, as well as in almost all other countries, there are many land meteorological observation stations run (or supervised) by the meteorological authority of the country. Synoptic observations are regularly taken at some or all of the principal and intermediate hours of observations agreed upon internationally, namely, 00, 06, 12, 18 and 03, 09, 15, 21 hours respectively. These times are Universal Time (same as Greenwich Mean Time). At international aerodromes and key stations, hourly observations are taken to meet aeronautical requirements.

All these synoptic observations include the surface wind speed and direction, but the value of the wind

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speed is the mean over a few minutes not exceeding 10 minutes preceding the time of observation. The standard height at which wind is measured is 10 metres above ground in a freely exposed area. In some stations, the actual height is more than 10 metres.

It should therefore be emphasized that averages based on such synoptic observations must be treated with caution if they are to be used in a wind survey and in the assessment of wind energy obtainable at a site. It is evident that the greater the number of observations per day, and the more they are distributed throughout the day and night, the more representative the averages will be. In other words, averages based on hourly observations would be the best, although they do not give the complete run of wind over the 24 hours of the day. The best averages are to be obtained by using recording instruments to provide the data.

There are 69 observation stations in the Egyptian region of U.A.R., of which 21 have recording instruments, 43 contain non-recording cup anemometers and the rest (only technically supervised by the Meteorological Department and made for special purposes by other organizations) contain no wind instrument and the speed is obtained by estimation.

It would be useful to give the methods of observation in these meteorological stations and discuss how each type of observation could be made use of in the wind survey over the region.

Wind measurements in meteorological stations

In the U.A.R., as well as in most other countries, there are three methods of observing wind speed:

(i) *Observations by personal estimation (visual)*

In this method the wind speed is estimated by the effect of the wind on objects such as trees, flags, smoke, etc. Such estimation can be fairly accurate but must be made by well-trained observers. The estimated speed may either be given in knots or as a "force" on the Beaufort scale.

It is to be noted that when the wind is reported as "force" a range of speed is meant and, if the average speeds are based on the mean of those ranges, the accuracy of such averages would further decrease.

Experience in the U.A.R. with this kind of observation showed that it could not be used for wind surveys connected with wind power utilization.

(ii) *Observations by non-autographic instruments*

This type of observation is sufficiently accurate and is made by cup anemometers but, as indicated before, such observations only give the mean wind speed for a few minutes preceding the time of observation. The extent to which such observations can be used to obtain annual averages for wind speeds for the preliminary survey is discussed later.

(iii) *Observations obtained from autographic instruments*

Instruments recording wind speed continuously obviously have the advantage of giving the complete run of wind from which the mean over any period can be obtained (a few minutes, one hour, a day ... up to a year). Moreover, some types show useful details of the variations of wind speed (gusts and lulls), as well as the diurnal variations of the mean wind speed indicating local characteristics such as sea and land breezes.

Recording instruments in the Egyptian region are either cup-generator anemometers, or Dines pressure tube anemographs. The latter is in much wider use in meteorological stations.

Methods of obtaining wind information especially suited to wind power use

The data required for this purpose can be classified according to the steps normally taken for utilizing wind power, namely:

(a) *Data for preliminary survey*

Data for preliminary survey are to indicate the relative windiness of the different districts of the country.

In this survey, it would be sufficient to obtain annual averages of wind speed. Appropriate averages already available at the Meteorological Service, such as those obtained from the continuous recordings of wind instruments, should be made use of. In an area where such averages are not available, a simple counter-cup anemometer read once a day (or even once a week) would suffice to obtain the required averages. In fact, the simple cup anemometer can be considered as the most practical and economic instrument for world-wide use in the study of local energy distribution in an area where wind power is to be utilized.

It is important that wind instruments should be all freely exposed and at a standard height (10 m) in order that the values obtained should be comparable.

There are also cup-generator anemometers whose cups are modified in form and which are especially designed to integrate the cube of the wind speed, and the readings give the wind energy in kilowatt-hours per square metre. This type of energy integrating instrument, however, is accurate only when the wind speed is between 5 and 15 m/sec, above which large errors are introduced. It is therefore useful in areas where low average wind speeds have to be harnessed.

For the preliminary study in the Egyptian region, the annual means of wind speed could be obtained from two sets of stations.

1. Where continuous recording was made and averages obtained from hourly means;
2. Where three observations only were taken

Table 1. Average annual wind speeds computed from different sets of observations for 1958

The set of observations on which the average annual wind speed (kts) was based	*Port Said*	*Alex-andria*	*Mersa Matruh*	*Hurg-hada*	*Cairo*	*Minia*	*Luxor*	*Siwa*
True average (hourly means)	9.1	8.8	10.6	12.5	5.9	7.3	3.8	6.4
24 synoptic observations	9.1	8.7	10.6	12.4	5.9	6.9	3.4	5.8
4 synoptic observations at 00, 06, 12 18 U.T..	9.0	8.6	10.6	12.8	6.0	6.9	3.3	5.5
3 synoptic observations at 06, 12, 18 U.T.	9.4	9.3	11.2	13.3	6.5	7.0	3.7	6.0

every day at 06,12 and 18 hrs U.T. (i.e., 08, 14, 20 hrs local time).

It is evident that the first set forms the most reliable basis of the survey, yet it was thought interesting to know how far the observations of the second set could be used.

For this purpose, a study was made to compare the averages of annual wind speeds obtained at a selection of stations (each representing a climatic district) computed from different sets of observations with the true average (see table 1).

This table shows the important fact that in areas where there is a reasonable wind average, greater than 7 knots, say (below which wind power could scarcely be economic) over the Mediterranean coastal region, and also where wind blows with steadiness even at low speeds, averages based on 24 "synoptic" observations can well be used, and even those based on only 4 synoptic observations at 6-hourly intervals may also be used. Those based on 3 synoptic observations are little higher than the true mean, but they could help (if that is taken into account) in the preliminary survey in areas lacking better means, and in drawing isovents in such areas. The case of Hurghada is somewhat different owing to its odd diurnal variation of wind speed (see figure 1).

At stations far inland, where the wind speed is generally low, and where excessive heating and

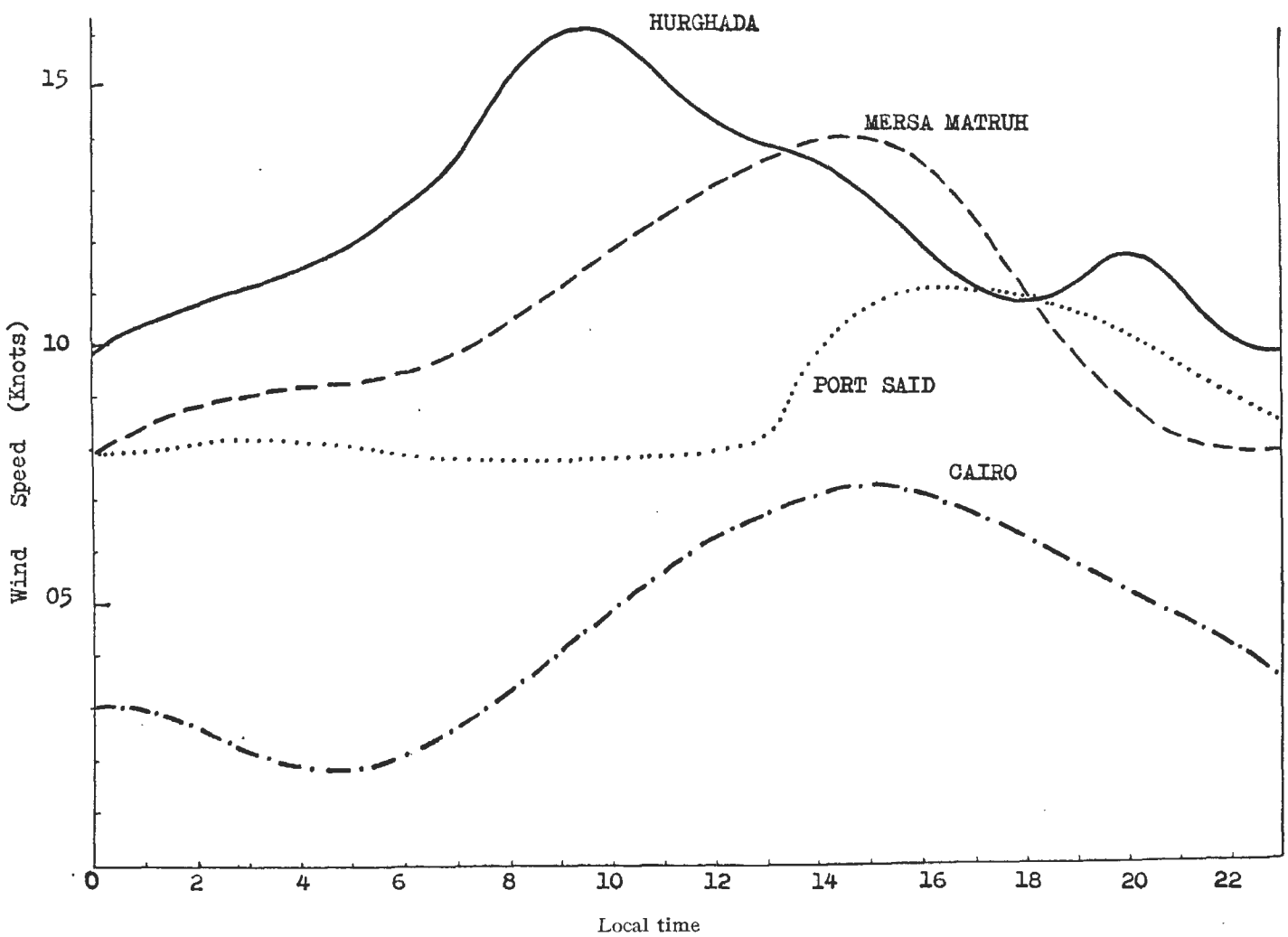

Figure 1. Diurnal variation of wind speed for some localities

marked vertical instability usually exist during the daytime, the wind speed is irregular. For this reason, the averages based on the different sets of synoptic observations bear no regular relation to the true mean, but they are not too far out from that true mean.

(b) *Data for second stage of survey*

After the preliminary survey, the following data should be obtained for the promising districts and sites to study the wind régime.

1. Hourly wind speeds throughout the year and for as many years as they are available (5 years would be sufficient in general).

The hourly means are essential for drawing the velocity-duration curve while the data for several years indicate the variation of data from one year to another. It should be stated here that the wind régimes of stations on the Mediterranean coast of the Egyptian region (such as Alexandria and Mersa Matruh) have been found to have the same form as those over the British Isles given by E. W. Golding (1), and the velocity-duration curves have the same shape. Therefore the simple average annual wind speeds over localities on the northern coast obtained from counter-cup anemometers were accepted as a measure of the wind régime. Advantage was taken of the curves relating the specific output and average wind speed for sites in the British Isles (2).

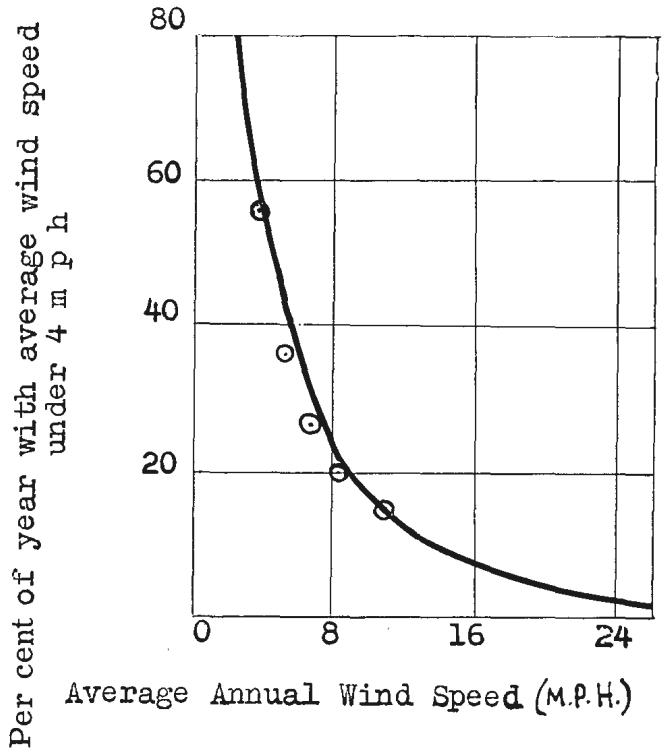

Figure 3. Percentage of winds under 4 mph related to average annual wind speed

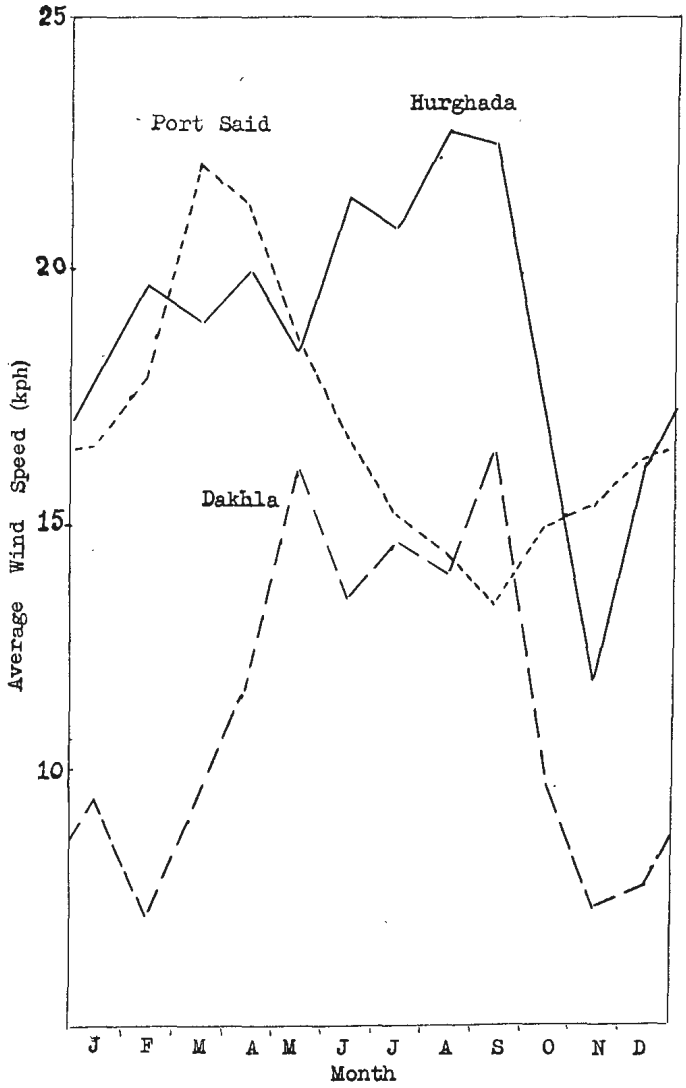

Figure 2. Average monthly wind speeds for some localities

2. Monthly average wind speeds. — These are important to evaluate and relate to requirements the obtainable energy in the different seasons.

Experience in the Egyptian region shows that there are marked variations in the mean monthly values of wind speed in the different districts. Figure 2 gives examples of such variations.

In most districts, the largest monthly averages occur in spring and the minimum in autumn (see the curve for Port Said as example).

As we go to the heart of the desert, the maximum occurs in the hot season, May-October (see curve for Dakhla).

Fortunately, spring and summer are fairly windy seasons, since it is in those months that energy is most needed for water pumping.

3. The diurnal variation of wind speed. — This determines the energy obtainable at the different hours of the day or night.

Figure 1 shows the diurnal variation of wind speed in some stations in the Egyptian region, and indicates how the hours of maximum wind speed can vary from one place to another in coastal stations. Inland stations, however, showed the normal diurnal variation with maximum in the afternoon and

minimum in the early morning. The above data were computed from hourly means of wind speed.

4. Average duration and frequency of calm or very light winds when energy could not be produced by wind driven plant.

Figure 3 shows a curve given by E. W. Golding (3) showing the relation between the annual percentage of winds under 4 mph and annual mean wind speed constructed from observations over many places in the world. Before making use of this curve in the Egyptian region, values available from Egyptian stations of varying average speeds were plotted over that curve (see the small circles). The points fell close to the curve, confirming that it could also be used in our area.

5. The prevailing wind direction. — This is especially important for the choice of a suitable site for installing the wind-driven plant. This information was obtained from the usual wind diagrams in the different months, based on hourly values of wind direction.

We may therefore conclude that data for the second stage of survey over promising sites could be obtained from hourly values of wind speed and direction and these in turn could be obtained from ordinary recording anemometers.

It is essential not to overlook the importance of standardizing the measuring methods so that the comparison of wind data at all sites are properly maintained and have the same degree of accuracy. The remaining important factors would be the free exposure and the height of the instruments above the ground. In the Egyptian region some of the wind instruments in meteorological stations are erected over buildings, but these are sufficiently high (about 10 m above the roof) to minimize the effect of the building. The remaining factor (height above ground) is taken care of by applying a small correction to reduce the values to 10 metres.

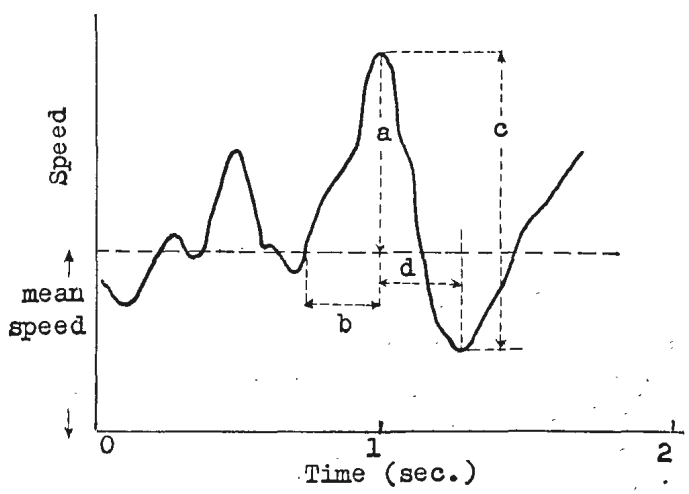

Figure 4. Autographic registration with high chart speed showing details of wind structure

a. gust amplitude
b. gust formation time
c. maximum gust lapse
d. gust lapse time

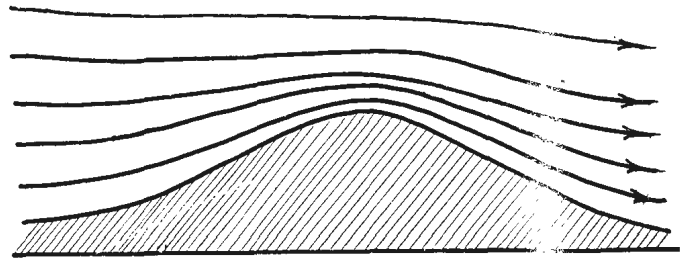

Figure 5. Acceleration of wind over hills

(c) *Detailed data for the study of the structure of the wind*

At certain sites, especially when large size wind-driven plants are to be used, comprehensive and detailed measurements of wind structure may be necessary to answer questions by designers of the wind power machines. Such data need special instruments for their determination and recording.

Autographic registration with high chart speeds can show clear details of the behaviour of wind speed with time (see figure 4), such as magnitude

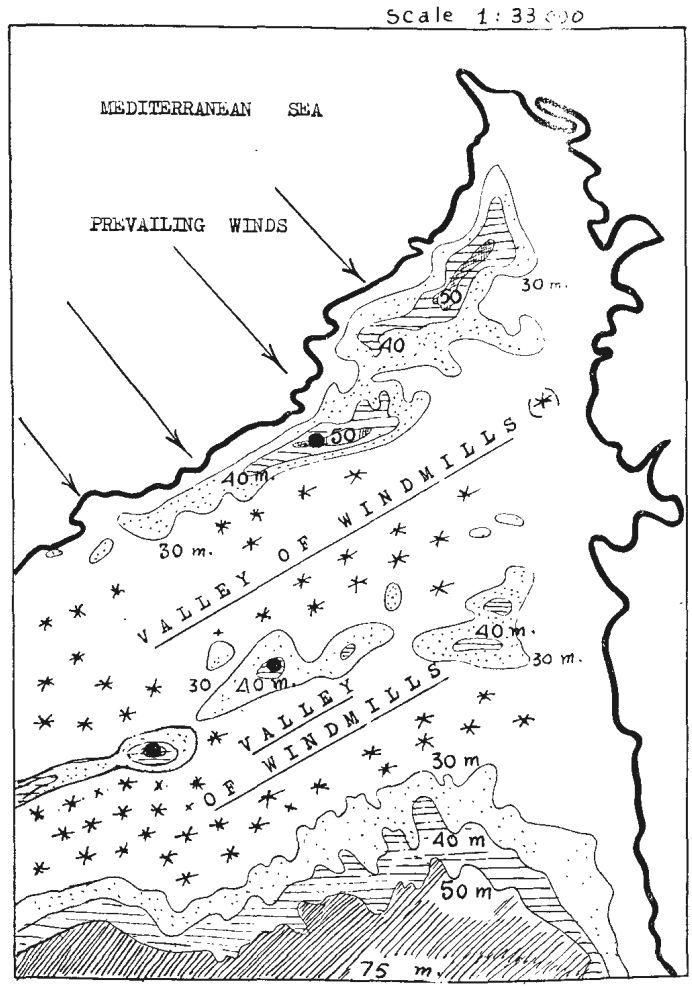

Figure 6. Map of Ras-El-Hekma showing: orography area of windmills, and hills chosen as wind power sites

of "gusts", time formation of a gust, its amplitude, etc., not only in a horizontal direction but also in the vertical. Accurate data on gusts can only be obtained by instruments which have a quick response to change in wind speed, such as hot wire anemometers, gust anemometers of the type developed by E.R.A., and pressure-plate anemometers.

The dines pressure tube anemometer, although it has a large time response (about 2 sec), has long been in wide use for the measurement of maximum gust speeds in the Egyptian region and in many other countries.

Selection of favourable sites

After the survey of wind over the different districts and the choice of promising areas, the next step would be to select favourable sites where the annual average wind speed would be higher than for the general surrounding area. A little increase in speed (V) would lead to a marked increase in the obtainable energy, since the latter is proportional to the cube of the speed (V^3).

In the selection of sites in the Egyptian region, certain phenomena were taken into consideration, of which the following seemed to be most important.

1. *Variation of wind with height*

On flat ground (such as the Nile Delta), increase of wind with height is not of importance in the selection of a site since the height of the windmill can only be increased within small limits with a corresponding increase in the cost of the tower. Other factors,

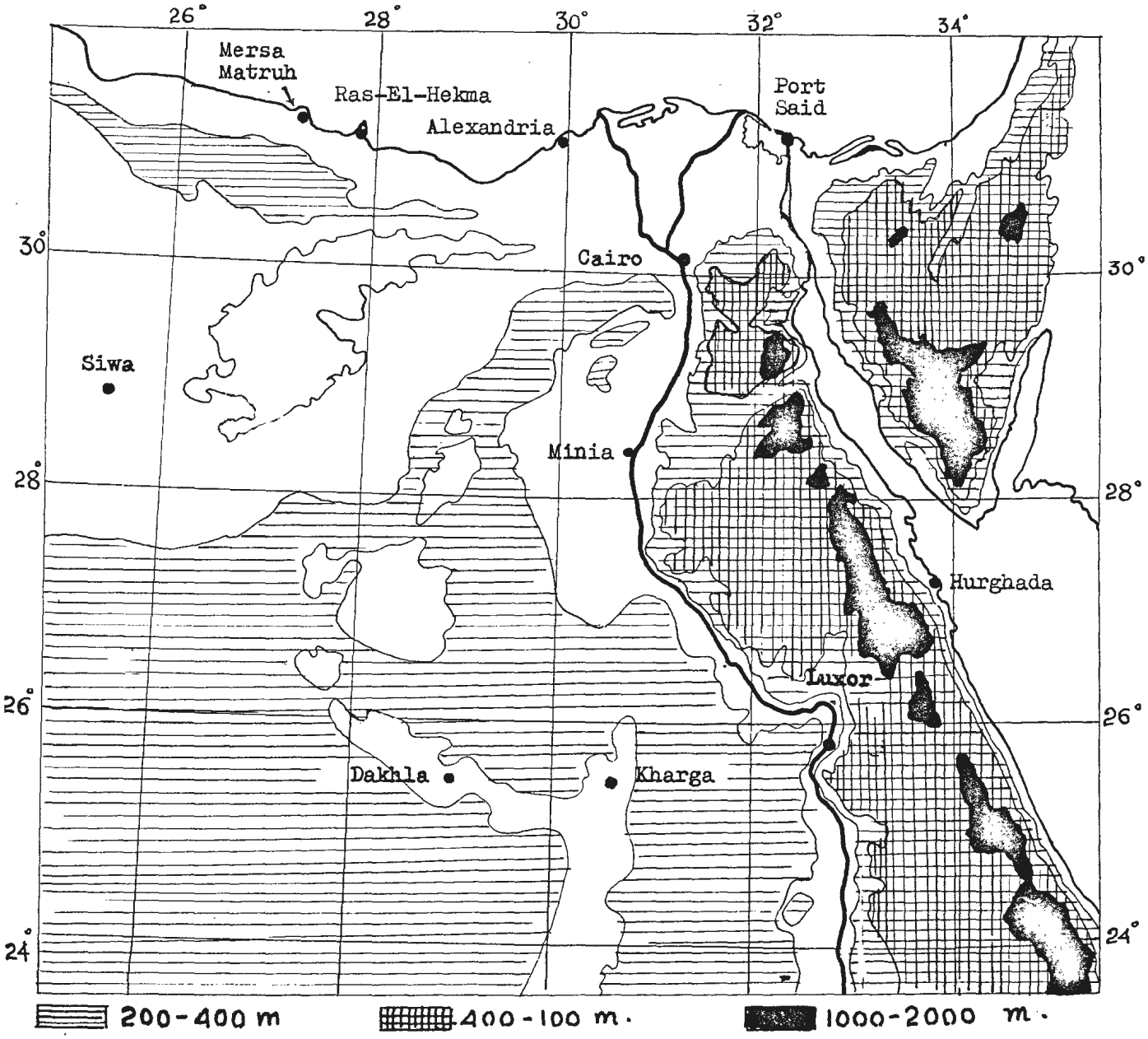

Figure 7. Map showing orography of the Egyptian region

such as free exposure (away from trees, buildings, etc.), are more important.

The variation of wind speed with height over hills is more complex than that over flat ground, and the increase of speed is not only due to the elevation of the hill but also to the compression of streamlines and acceleration of the wind (see figure 5).

The Mediterranean coastal areas in the Egyptian region are rather hilly in many places (see figures 6 and 7). Therefore, in the selection of sites, the different hills in the area were investigated in preference to flat ground.

2. *Nature of the surface*

The nature of the surface has an effect upon the air flow near the ground. Over a rough surface, the flow will be more turbulent than over smoother surfaces of land or sea.

The roughness can be due to the actual nature of the surface (for instance, rocky) or to the presence of obstacles (such as trees, buildings, etc.). This applies to both flat ground and hill surface. Also, air flow reaching a smooth hill after the passage for some time over rough ground will reach the hill as a turbulent flow and the advantage of the smoothness of the hill will be lost.

Bearing the above facts in mind when selecting suitable sites over the coastal zone, priority was given to those smooth hills directly facing, or close to, the sea. For such hills, with the prevailing wind from the sea, the air reaches the hill after passing over long stretches of smooth sea surface. Moreover, air arriving directly from over the sea has a further advantage of being more stable than that passing over heated ground and therefore less turbulent. Figure 6 gives an example of chosen hills in the area of Ras-el-Hekma.

These advantages may apply to many other places on the northern coast of Africa.

3. *Size and slope of hills*

In the selection of wind power sites over the hilly parts in the Egyptian region, due regard was given to the following useful points :

(*a*) The air stream, especially in stable weather conditions, tends to flow "around" isolated small obstacles rather than ride above them (see figure 8).

(*b*) Hills or cliffs of very steep slopes tend to make the air flow turbulent (figure 9). Such turbulent effect would produce dangerous stresses on the blades of the windmill.

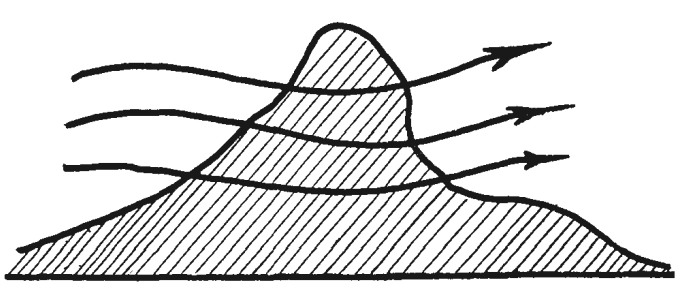

Figure 8. Air flow around isolated small obstacles

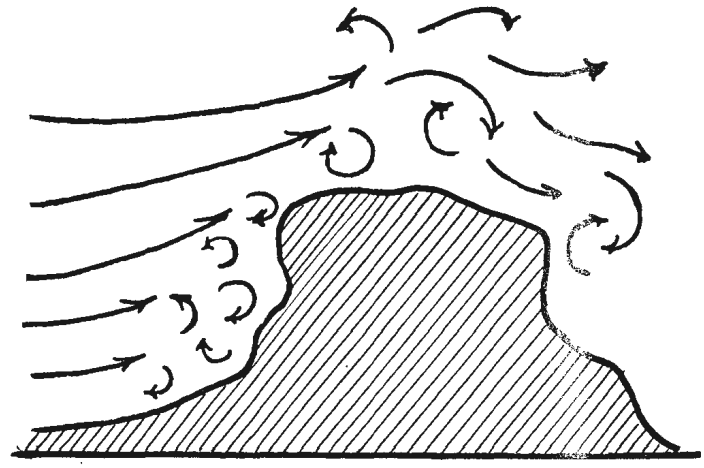

Figure 9. Air flow over steep and rough terrain

For the above reasons, a chain of hills or a fairly large hill with an aerofoil shape and reasonable slope would be most suitable as a wind power site. Figure 6 shows some of the hills chosen at Ras-el-Hekma.

4. *Orographical effects in deflecting and accelerating winds*

Orography plays an important role in screening, accelerating, and deflecting winds over certain localities. In the Egyptian region the effect of orography has been noted over many localities and the following are examples of the effect of long chains of mountains (or even hills only a few hundred metres high) in deflecting winds to flow parallel to them. This is most noticeable on the northern Red Sea coast where, not only are the prevailing winds persistently NW-N, but also the winds are accelerated, and fresh to strong winds are not infrequent, leading to a high average annual wind speed. Figure 10

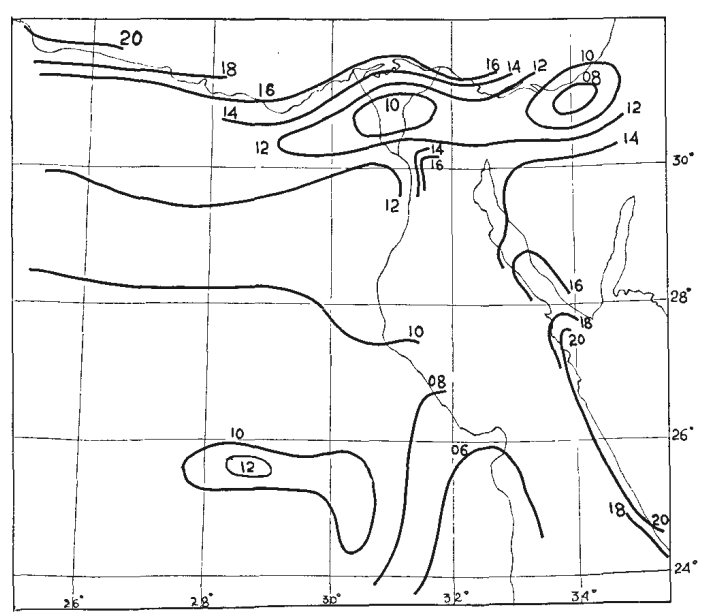

Figure 10. Mean annual isovents (kph)

shows that the coastal area of the northern Red Sea is one of the windiest localities in the Egyptian region.

Similar effects occur over other localities, such as the Cairo area, where the frequency of the NE wind (fresh or strong at times) is greater than at all other localities in surrounding areas. This is due to the effect of the chain of hills running NE-SW (see figure 7).

5. *Exposure*

Free exposure away from trees, buildings, etc., is an important factor in the selection of sites where the windmill is to be installed.

It is for this reason that hills overlooking the sea (when the prevailing winds are from the sea) have a superior exposure. A distance away of about 10 times the height of the obstacle would be enough for the site to be considered freely exposed to wind.

The shielding effect of high ground is known and places in the lee of hills not only have low average wind speeds but also suffer from excessive turbulence. Such places were excluded during the survey for the selection of sites for the installation of the electric generating windmill on the northern coast. The non-electric water-pumping windmills, which are used over that area (over one hundred), are mostly situated in the low ground of the valley (see figure 6).

This once more emphasizes the advantage of using wind-driven electric generators which can be installed in a favourable site on a hill where the energy produced can, more economically, work a number of pumps on a group of wells fairly close to each other. In this case the distance of the chosen site on the hill should be carefully studied in relation to the group of wells, since the economic consequences of the gain of power should not be lost in the cost of transmission. The best place in this case is to install the generating windmill in the "centre of gravity" of the group of wells, where the sum of lengths of the transmitting cables would be a minimum.

Acknowledgement

I wish to thank the Director-General of the Meteorological Department of U.A.R. for permission to obtain the data used in this paper.

I also wish to thank the General Desert Development Authority for the facilities they have provided.

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2. Tagg, J. R., Wind data related to the generation of electricity by wind power, *E.R.A. Tech. Report*, c/T 115, p. 32, 1957.
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Summary

Windmills have long been in use in both regions of the U.A.R., mainly for irrigation purposes in the semi-arid zones.

Great efforts have been made in recent years to develop the desert areas in the Egyptian region, especially along the Mediterranean coastal zone where many windmills are in use.

The Meteorological Department felt the urgent need for an expert to organize the efforts and give advice on the problem of utilization of wind power, and invited E. W. Golding for that purpose through the World Meteorological Organization.

With the visit of Mr. Golding, the utilization of wind energy took a new phase. The major change in this new phase lies in the use of an electric generating windmill to drive a group of water pumps, instead of the system of having a multi-blade water pumping windmill over each well. The big advantage in this new system is a reduction of cost, as well as a gain of more wind energy on summits of hills, whereas most of the present windmills are located on the low ground of valleys shielded by high ground.

Wind survey in the Egyptian region revealed many useful results, of which the following seem to be particularly interesting :

1. The map of mean annual isovents showed that the Red Sea and the Mediterranean Sea coasts are fairly windy, except over the extreme eastern part of the latter where the speed falls to less than half its value over the rest of the coast.

2. Monthly averages of wind speed were found to suffer large variations, but in general the highest values occurred in spring and summer; and the lowest in autumn.

3. Diurnal variation of wind speed followed the normal pattern with a maximum in the afternoon and a minimum in the early morning, except on the Red Sea coast where the variation was rather peculiar with a main maximum at 9 a.m.

4. Velocity-duration curves for stations on the Mediterranean coast were found to have the same shape as those for stations in the British Isles given by Golding (1) indicating similarity of wind régimes.

5. The curve constructed by Golding (3) showing the relation between the percentage of wind speeds below 4 mph and the average annual wind speed for different places over the world was found to apply also to different localities in the Egyptian region.

6. In studying the extent to which data already available at the Meteorological Department can be used for wind power purposes, it was found that averages based on only 4 "Synoptic observations" at 6-hourly intervals can give useful indication of windiness at places lacking better averages.

7. Orographic effects were found to play an important role in accelerating and deflecting winds. The effect is especially marked on the Red Sea.

RECHERCHES SUR LE COMPORTEMENT DU VENT ET ÉTUDE DE SITES APPROPRIÉS POUR L'ÉTABLISSEMENT DE CENTRALES ÉOLIENNES

Résumé

On se sert d'aéromoteurs depuis longtemps dans les deux régions de la République arabe unie, plus spécialement aux fins d'irrigation dans les zones semi-arides.

On a fait de gros efforts, au cours de ces quelques dernières années, pour mettre en œuvre les régions désertiques de la région égyptienne, particulièrement le long de la côte de la Méditerranée, où nombre d'éoliennes sont actuellement en service.

Le service météorologique s'est rendu compte de l'urgence qu'il y avait à prendre conseil auprès d'un expert pour assurer l'organisation des efforts et obtenir des éclaircissements sur les problèmes que soulève l'utilisation de l'énergie éolienne, et il invita M. E. W. Golding dans ce but, par l'entremise de l'Organisation météorologique mondiale.

L'utilisation de l'énergie éolienne entra dans une nouvelle phase avec la venue de M. Golding. Le changement profond qui la caractérise, réside dans l'emploi d'un aéromoteur producteur d'électricité entraînant un groupe de pompes, au lieu de l'ancien système qui consistait à prévoir une éolienne à pales multiples à la bouche de chaque puits pour en pomper l'eau. Le gros avantage du nouveau système est constitué par la réduction de coût qu'il autorise, ainsi que par l'obtention d'un supplément d'énergie éolienne au sommet des collines, en se rappelant que la plupart des aéromoteurs actuellement en service se trouvent à faible altitude, dans des vallées protégées par les hauteurs avoisinantes.

Les recherches menées sur le vent dans la région égyptienne ont mis plusieurs résultats utiles en lumière, dont les suivants semblent être particulièrement intéressants :

1. La carte des isovents annuels moyens prouve que le vent souffle assez fréquemment sur les côtes de la mer Rouge et de la Méditerranée, sauf à l'extrême Est de celle-ci, où sa force tombe à moins de la moitié de ce qu'elle est sur le reste de la côte.

2. On a observé que les moyennes mensuelles de la force du vent étaient sujettes à d'amples variations mais, en général, que les plus grosses valeurs se présentaient au printemps et en été, avec un minimum en automne.

3. Les variations diurnes de la force du vent se conforment au régime normal avec maximum l'après-midi et minimum de bonne heure le matin, sauf pour la côte de la mer Rouge, où les résultats furent assez curieux, avec maximum principal à 9 heures du matin.

4. Les courbes force-durée pour les postes de la côte de la Méditerranée présentent la même forme que celles qui furent relevées aux Iles britanniques par Golding (note bibliographique 1) ce qui indique une similitude des régimes du vent.

5. La courbe construite par Golding (note bibliographique 3) qui indique les rapports entre le pourcentage des forces du vent inférieures à 4 milles à l'heure, ou 6,4 km, et la force annuelle moyenne du vent pour divers points du globe, est également applicable à divers lieux de la région égyptienne.

6. En étudiant la mesure dans laquelle les données déjà disponibles au service météorologique peuvent être utilisées pour les besoins des centrales éoliennes, on a observé que des moyennes ne reposant que sur quatre « observations synoptiques » prises toutes les six heures peuvent donner des indications utiles sur le régime des vents en des lieux pour lesquels on n'a pas de meilleures moyennes.

On a observé l'importance du rôle de l'orographie dans l'accélération et la déviation des vents. Cet effet est particulièrement sensible sur la côte de la mer Rouge.

WIND MEASUREMENTS IN RELATION TO THE DEVELOPMENT OF WIND POWER

J. R. Tagg *

In developing the wind power potential of any isolated or under-developed area, wind measurements have to be made for a number of different purposes. It is first necessary to establish that the wind flow is sufficient to make its exploitation economic. When this has been done, further information will be required to guide the designer so that he may make the best use of the prevailing wind régime. He will also need to know the greatest wind speed which wind plant may have to withstand during storms. When a wind-driven machine has been constructed, it will be desirable to see how closely its performance matches up to its design specification in winds of different speeds.

The degree of turbulence present in the natural wind will vary with place, with height above ground, and with prevailing meteorological conditions. The effects of gusts upon wind measuring instruments (and upon wind-driven machines) will vary widely according to their mechanical design and speed of response. Due consideration must therefore be given to the characteristics required when selecting an anemometer to carry out wind measurements for a particular purpose.

Methods of wind measurement may be considered according to the nature of the physical effect upon which they are based. Some of these effects provide a measurement which gives true wind velocity; others, to a greater or lesser extent, are dependent also upon air density. This point is of some importance, since the power which a machine can extract from the wind is proportional to the rate of change of momentum of the air passing through the effective working area.

Complete descriptions of anemometers cannot be given. They are to be found in standard works on anemometry such as Ower (1), Sheppard (2), and others, covering particular instruments.

Anemometers available

Anemometers which depend upon the rate of dissipation of heat from a body placed in the air stream indicate true wind velocity independently of air density. The electrically heated hot-wire anemometer is predominant in this class. It is the only one likely to be of use for wind power applications, when it may be used for research purposes, the readings of anemometers of other types being compared with its indications.

Since the output response of uncorrected hot-wire anemometers decreases with increasing wind speed, various linearising devices have been used in control equipment. Compensation has also to be made for variations of air temperature. Sheppard and Ower discuss some of the many contributions which have been made on the subject. Deacon and Samuel (3) have described one particularly simple method of compensation applicable to hot-wire anemometers for use in the atmosphere.

Anemometers which give an indication dependent upon air density as well as air velocity, are of two kinds. The first makes use of the relationship between the hydrostatic pressure and the velocity at any point in a moving fluid according to Bernouilli's equation. The second operates by virtue of the pressure or "drag" exerted by a fluid stream upon a suitably mounted sphere, plate, or other solid body.

The Pitot-static tube, the most important member of the first sub-group of anemometers, has been universally adopted as a standard laboratory instrument for measuring air-flow. In 1892, it was modified by Dines, who devised a form suitable for meteorological use. The Dines anemograph has since been used all over the world as a self-contained recording instrument. Its response to changing wind velocity is severely affected by the volume of air contained within the tubes which connect the velocity and pressure orifices to the float chambers. Noetzlin (1941), and later Sanuki (4), showed how this instrument over-estimates the mean wind speed in gusty winds. It is particularly unfortunate that pressure-tube anemometers are subject to these errors, as they have been used to gain so much information on wind flow.

Modern developments in pressure transducers may give the simple Pitot-static tube a new use as a research instrument in the development of wind power. By their use, reductions may be made in the physical size of the head, and in the length and diameter of the static and velocity tubes. This will enable recordings to be made with improved accuracy and frequency response. Insensitivity at low wind speeds will, however, remain a disadvantage.

Other members of the first sub-group of pressure-sensitive anemometers include Venturi tubes, plate orifices and shaped nozzles, all of which are intended to measure air-flow through pipes or ducts. Their application to wind power is restricted to measuring

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the air flow through wind-driven machines employing a pneumatic power transmission system.

The second sub-group of pressure-sensitive anemometers comprises those instruments in which a body, freely exposed to the air-flow, is allowed to move against gravity or the restraint of a spring. Sherlock and Stout (5) produced one successful uni-directional instrument of this type in which a flat plate is held facing the wind by means of a tail vane.

More recently, a light perforated sphere has been used as the active element in a range of bi-directional and omni-directional anemometers. They have been developed by the Electrical Research Association for research work on wind power (6, 7).

By adopting modern techniques, a well-damped, stable response to a sudden change of wind speed can be completed in less than 0.1 seconds. This rapid response has been instrumental in developing a successful method for testing the performance of wind-driven machines with some precision.

Amongst velocity anemometers, two groups of rotational anemometers are of interest. Because of slight bearing friction both types have a speed of rotation which depends slightly upon air density. The first group includes all the modern variations of the Robinson cup anemometer. Certain readily available designs have achieved a world-wide status as standard meteorological instruments and have been used to collect a vast quantity of information on wind flow. Because of inertia effects, all instruments of this type tend to over-estimate the mean wind speed in gusty winds. The error can be large at low wind speeds, but becomes less as the mean wind speed increases.

The second group of rotational anemometers includes all types of "windmill" and vane anemometers. Unlike the cup anemometer, they have to be held to face the wind by a tail vane. This fact complicates their mechanical design. As little is known of their response to change of direction in gusty winds, their use is limited to the performance testing of wind plant under steady wind conditions.

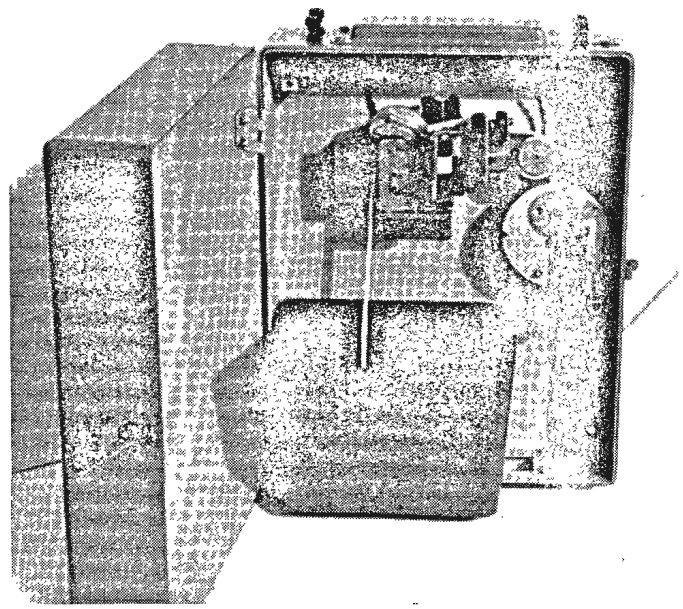

Figure 1. E.R.A. impulse recorder (Series 2)

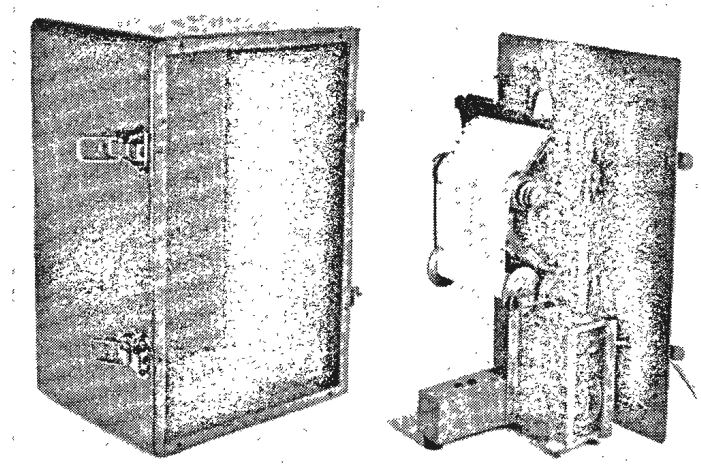

Figure 2. E.R.A. impulse recorder (Series 3)

Measurement of wind flow

A detailed account of the recommended procedure to be followed in investigating the wind power potential of an area has been given elsewhere (8). It is suggested that cup anemometers be used as they are omni-directional, reliable, robust, readily available and cheap. The relative frequency of different hourly mean wind speeds may be established by cup-contact anemometers connected to recorders (see figures 1 and 2) installed at a few widely distributed sites. Similar wind-flow conditions may be assumed to prevail at a number of potential wind power sites immediately surrounding each recorder. These sites are equipped with less costly cup-counter anemometers which integrate the run-of-wind by means of a six-figure revolution counter. Thus the relative wind flow is obtained for each site and, with experience, predictions can be made of the available wind energy.

Many years of continuous records for mean hourly wind speeds are available from some meteorological stations. Current records are most useful for making a graphical comparison with the results of the wind survey. It has been shown that the annual average wind speed can vary by as much as 20 per cent above or below the long-term average value. It follows that if the comparison can be made on a short-term (e.g., 1 year) basis, and the result can be related to the long-term average value for a meteorological station within the area of the survey, the accuracy of any estimates will be much improved.

Not all meteorological station records are of such use. It will often be found that the available figures represent average values of a series of spot readings of wind velocity taken at regular or even irregular intervals. The results are then only of value in giving a limited indication of trends.

Installation of anemometers

Many workers have, by experiment, sought to show that the increase of wind velocity with height above ground can be expressed with sufficient accuracy by a power law of the form —

$$V_h = V_o h^\alpha$$

where V_o is the mean wind speed at a standard height and V_h the mean wind speed at a height h. This approach is of little value except for winds blowing over unobstructed level country. Such a law can then only be true in the sense of a long-term average value. Short-term relationships are dependent upon many meteorological factors and also upon the shape of the ground. Nevertheless it is still desirable to expose anemometers at a standard height and measurements of wind velocity at meteorological stations are generally made at 10 metres (33 feet). It is reasonable to adopt this height when wind survey measurements are made over level country. However, for wind power, the superiority of hill-top sites over those on level ground will be so marked that they will always be chosen where possible. Over most hills, the accelerated air-flow, due to the presence of the hill, will persist down to within a few feet of the summit. Measurements made at 3 metres will not differ markedly from similar measurements made at 10 metres. If, however, the hill has an extensive flattened area at the summit, the accelerated air will tend to pass well clear of the ground. Wind measurements should then be made at 10 metres. Installation of cup-counter anemometers at the lower level will permit them to be read from the ground. This advantage, together with the reduced cost of the supporting pole, will justify installation at 3 metres wherever the ground contours permit.

It is not unreasonable to point out that anemometers should always be mounted at the top of a slim supporting structure, so that their indications are not influenced by surrounding obstacles. The air speed in the wake of a pole a few inches in diameter will be appreciably reduced for many diameters down-wind. The effect of such a wake upon a cup-anemometer will depend upon whether it strikes the cups moving with or against the wind.

Wind speed recorders

When the first wind survey was instituted (8), suitable recorders were not available and had to be developed. Operating conditions at isolated wind measuring sites were both unusual and severe, but two different types of recorder were evolved successfully to meet them. Three factors influenced their design. The instrument had to be reliable, i.e., robust, when maintained by local observers who were not used to handling delicate equipment. They had to be economical in their use of energy which, because the sites were isolated, had to be obtained from batteries. The use of liquid ink as a recording medium had to be avoided as it tends to be unreliable in changing temperatures and humidities.

The recorder shown in figure 1 is preferred for use in areas where long and frequent periods of calm weather do not occur. Its operation, which differs from almost all other recorders, can be explained as follows: a mercury switch, in a cup-contact anemometer, makes a brief contact once during the passage of one-twentieth of a mile of wind. This action energises a solenoid supplied from a group of dry Leclanché cells. Movement of the solenoid armature operates a ratchet wheel by means of a pawl. This movement is then transferred to the narrow paper tape by a pegged driving wheel. The gearing is such that the paper tape is drawn off the stock spool at the rate of one-sixteenth of an inch for each mile of wind passing the anemometer. The tape then falls freely into a box from which it is re-spooled by hand.

An hourly time switch energises a second solenoid from the battery. The armature movement is arranged to press a short-endless band of inked typewriter ribbon against the paper tape, and so make a mark. At the same time, the inked band is moved round a short distance to prevent it from drying out at one spot. The record is analysed to obtain hourly mean wind speeds by measuring the distance between successive dots, using a simple scale. In a dead-calm, one or more dots may be superimposed. This is not likely to happen many times at any site being considered for wind power exploitation. Hourly marks separated by as little as one thirty-second of an inch, corresponding to a wind speed of 0.5 mph, can be distinguished clearly.

The recorder shown in figure 2, also supplied from a group of Leclanché cells, is used when the indications of more than one cup-contact anemometer are to be recorded simultaneously. Four channels can be accommodated in this instrument.

Operation of the mercury switch in the anemometer energises a solenoid. Movement of the armature is transferred to a disc by a pawl and ratchet wheel. The disc has a number of pins around its edge. A second electrical contact, operated at intervals by these pins, energises a second solenoid mounted above the recorder chart. The chart is driven at a suitable rate — in this case three inches per hour — by a powerful eight-day clock. The clock is also arranged to draw a typewriter ribbon across, but clear of, the paper chart. Operation of the second solenoid produces a dot on the paper chart after each two miles of wind have passed the anemometer. The hourly mean wind speed can then be obtained by counting the spaces between successive dots.

Periodically it is desirable to check the ability of the cells to supply the short pulses of current necessary to operate the solenoids. Even when they are nearly discharged, their life can be extended by putting another cell into circuit. This should not be done too soon as excessive current causes accelerated wear on the mechanical parts of the recorder. This point is also of importance when the Leclanché cells are replaced by lead-acid secondary cells. Care should then be taken to ensure that the voltage used is not excessive, as secondary cells have a very low internal resistance compared with dry cells.

If ample power supplies are available at the wind measuring site, other instruments can be used to provide a record which is more convenient to analyse. One such instrument, available commercially, will print both the hourly mean wind speed and the time of day in figures on a paper tape.

Initially, gaps in the records may cause some concern. This is unnecessary if there are sufficient readings available from nearby sites. These integrated run-of-wind figures should be plotted continuously against time as a more or less straight line on graph paper. A similar integrated run-of-wind curve should be obtained for each recorder as the charts are analysed. Should a gap occur, it will then be possible to estimate the run-of-wind for the missing period by visual comparison with the other nearby sites. For periods of a week or less, the error incurred will be negligible.

The estimation of available wind energy

The characteristic wind flow for any site — its wind régime — is conveniently described by a velocity-duration curve (see curve A in figure 3). This is a cumulative frequency curve, or ogive, showing the duration in hours for winds exceeding each integer value of hourly mean wind speed. It is obtained by simple analysis of the charts from either

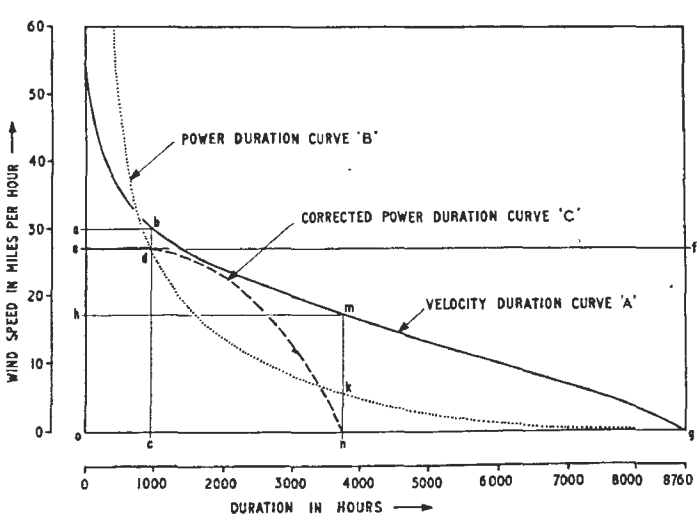

Figure 3. Showing the method of obtaining a corrected power duration curve

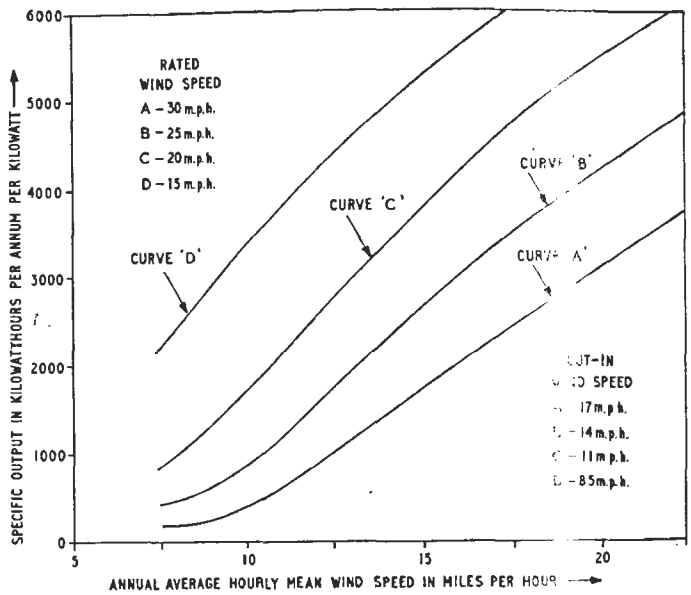

Figure 4. Showing the relationship between the specific output and the annual average hourly mean wind speed

of the recorders described above. Shorter periods than one hour could be used for the analysis, but this would greatly increase the labour required without improving the accuracy.

By cubing the ordinates of curve A and replotting them to any convenient scale, the power-duration curve B is obtained. The area under this curve then represents the energy in the wind at the site. The units of energy depend upon the scale chosen, but they are unimportant as will be seen later.

In comparing the value of one site with another, it is assumed that any windmill which may be installed operates at constant efficiency, and that it gives its full output at a wind speed *oa* (or *cb*). The ordinate *cb* is cubed and plotted as *cd*. This represents the full output power of the machine. Power is extracted from the wind at all speeds above *oh* (or *nm*). The corresponding power ordinate is *nk*. The specific output of the machine, i.e., the energy produced in kilowatthours a year for each kilowatt of installed capacity, is now given by:

$$\frac{(\text{area } oedkn) \times 8\,760}{(\text{area } oefg)}$$

Figure 4 shows how the specific output varies for four idealised machines with different operating limits. These curves have been prepared by analysing velocity-duration curves for a large number of sites having widely different annual average wind speeds.

Performance of wind plant

The power in the wind under normal sea level conditions is approximately $0.0000053\ Av^3$, where A is the area swept by the rotor of the machine in sq ft and v is the wind velocity in mph. Betz (1927) has shown that the maximum fraction of this power

which can be extracted by a wind-driven machine, i.e., the overall power coefficient, is 16/27 or 0.593. If the actual output power characteristics of a machine are known from performance tests, a close estimate can be made of the energy which such a machine will produce in any known wind régime.

The over-all power coefficient is first calculated for values of wind speed within the working range. In practice it will vary from zero at the cut-in wind speed to a maximum value of probably not more than 0.35. In figure 3 the portion "dk" of curve B may now be corrected for variation of the over-all power coefficient. Each ordinate representing the output power at an integer value of wind speed is multiplied by the overall power coefficient at that speed. The result is then divided by the over-all power coefficient at full output (or maximum power output) and plotted to give the corrected power-duration curve C in figure 3. The corrected specific output now given by

$$\frac{(\text{area } oedn) \times 8\,760}{(\text{area } oefg)}$$

is considerably larger than before. This method of producing an estimate of energy output has been confirmed experimentally by measurements which were made on two different wind-driven generators (9).

A method of obtaining the power output characteristic of a wind-driven machine will be given at another session of this conference (10). The author also specifies the characteristics required of suitable wind measuring and recording instruments. Both windmill type rotational anemometers and sphere type pressure anemometers have been used successfully in the past (see figures 5 and 6). The output

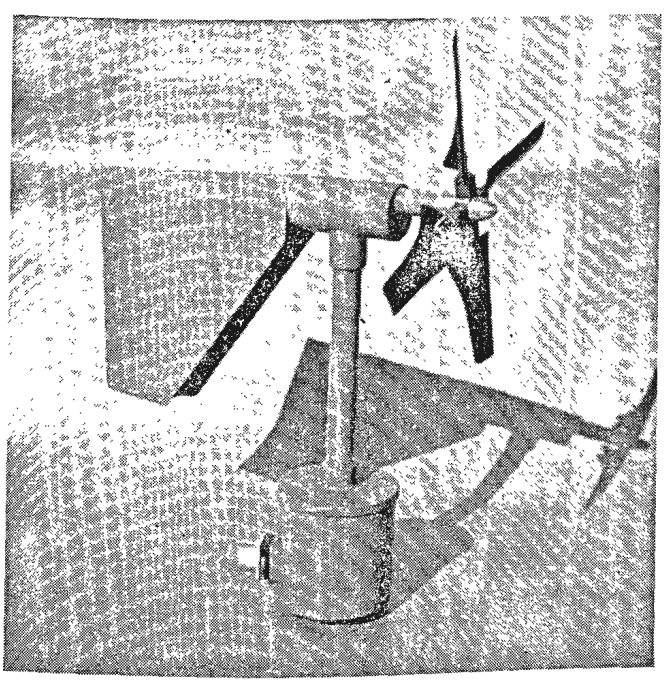

Figure 5. E.R.A. "windmill" anemometer

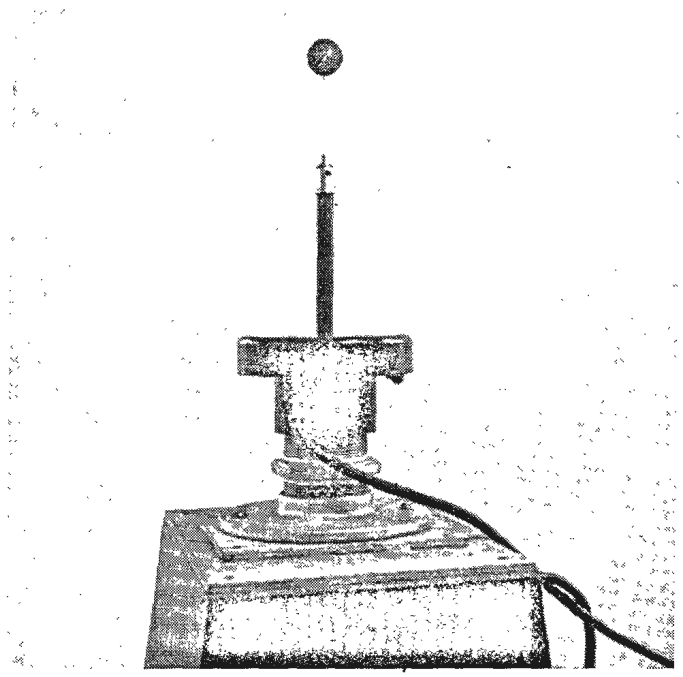

Figure 6. E.R.A. miniature gust anemometer

from either anemometer has been fed into high-speed recorders of the potentiometer-reset type. More recently, direct-writing galvanometer recorders using ultra-violet light-sensitive recording paper have greatly eased the problem of obtaining a sufficiently sensitive and rapid response without the use of amplifiers.

Measurement of maximum wind speeds

Extreme values of wind speed may be recorded in several ways. Standard Dines anemographs are available for wind speeds up to 150 mph. Cup-generator anemometers — cup anemometers incorporating an ac tacho-generator — may be fitted with specially lightened aluminium alloy cups of the accepted standardised shape. Their output may then be fed into conventional pen recorders. Alternatively, they can be used with maximum indicating AC voltmeters to record the maximum wind speeds attained during any period.

The investigation of the maximum wind speeds likely to occur in any period is essentially a problem dealing with random phenomena. Such information, when provided for design purposes, can only be expressed in terms of probabilities. The approach to this subject should therefore conform to accepted statistical methods. It is likely to involve the automatic analysis for the probability distribution of various wind speeds within appropriate sample periods. The Electrical Research Association is currently carrying out a programme of research along these lines. During this work it is intended to develop the read-out of the sphere type gust anemometer so that it may be recorded directly on to magnetic

tape in either analogue or digital form. Analysis and subsequent computation of the records may then be carried out automatically.

This paper has attempted to show how the wind measurements necessary for the economic development of wind power may be most conveniently carried out. It is suggested that if the procedure described above is adapted to local needs, valuable information will be obtained for a relatively small outlay of time and money.

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Summary

The successful exploitation of wind power calls for three types of wind measurement. Sufficiently windy sites must be shown to exist. The designer of wind plant must be provided with information on prevailing wind régimes. The performance of prototype machines must be assessed in winds of different speeds.

The paper reviews the various types of anemometer and examines their suitability for different kinds of wind measurement.

An outline scheme is given for the investigation of the wind flow over an area. Comments are made on the installation of anemometers. The use which can be made of existing wind data is considered in relation to the wind measurements actually carried out.

Two specially developed wind speed recorders are illustrated and described. They are particularly suitable for continuous operation at isolated sites with only a minimum of routine maintenance.

A method is shown for comparing the value of one site with another in terms of specific output. If the power output characteristic of an actual machine is known, a close estimate can be made of the energy which it will produce in a given wind régime.

Mention is made of several methods of recording extreme wind speeds for design purposes.

MESURES DU VENT PAR RAPPORT AU DÉVELOPPEMENT DE L'ÉNERGIE ÉOLIENNE

Résumé

L'exploitation bien conduite de l'énergie éolienne exige trois genres de mesure du vent. Il faut d'abord s'assurer de lieux où le vent souffle suffisamment. Le réalisateur d'une centrale éolienne doit être pourvu de tous renseignements sur les régimes des vents régnants. Le rendement de certains prototypes doit être évalué dans des vents de vitesses diverses.

Dans le présent mémoire on passe en revue les divers types d'anémomètres et on examine la manière dont ils s'adaptent aux différents moyens de mesure du vent.

On donne un résumé en vue de recherches sur les courants des vents sur une région donnée. On présente des commentaires sur l'installation des anémomètres. On étudie l'emploi que l'on peut faire des données connues sur le vent en relation avec les mesures réelles actuellement exécutées.

On décrit deux anémomètres spécialement mis au point. Ces dispositifs se prêtent particulièrement bien au fonctionnement continu en des lieux isolés, avec un minimum d'entretien courant.

On indique une méthode qui sert à comparer la valeur d'un site à celle d'un autre, en fonction du débit spécifique. Si la caractéristique de débit d'énergie d'une machine en fonctionnement est connu, on peut faire une évaluation serrée de l'énergie qu'elle produira dans un régime donné de vent.

On mentionne plusieurs méthodes d'enregistrement des vitesses maxima du vent aux fins de la préparation.

SURVEY OF EXISTING WIND OBSERVATIONAL INFORMATION

World Meteorological Organization, Geneva

It has been estimated that the wind power of the atmosphere available for turbines is of the order of 2×10^{10} kilowatts. The wind is thus a very important potential source of energy. The problem is, however, to determine to what extent this source of power can be used economically. It is generally recognized that one of the first steps for this purpose is to obtain statistics of wind speeds.

The ideal statistic for assessment of wind energy

The overall efficiency of a given wind turbine varies with the wind speed but the variation is not linear. The machine thus starts generating only when a certain threshold value of the wind speed is exceeded and if on the other hand the wind is too strong, the turbine would be subject to increased stress with increasing wind speed without a corresponding increase in output. The ideal statistic for the assessment of wind energy would therefore be one which showed the percentage frequency of the time, or ranges of duration, in hours when the wind blew at different speeds or within different ranges of speed.

It is, however, very difficult to obtain wind statistics in this ideal form, first because many of the data are discontinuous in the time scale so that exact statistics of duration cannot be calculated, and, secondly, because even if anemograph records do exist, their analysis by breaking down the traces and evaluating mean velocities for short intervals of time presents a formidable and time-consuming task. Although such analysis might be available for certain selected meteorological observing stations, they would not normally exist for a network of stations sufficient to enable an assessment of wind energy to be made particularly in arid zone countries. In order to obtain a general survey of those localities where the utilization of wind energy over a large geographical area is of economic value, some simpler and more accessible statistics may, however, be used.

Using the wind data available

The simplest wind statistic to calculate and one which is the most readily obtainable for meteorological services is the mean scalar wind speed. Empirical methods may be used with this parameter in estimating the specific criteria necessary for an assessment of the wind energy potentialities. For example, diagrams have been constructed showing the percentage of time during which the wind blows at speeds in excess of certain specified values over a range of annual mean wind speeds. Such diagrams have been prepared for stations in South Africa and figure 1 was constructed from statistics of wind frequencies within specified ranges of speed and the respective mean wind speed values for a number of different stations where hourly observations have been made over a period of years. Golding and Stodhart[1] have shown how to obtain a relationship, applicable to the British Isles, between annual mean wind speed and specific power output (figure 2).

[1] Golding, E. W. and Stodhart, A. H., The selection and characteristics of wind power sites, *Electrical Research Association, Technical Report Ref. C/T108*, 1952.

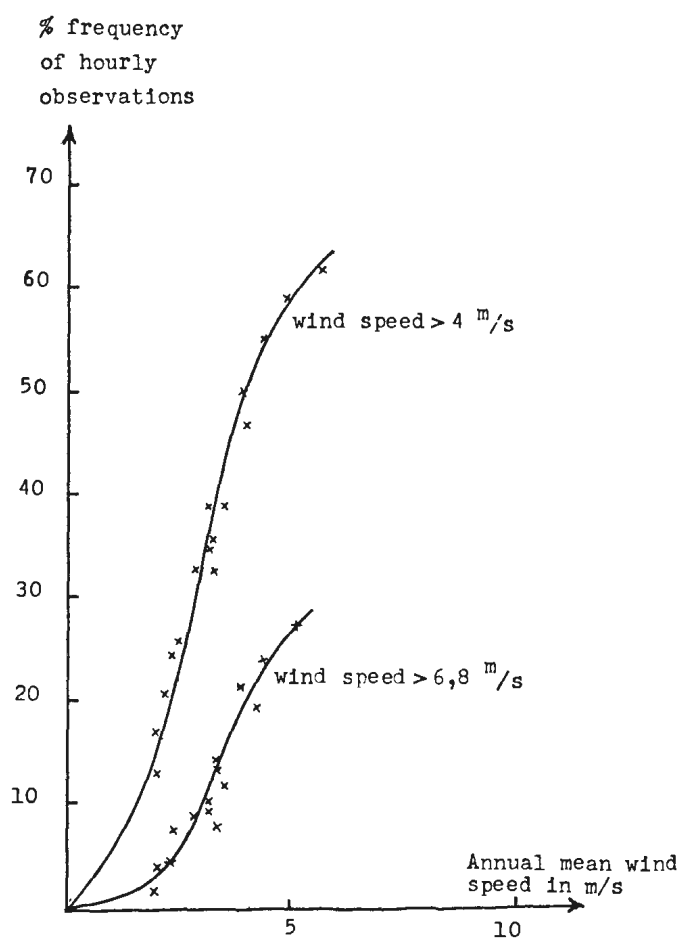

Figure 1. Relation between mean wind speed and percentage frequency of observations exceeding specified criteria

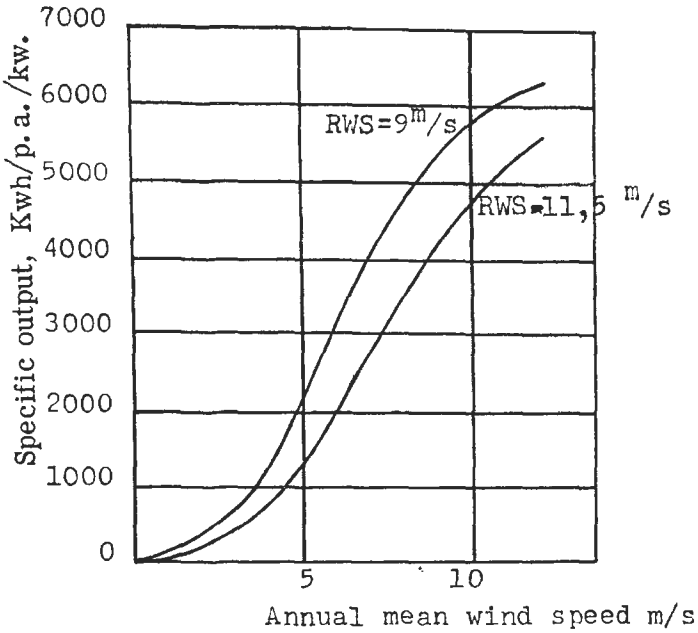

Figure 2. Graph showing relationship between output and mean wind speed. (RWS = Rated wind speed = speed at which wind generator gives full power output)

The mean scalar wind speed may thus be used in conjunction with diagrams of the above type to obtain an approximate estimate of the wind energy potentialities. A very rough estimate on a world scale may be obtained with the aid of figures 3 and 4 which illustrate the mean scalar wind speed pattern in metre per second over the globe for January and July respectively.

Regularly published wind measurements

The best way to obtain wind information in order to study the potential wind energy is to write to the various meteorological services concerned. Most countries publish wind observations together with other meteorological elements in monthly or annual bulletins which are distributed all over the world. However, the delay in publishing observations is sometimes considerable and the layout varies very much from country to country. In addition, the user is not always informed of the method of calculation of mean winds or even whether the various stations for which wind data are given are equipped with wind measuring instruments. Examples of the kind of information such bulletins give in so far as wind is concerned is shown below for three different countries or regions, namely, the West Indies, Thailand and the United Arab Republic.

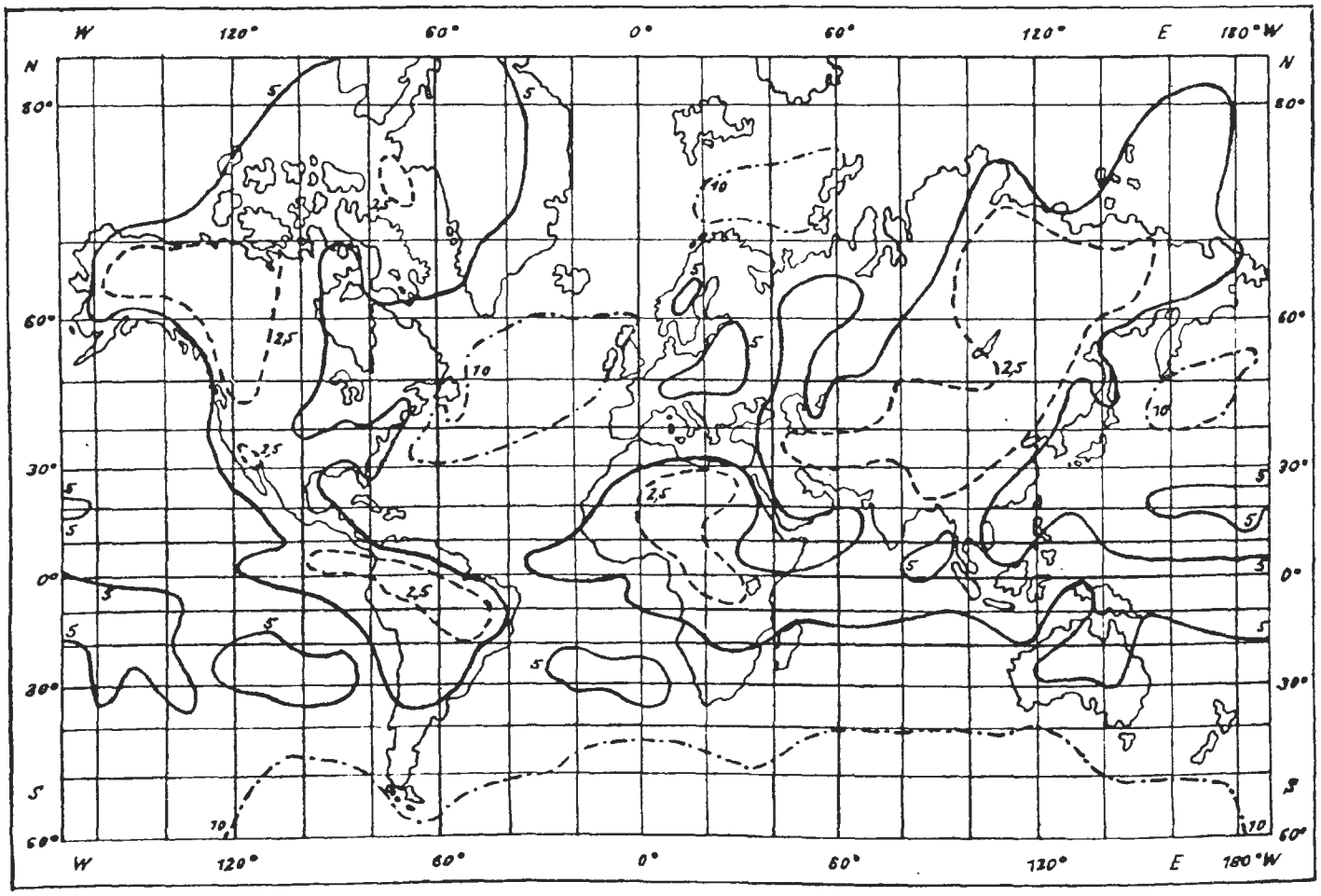

Figure 3. Mean scalar wind speed pattern in m/sec — January. (Lauscher — Archiv für Meteorologie, Geophysik und Bioklimatologie, 1951)

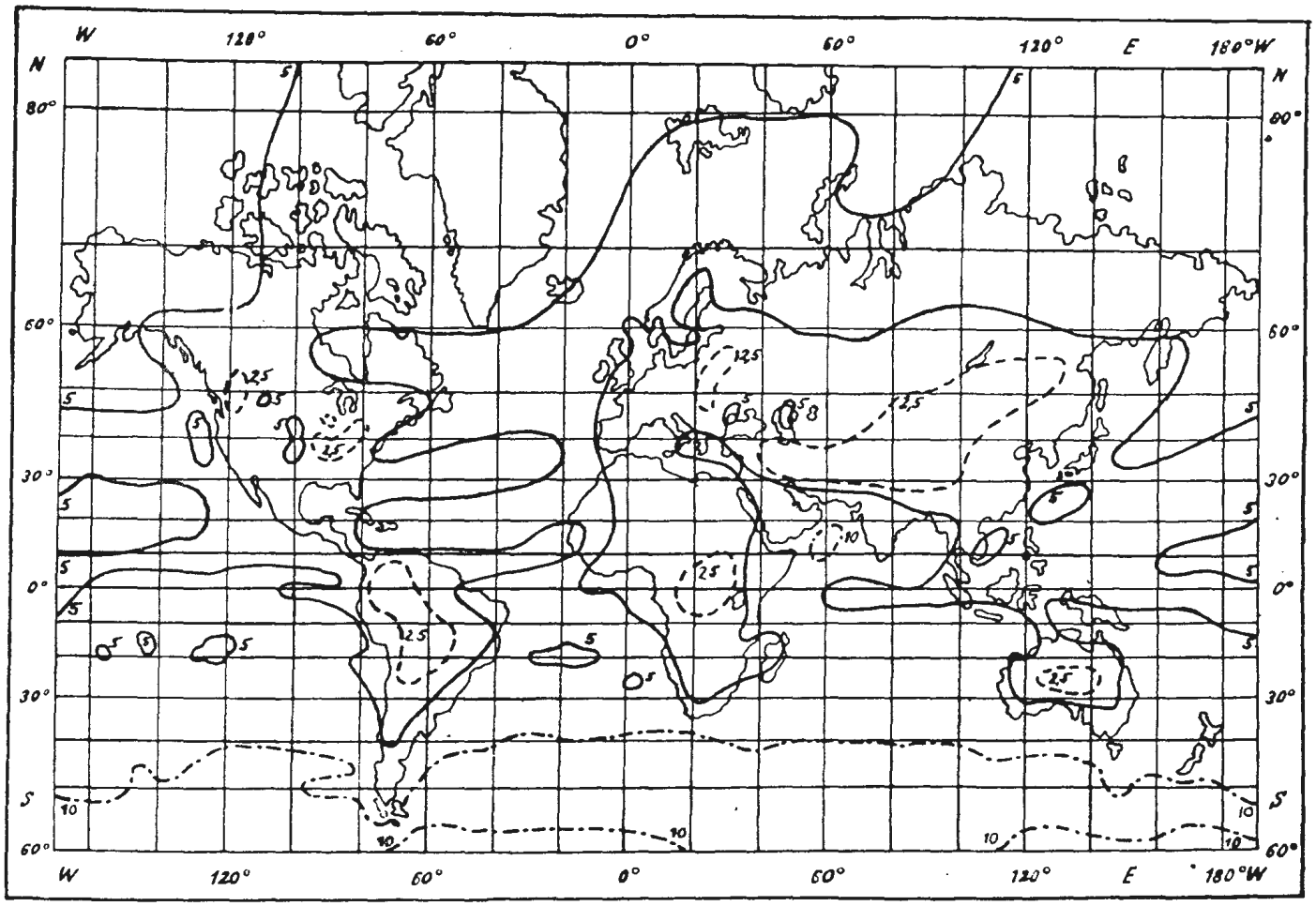

Figure 4. Mean scalar wind speed pattern in m/sec — July. (Lauscher — Archiv für Meteorologie, Geophysik und Bioklimatologie, 1951)

The West Indies Meteorological Service, Trinidad, publishes monthly and annual means for a great number of meteorological elements in an annual bulletin. The mean annual wind speeds listed in table 1 are thus taken from this bulletin for 1958.

Thailand publishes many meteorological data in the form of monthly and annual bulletins. The annual mean wind in Beaufort is given in a publication entitled: "Climatological data for the 10 year period 1943-1952" for 24 stations and these data are reproduced in table 2.

The United Arab Republic publishes both an annual and a monthly bulletin. In the monthly bulletin the frequency distribution of the wind direction for certain wind speed intervals is tabulated for about 30 stations. There are thus no mean wind speeds in this publication. Table 3 contains an example of a page from the "Monthly Weather Report" for February 1958.

Special surveys of existing wind observational information

As pointed out above, the annual and monthly bulletins do not provide information on all the data available. If a more thorough investigation is to be

Table 1. Mean annual wind speed at 23 stations in the West Indies published in the West Indies Meteorological Service, climatological summaries, 1958

Station	*Wind speed in knots*
Green Turtle Cay, Abaco	8.9
West End, Grand Bahama	8.2
Alice Town, Bimini	8.9
Harbour Island	10.2
Windsor Airport, Bahamas	9.1
The Bight, Cat Island	7.5
Mongrove Cay, Andros	5.0
Riding Rock, San Salvador	11.4
George Town, Exuma	10.2
Clarence Town, Long Island	9.6
Albert Town, Fortune Island	8.7
Abraham's Bay, Mayaguana Island	8.5
Duncan Town, Ragged Island	9.9
Matthew Town, Inagua	8.0
Negril Point Lighthouse	3.6
Palisadoes Airport	7.7
Morant Point Lighthouse	9.4
Belize, British Honduras	4.6
Codrington, Barbados	7.1
Seawell Airport, Barbados	11.7
Pearl's Airport, Granada	8.2
Piarco Airport, Trinidad	5.0
Atkinson Field, British Guiana	3.4

Table 2. Mean annual wind force at 24 stations in Thailand published in climatological data for the 10-year period 1943-1952

Station [a]	*Wind force in Beaufort (0-12)*
Bangkok	1.2
Don Muang	1.5
Lopburi	1.6
Nakhon Sawan	1.2
Phitsanulok	1.0
Sattahib	2.4
Chanthaburi	1.6
Uttaradit	1.2
Chiangmai	0.9
Chiangrai	0.9
Mae Hongson	1.3
Nakhon Ratchasima	1.2
Ubon Ratchathari	1.1
Udon Thani	1.1
Prachuap Khirikhan	2.2
Songkhla	2.2
Hua Hin	1.6
Chumphon	1.5
Ban Don	1.5
Phuket	1.1
Nakhon Si Thammarat	1.5
Roi Et	1.7
Aranyaprathet	1.2
Mae Sot	0.8

[a] Some of these stations are equipped with anemographs of the Dines Pressure Tube Pattern, but there is no indication in the publication as to which of the stations have this instrument.

carried out on the practicability of using wind energy, it is necessary to conduct an inquiry with the meteorological services concerned. An example of such an inquiry is given below. It was undertaken in connexion with a symposium on solar and wind energy organized by the Government of India and UNESCO in the autumn of 1954 and concerned mainly the arid and semi-arid regions of the world.

A large number of countries were requested to supply the WMO secretariat with all available wind observational information. The result of the inquiry was published in WMO Technical Note No. 4 "Energy from the wind". This note contains not only the results of the inquiry but also a chapter dealing with the general principles of wind energy and the first part of the present paper is a summary of this chapter. The results of the inquiry are presented country by country. For each country, a list of wind stations is given indicating the latitude, longitude and altitude of each station, the period covered by the record and whether the record is autographic, instrumental, non-autographic or visual. The note also states whether the records are published or unpublished.

Mean seasonal and annual wind speeds are given for some of the stations. On the basis of these figures and present knowledge of the general circulation a brief summary of the wind regime for each continental region has been included. No attempt is made in these summaries to judge the practicability of tapping the wind regime as a source of energy. Such conclusions are left for the engineer or the economist and the note deals only with the meteorological side of the question.

For the purpose of the present paper it will suffice to give a very brief summary of the data presented in the Technical Note. In table 4 the number of instrumental stations listed in the note is indicated for each country. The number of these stations for which mean wind speed values appear in the note is also given. The highest and lowest mean annual wind speeds reported in each country are listed to give a brief idea of the magnitude of the winds. The countries are listed by continent. Brazil preferred to present the annual mean wind speeds in the form of a map (figure 5) with isopleths of the speeds.

The summaries of the wind regime for each continental region given in the Technical Note are published below.

Africa

The continent of Africa straddles the tropical and equatorial zones of the globe. Only in the extreme south does it truly touch the wind regime of the temperate westerlies.

The northwest and southwest coasts of the continent are exposed to the prevailing circulation around the Atlantic sub-tropical anticyclones. The cool ocean currents which flow along these coasts cause a sharp land sea temperature contrast. This injects the offshore component of the wind with new energy, creating a vigorous sea breeze effect.

The picture for the realization of wind energy potentialities in the continent of Africa is a promising one. Very favourable sites can be found along the coasts of Tunisia, French and Spanish West Africa, in the Cape Verde and Canary Islands and in Madagascar. It is highly probable that similar good sites exist throughout the whole length of the African coast from Egypt to French West Africa and along the western and southwestern coasts of the Union of South Africa. Sites could perhaps be found along the Red Sea coast which are favourable in certain months of the year. All these favourable coastal sites possess wind regimes which, particularly in summer, are reinforced to a great extent by sea-breeze effect caused by strong insolation. During the warm months the winds blow, therefore, with fairly steady day-to-day regularity.

Inland regions are less favourable but possible good sites may exist in a number of regions such as British East Africa and Sudan. Mean wind speeds are lacking for extensive areas so that it is difficult to make accurate conclusions here. Nevertheless, a glance at the tables for Africa shows that wind stations and records are available within meteorological services in a large part of the continent. Further conclusions cannot be drawn until these data have been studied in detail.

Table 3

District and station	Calm (hours)	Variable (hours)	Un-recorded (hours)	Wind speed in knots	Number in hours of occurrences of wind blowing from the ranges of directions indicated																
					N	*NNE*	*NE*	*ENE*	*E*	*ESE*	*SE*	*SSE*	*S*	*SSW*	*SW*	*WSW*	*W*	*WNW*	*NW*	*NNW*	*All directions*
Coastal																					
				1-10	7	9	20	38	117	50	22	8	12	30	24	14	7	9	16	7	390
				11-27	1	0	0	0	5	5	4	0	21	40	45	11	5	1	1	2	141
Jableh . . . . (A)	137	0	0	28-47	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0	0	4
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	8	9	20	38	122	55	26	8	33	71	71	26	12	10	17	9	535
				1-10	1	0	0	0	22	52	15	21	7	48	27	18	4	0	0	0	215
				11-27	1	0	0	0	10	1	0	1	0	2	0	4	2	0	0	0	21
Bouka	403	0	33	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	2	0	0	0	32	53	15	22	7	50	27	22	6	0	0	0	236
Western Inland																					
				1-10	22	52	28	29	45	20	11	20	28	19	9	23	32	11	15	12	376
				11-27	4	3	0	0	1	1	0	0	0	0	3	3	7	33	24	12	91
Damascus . . (A)	202	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	3
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	26	55	28	29	46	21	11	20	28	19	12	26	39	45	41	24	470
				1-10	20	51	93	25	14	0	5	11	18	4	16	13	12	8	8	4	302
				11-27	7	16	21	8	1	0	2	8	17	17	12	3	0	5	3	1	121
Aleppo . . . (A)	249	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	27	67	114	33	15	0	7	19	35	21	28	16	12	13	11	5	423
				1-10	38	18	23	51	45	0	1	5	14	8	10	32	38	22	34	33	372
				11-27	10	7	0	1	0	0	0	0	2	1	8	33	45	5	8	2	122
Hama . . . . (A)	177	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	48	25	23	52	45	0	1	5	16	9	18	65	84	27	42	35	495
				1-10	0	0	1	13	23	42	21	23	20	7	6	4	5	0	0	0	165
				11-27	0	0	2	4	3	0	0	2	8	2	2	5	4	0	0	0	32
Kharabo	475	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	0	0	3	17	26	42	21	25	28	9	8	9	9	0	0	0	197
				1-10	57	15	0	0	0	0	0	0	0	0	28	43	45	4	2	2	196
				11-27	6	0	0	0	0	0	0	0	0	0	7	20	10	0	0	0	43
Salamiyie	433	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	63	15	0	0	0	0	0	0	0	0	35	63	55	4	2	2	239

Table 3 *(continued)*

District and station	Calm (hours)	Variable (hours)	Un-recorded (hours)	Wind speed in knots	Number of hours of occurrences of wind blowing from the ranges of directions indicated																
					N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	All directions
Western Inland																					
				1-10	1	0	0	0	36	0	0	3	0	8	0	20	0	0	0	0	68
				11-27	1	0	4	0	38	1	0	3	0	0	0	8	0	0	0	0	55
Fiq	12	0	532	28-47	0	0	0	0	3	0	0	2	0	0	0	0	0	0	0	0	5
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	2	0	4	0	77	1	0	8	0	8	0	28	0	0	0	0	128
				1-10	0	0	1	0	26	0	5	0	6	0	2	0	16	0	0	0	56
				11-27	0	0	4	0	8	0	3	0	1	0	0	0	5	0	0	0	21
Tell Shihab . . .	7	0	588	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	0	0	5	0	34	0	8	0	7	0	2	0	21	0	0	0	77
Desert																					
				1-10	27	17	21	16	13	0	13	10	12	11	64	62	55	32	37	40	430
				11-27	2	4	5	0	0	0	0	0	0	1	16	8	14	4	0	5	58
Palmyra . . . (A)	184	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	29	21	26	16	13	0	13	10	12	12	79	70	69	36	37	45	488
El-Gemirah																					
				1-10	3	5	6	12	0	8	19	8	17	51	51	29	22	19	3	12	265
				11-27	0	0	1	4	0	0	5	1	2	8	3	2	2	2	1	0	31
Deir Essor . . (A)	376	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	3	5	7	16	0	8	24	9	19	59	54	31	24	21	4	12	296
				1-10	19	5	1	6	2	0	2	0	3	0	2	1	12	2	9	6	70
				11-27	0	0	0	1	0	0	1	1	1	0	3	0	1	0	2	1	11
Raqqa	3	0	588	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	19	5	1	7	2	0	3	1	4	0	5	1	13	2	11	7	81
North-Eastern																					
				1-10	79	19	23	41	19	3	1	4	7	10	13	22	8	17	7	72	345
				11-27	112	4	12	18	5	0	0	0	0	0	1	3	1	0	0	33	189
Qamishlie . . (A)	138	0	0	28-47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				⩾ 48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				All speeds	191	23	35	59	24	3	1	4	7	10	14	25	9	17	7	105	534

Table 4

Country	A	B	Min. (m/s)	Max. (m/s)
Africa				
Algeria	6	6	1.4	4.6
Angola	6	6	1.1	3.6
British Central Africa	17	17	—	5.1
British East Africa	21	10	2.0	5.4
British West Africa	52	6	1.4	5.1
Canary Islands	17	14	2.9	7.4
Cape Verde Islands	2	2	5.3	5.8
Egypt	50	5	2.4	5.0
French Equatorial Africa	11	—	—	—
French West Africa	2	2	3.1	7.0
Libya	10	8	2.7	6.3
Madagascar	10	6	4.5	8.3
Madeira	1	1	1.6	1.6
Mozambique	41	—	—	—
Spanish Guinea	2	—	—	—
Spanish Morocco	7	1	4.5	4.5
Spanish West Africa	2	2	2.5	4.2
Sudan	14	13	1.5	4.4
Union of South Africa	22	18	1.9	6.3
Tunisia	12	11	2.6	5.9
Asia				
Arabia	5	5	1.7	5.6
Burma	11	11	0.7	3.6
Ceylon	3	3	2.3	4.2
Hong Kong	1	1	3.9	3.9
India	18	18	1.4	4.9
Iran	14	5	0.6	3.8
Iraq	1	1	4.1	4.1
Israel	33	10	2.4	5.1
Macao	1	1	3.1	3.1
Pakistan	49	31	0.5	4.0
Turkey	74	74	0.5	3.8
Australia				
Australia	26	2	4.6	7.1
North America				
Canada	25	25	1.7	6.6
South America				
Argentina	31	31	0.6	5.0
Brazil	66	—	(see figure 5)	
Uruguay	22	—	—	—

A = Total number of instrumental wind stations.
B = Number of stations for which annual mean wind speeds are given in the technical note.
Min. = The lowest speed in m/s reported from any station.
Max. = The highest speed in m/s reported from any station.

Asia

The continent of Asia extends from the equator to the polar seas. The main features of the circulation from the point of view of steady wind flow are the outflow from the Siberian anticyclone in winter and the influx of the monsoon across the equator into India and South East Asia in summer. Much of the continent falls under regimes of light and variable winds, particularly during the transition seasons.

Persistent strong winds may blow along the Pacific coast of the continent in winter. Constant north-east trade winds blow in winter around the subtropical Pacific anticyclone across the Philippine Islands and neighbouring seas.

In summer there are persistent northerly winds along the Arctic coast. South-easterly winds along the North Pacific coast blow around the Pacific anticyclone which has shifted northwards, following the movement of the sun. The Indian SW summer monsoon is stronger than the NE winter monsoon. Thus the mean speed for Bombay during the height of the former season is 6.3 m/s compared with only half that value in winter.

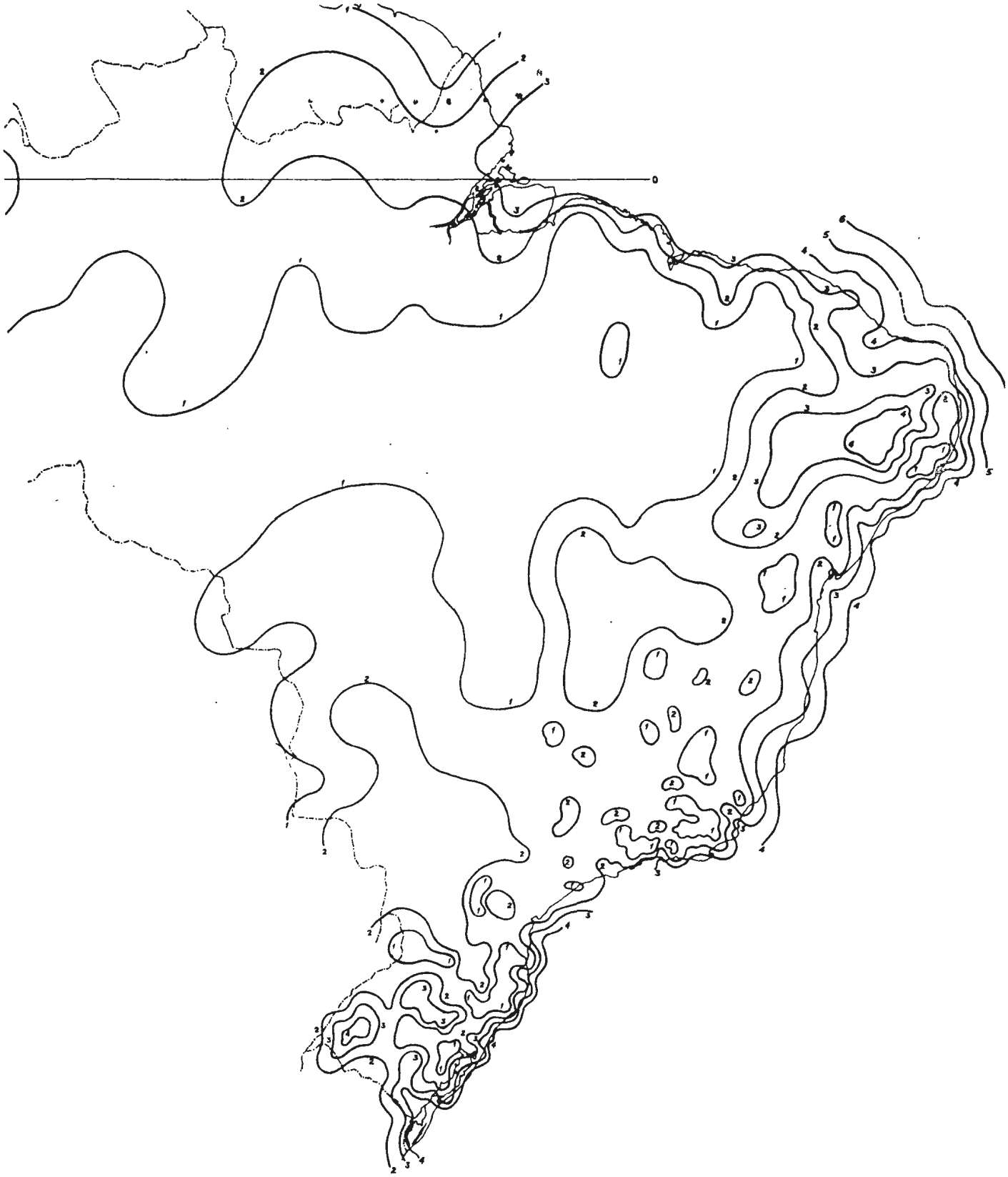

Figure 5. Mean annual wind speed in Brazil

A number of areas appear suitable for the utilization of wind energy. Favourable sites should exist in India, Pakistan, Israel and along the Arabian coast, although the economic generation of power for purposes other than domestic may be confined in some areas to certain months of the year.

Australia

Australia largely falls under the influences of the circulation around the subtropical anticyclonic belt. The north of the continent is dominated by a south-easterly trade wind circulation while the extreme south and south-west extends into the belt of prevailing westerlies. The centre of the continent possesses a light variable wind regime. The whole regime, south-westerly trades in the north, light variable winds in the centre, and variable westerlies in the south, shifts northwards and southwards with the sun according to the season of the year. These climatic wind regimes are, however, considerably modified by day-to-day variability caused by migratory pressure systems.

The strong sea breeze effects play a very important role in the wind regime of the entire coastal belt of Australia. This phenomenon is highly developed and good advantage may be taken of it in planning any project for the utilization of wind energy in the coastal areas of this continent.

North America

The northern half of the North American continent is largely subject to the wind variability of the temperate westerlies. Along the Pacific coast of the United States persistent north-west winds blow in summer around the eastern side of the Pacific subtropical anticyclone. The on-shore component south of about 40°N is intensified by a strong sea breeze effect.

In tropical latitudes the trade wind circulation produces steady east or north-east winds in exposed places.

Areas most suitable for the utilization of wind energy are to be found along the coasts and in the region of the Great Plains east of the Rocky Mountains where the flat relief affords little obstruction to wind flow. Thus the mean wind speeds at Swift Current and Churchill show useful values for wind energy purposes.

One of the windiest places in the North American area is probably off the south coast of Newfoundland. Wind energy meters installed on the French Islands of Miquelon and Saint Pierre show annual mean totals of 5 800 and 5 250 kw/h/m^2 respectively.

South America

The South American continent extends from the northern hemisphere tropics deep into the strong westerly belt of the Southern Ocean. General westerly winds are observed in all seasons south of about 40°S latitude. In all seasons east and north-east winds prevail along the coast of Brazil from 10°S to the equator. The north-east trade winds of the northern hemisphere are observed to the north; these are stronger and more persistent in the latter half of the southern hemisphere summer when the doldrum belt is furthest south.

Along the coasts of Peru and Chile strong SW winds blow around the Pacific subtropical anticyclone. The gradient is intensified in summer by the sharp temperature contrast between the cold ocean current and the hotter inland areas. This cold ocean current caused by upwelling, is similar to those other currents which are found in subtropical latitudes off the western coasts of the continents which border the eastern sides of the vast subtropical anticyclones.

Light and variable winds exist over much of the central part of the continent but sites offering good wind energy potentialities may be found in many coastal regions, particularly along the western coast. Good sites may also be found south of about 40°. Cape Horn, in fact, has long been recognized as one of the windiest places in the world.

Wind stations set up specially for the investigation of wind power potentialities

So far we have dealt with the type of wind data which are published or may be obtained from meteorological services. These data should suffice for making a broad survey of the possibilities of utilizing the wind energy in any given country. These data would not, however, be sufficient for engineers to select sites at which generators should be installed or to enable the economist to determine in detail the economic aspects of the question. For such a purpose it is necessary to carry out detailed field investigations. More detailed studies of the wind energy possibilities of this nature have been undertaken in many countries and special wind stations have been set up.

In French West Africa, for instance, wind energy counters designed for this specific purpose were used in the years from 1948 to 1952. Twenty different stations were equipped with such instruments. Many other countries have undertaken similar investigations, some of which have been sponsored by WMO under the Expanded Programme of Technical Assistance.

Conclusion

It can be seen from this paper that existing wind observations are not always available in an ideal form for use in wind energy calculations. There is, however, a general trend for the climatological departments of meteorological services to calculate the frequency distribution of meteorological data instead of means. Another factor favourable for wind energy calculations is the increasing storage of climatological data, including wind data on punch-cards. These cards greatly simplify the extraction of the wind statistics most suitable for this purpose.

Summary

The simplest wind statistic to calculate and one which is the most readily obtainable from meteorological services is the mean scalar wind speed. But that is not the ideal statistic for the assessment of wind energy. Because of the character of the wind turbine, the ideal statistic would be one which showed the percentage frequency of the time when the wind blew at different speeds. It is however shown that in order to obtain a very general assessment of the wind energy potentialities the monthly or annual mean wind speed may be used by utilizing empirical methods. Two examples are given. Figure 1, that has been constructed from statistics of wind frequencies for stations in South Africa, shows the relation between mean annual wind speed and percentage frequency of hourly observations exceeding two different wind speeds. Figure 2 shows a relationship, applicable to the British Isles, between annual mean wind speed and specific power output. The mean scalar wind speed pattern over the whole earth for January and July are given in figures 3 and 4.

It is pointed out that the best way to obtain wind information in order to study the potential wind energy in more detail is to write to the various meteorological services concerned. The monthly or annual meteorological bulletins regularly published by most countries may however also be most useful. Examples of the kind of information such bulletins give in so far as wind is concerned are shown for three different countries or regions—namely, the West Indies (table 1), Thailand (table 2) and United Arab Republic (table 3).

Example is also given of a special survey of existing wind observational information carried out by WMO in connexion with a symposium on solar and wind energy organized by the Government of India and UNESCO in 1954. This survey, concerning mainly arid and semi-arid regions of the world, was later published as a part of the WMO Technical Note No. 4, "Energy from the Wind". A very brief summary of the data presented in this Technical Note is shown in table 4 and figure 5. Summaries of the wind regime for each continental region are also given.

The data which are published or may be obtained from meteorological services are however not always sufficient for engineers to select sites at which generators should be installed. For such purposes it may be necessary to carry out detailed field investigations by setting up special wind stations. Many countries have undertaken such investigations, some of which have been sponsored by WMO under the Expanded Programme of Technical Assistance.

Finally attention is called to the general trend for the climatological departments of meteorological services to calculate the frequency distribution of meteorological data instead of means, which together with the increasing storage of data on punch-cards greatly simplify the extraction of the wind statistics most suitable for wind energy calculations.

ÉTUDE SUR LES DONNÉES DISPONIBLES RELATIVES À L'OBSERVATION DU VENT

Résumé

L'élément le plus facile à calculer des statistiques relatives au vent, et celui que l'on peut se procurer le plus facilement auprès des services météorologiques, est la vitesse scalaire moyenne du vent. Mais ce n'est pas l'élément idéal pour l'évaluation de l'énergie éolienne. Eu égard aux caractéristiques de la turbine à air, le renseignement statistique idéal serait celui qui nous donnerait la fréquence en pourcentage du temps pendant lequel le vent souffle et les vitesses qui correspondent à ces pourcentages. On démontre cependant que pour obtenir une évaluation très générale des possibilités de l'énergie éolienne, la moyenne mensuelle ou annuelle de la vitesse peut être employée en ayant recours à des méthodes empiriques. On en donne deux exemples. La figure 1, qui a été établie d'après des statistiques relatives aux fréquences du vent pour des postes en Afrique du Sud, donne le rapport entre la vitesse annuelle moyenne du vent et la fréquence en pourcentage des observations horaires qui dépassent deux vitesses données. La figure 2 indique un rapport applicable aux Iles britanniques, entre la vitesse annuelle moyenne du vent et le débit spécifique d'énergie. Le régime des vitesses moyennes scalaires du vent sur l'ensemble du globe pour janvier et juillet est donné aux figures 3 et 4.

On souligne que le meilleur moyen d'obtenir des données sur le vent afin d'étudier l'énergie potentielle plus en détail, consiste à se mettre en rapport avec les divers services météorologiques en cause. Les bulletins météorologiques mensuels ou annuels qui sont publiés régulièrement par la plupart des pays peuvent également être fort utiles. Des exemples du genre d'informations que ces bulletins fournissent en ce qui concerne le vent, sont donnés pour trois pays ou régions : les Antilles (tableau 1), la Thaïlande (tableau 2), et la République arabe unie (tableau 3).

Un exemple est également donné d'une étude spéciale concernant les renseignements ayant trait aux observations faites sur le vent et préparée par l'Organisation Mondiale Météorologique en liaison avec une discussion sur l'énergie solaire et celle du

vent, organisée par le gouvernement de l'Inde et l'UNESCO en 1954. Ce travail qui portait principalement sur les régions arides et semi-arides du monde a, par la suite, été publié dans le cadre de la note technique n° 4 de l'organisation et intitulée « Énergie en provenance du vent ». On trouve un très bref sommaire des données présentées dans cette note technique au tableau 4 et à la figure 5. Des sommaires sur le régime du vent pour chaque région continentale sont également donnés.

Les données publiées ou que l'on peut se procurer auprès des services météorologiques ne sont cependant pas toujours suffisantes pour permettre aux ingénieurs de choisir les sites où il faut installer des centrales éoliennes. Dans ce but, il peut être nécessaire de procéder à des recherches détaillées sur place en organisant des stations anémométriques spéciales. Nombre de pays ont entrepris de telles recherches et certaines d'entre elles ont été faites sous les auspices de l'OMM, dans le cadre du programme élargi de l'Assistance Technique.

Finalement on attire l'attention sur la tendance générale, qu'ont les divisions climatologiques des services météorologiques, de calculer la répartition en fréquence des données météorologiques plutôt que des moyennes, ce qui, avec l'augmentation des archives constituées par des cartes perforées, simplifie beaucoup l'extraction des statistiques ayant trait au vent qui sont les plus indiquées pour le calcul de l'énergie éolienne probable.

Agenda item II.B.2

THE DESIGN AND TESTING OF WIND POWER PLANTS:

(*a*) Design

(*b*) Testing

Point II.B.2 de l'ordre du jour

PLANS ET ESSAIS D'INSTALLATIONS ÉOLIENNES :

***a*) Plans**

***b*) Essais**

Chairman — Président

Emanuele CAMBILARGIU

Rapporteur

Louis VADOT

PLANS ET ESSAIS D'INSTALLATIONS ÉOLIENNES

Louis Vadot *

Caractères fondamentaux de l'énergie éolienne

Il est nécessaire de rappeler tout d'abord les caractères propres à l'énergie éolienne, ces caractères ayant une influence fondamentale sur la constitution et l'utilisation des machines appelées à transformer cette énergie.

Deux faits essentiels dominent le problème de l'utilisation de l'énergie du vent : d'une part, la grande dilution de cette énergie dans l'espace, d'autre part, son irrégularité considérable et imprévisible.

On se trouve ici en présence d'une de ces énergies dont l'apparente gratuité donne toute son importance à l'économie de la construction, le prix de revient de l'énergie produite, dépendant uniquement du prix d'achat de l'appareil, de son entretien et du temps d'utilisation.

La puissance totale existant sous forme cinétique dans une veine d'air de 1 m² de section a pour expression :

$$N_t = 0{,}000\,613\ v^3$$

la puissance N_t étant exprimée en kW et la vitesse du vent v en m/s.

Le théorème de Betz indique la part de cette puissance qui est théoriquement récupérable; cette part ne représente que les 16/27 de la puissance totale, en sorte que l'on obtient comme puissance théoriquement récupérable par m² de section de vent :

$$N_b = 0{,}000\,364\ v^3$$

avec les mêmes unités que précédemment.

Il faut enfin tenir compte du rendement de la machine. Ce rendement, suivant le type d'appareil et la qualité de la construction, oscillera entre 80 p. 100 pour d'excellentes machines et 50 p. 100 pour des machines médiocres.

Il est raisonnable d'adopter comme valeur moyenne pour une première évaluation le chiffre de 70 p. 100, ce qui donne comme puissance effectivement utilisable par m² la valeur suivante :

$$N_{\text{eff}} = 0{,}000\,255\ v^3$$

Dans ces conditions et pour un vent de 10 m/s, la puissance qu'il est possible de recueillir effectivement par m² de surface balayée est de 0,25 kW seulement. Or, un vent de 10 m/s ne s'obtient que pour un nombre assez réduit d'heures dans l'année, ce qui diminue d'autant la puissance moyenne disponible annuellement. Suivant les conditions locales de vent, l'énergie annuelle disponible par m² de surface balayée peut varier entre 100 kWh pour des zones faiblement ventées et 500 kWh pour des zones fortement ventées. Ces chiffres montrent que le prix de la construction de la machine doit être particulièrement étudié pour rendre compétitif l'emploi de l'énergie éolienne.

L'irrégularité de la valeur de l'énergie disponible dans le vent est un autre facteur jouant un rôle très important sur la conception de la machine éolienne. L'irrégularité de la vitesse du vent disponible se manifeste de différente manière suivant l'échelle de temps que l'on considère, ainsi d'ailleurs que suivant la dimension de la machine.

On constate tout d'abord des variations importantes et très rapides à caractère aléatoire représentant l'effet de la turbulence atmosphérique au voisinage du sol. Puis, par des enregistrements de durée suffisamment longue, on observe des variations de la valeur moyenne de la vitesse du vent. Ces dernières variations sont plus directement liées aux facteurs météorologiques. Le premier type d'irrégularité a une influence considérable sur la résistance, et par conséquent sur la conception de la machine; le deuxième type d'irrégularité a principalement une influence sur le mode d'utilisation de l'énergie éolienne.

Indépendamment des irrégularités de turbulence et des irrégularités moyennes affectant le mode d'utilisation de l'énergie éolienne, un caractère fondamental et fâcheux de cette énergie réside dans l'écart considérable existant entre la puissance moyenne d'utilisation de la machine et la puissance accidentelle qu'elle fournirait en cas de tempête si des dispositifs particuliers n'étaient pas prévus. Il n'est pas rare de rencontrer des vitesses de vent en cas de tempête atteignant cinq fois la valeur de la vitesse moyenne pour laquelle la machine est équipée. Dans ces conditions, les efforts sur les structures fixes sont 25 fois plus forts et la puissance disponible dans la veine d'air 125 fois plus forte. On conçoit dès lors la nécessité de prévoir des dispositifs particuliers pour permettre à la machine de s'adapter à des conditions aussi variables.

Il convient enfin de noter que l'énergie éolienne disponible est influencée par le relief, en sorte que cet élément doit être pris en considération dans l'établissement d'un projet.

Principalement dans les régions vallonnées, seules les lignes de crête seront utilisables. Il résulte de l'effet du relief qu'on peut être amené à concentrer

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les zones de production en quelques points, ce qui influe sur le choix de la puissance à équiper par machine. De même, et pour une raison analogue, on peut être amené à concentrer en quelques points les machines éoliennes, cependant que les machines réceptrices seront réparties suivant les besoins. Un cas typique de ce genre sera l'emploi de l'énergie éolienne pour alimenter des pompes d'épuisement dans une région très vallonnée. Les pompes devront être installées dans les dépressions où le vent est faible, cependant que les machines éoliennes seront placées sur les crêtes. La dissociation obligatoire existant dans ce cas entre machines éoliennes productrices d'énergie et machines réceptrices conduit à l'adoption d'un moyen de transmission d'énergie et peut favoriser le groupement de plusieurs machines réceptrices alimentées par une même machine génératrice d'énergie.

Caractères fondamentaux du type d'utilisation de l'énergie

L'élément dominant ce problème est l'extrême irrégularité de l'énergie du vent. Cet élément impose dans une certaine mesure le type d'utilisation. Il sera traité ailleurs des problèmes particuliers de l'accumulation de l'énergie ou de la combinaison avec une autre source d'énergie. Néanmoins, on peut dire que seuls peuvent être retenus comme admissibles les types d'utilisation qui s'accommodent de l'irrégularité de la production d'énergie. A une époque où les horaires de travail n'étaient pas fixés ni imposés par l'interdépendance sociale, l'utilisation de l'énergie éolienne pouvait adapter son rythme de travail aux caprices du vent. Ceci peut être considéré comme possible dans certains cas et certaines régions, mais dans la grande majorité des cas, il faudra rechercher une utilisation qui n'oblige pas le travailleur à s'adapter au rythme du vent. Dans ces conditions, les utilisations les plus importantes seront celles qui offrent naturellement des moyens d'accumulation simples ou des moyens de compenser les effets de l'irrégularité de production. La production d'énergie électrique et le pompage de l'eau seront très certainement les deux applications principales de l'énergie éolienne. Il ne serait pas déraisonnable de considérer aussi la production directe de chaleur par freinage de la roue comme application domestique présentant un certain intérêt par suite de la possibilité d'accumuler facilement de la chaleur. Ce type d'utilisation n'a toutefois pas encore été envisagé de façon industrielle.

Le type d'utilisation de l'énergie éolienne joue un rôle dans la conception de la machine et influe de deux manières :

a) Par la vitesse de l'appareil récepteur nécessitant ou non un organe multiplicateur de vitesse entre la roue de l'éolienne et le récepteur (ce multiplicateur sera parfois un réducteur de vitesse pour certaines pompes à vitesse lente);

b) Par la nécessité ou non de régler la vitesse à une valeur constante.

Problèmes principaux que pose actuellement la mise en œuvre de l'énergie éolienne

La technique des éoliennes est déjà bien évoluée, mais elles ne peuvent pas encore, dans la plupart des cas, concurrencer les autres sources possibles d'énergie. Il reste à franchir le cap décisif de l'utilisation économique.

L'obtention des conditions économiques favorables posera notamment les problèmes suivants :

a) Adaptation des caractéristiques de la machine aux conditions de vent et au type d'utilisation;

b) Choix des dimensions et de la puissance équipée par machine;

c) Répartition de l'énergie désirée sur une ou plusieurs machines;

d) Choix du mode de construction, possibilité de réalisation en série, emploi de matériaux nouveaux (matières plastiques en particulier);

e) Adaptation aux conditions climatiques du point de vue de l'entretien et de la tenue aux corrosions.

Dans le domaine des essais, et toujours avec le même souci de réalisation économique, il convient de fixer les normes pour les petites machines d'une part, et pour les grandes d'autre part, ces dernières se présentant généralement d'une manière assez différente par suite de leur emploi en conjugaison avec un réseau d'énergie.

Mémoires présentés

C'est l'ensemble de ces problèmes qu'il aurait été souhaitable de voir traiter, étant donné l'objet particulier de cette Conférence. Certains de ces points n'ont été qu'abordés et d'autres ont été complètement ignorés; ceci tient sans doute à une participation relativement faible et malheureusement très incomplète.

Quatorze rapports ont été retenus, et les sujets traités peuvent être classés en cinq catégories :

1. Questions d'ordre général et calculs théoriques (Sterne, W/30; Hütter, W/31; Santorini, W/37).

2. Description et expérience des grosses machines (Juul, W/17; Armbrust, W/34; Kiss, W/36).

3. Description et expérience des petites machines (Moriya, W/5; Villinger, W/27; Havinga, W/32; Cambilargiu, W/39).

4. Essais pour la détermination de la puissance (Clausnizer, W/3; Delafond, W/9; Morrison, W/24).

5. Essais pour la détermination des efforts (Morrison, W/24; Askegaard, W/15).

Il est regrettable qu'aucun rapport ne provienne de France, où s'accumulent actuellement les essais et les études dans le domaine des grosses et moyennes machines, de l'URSS, qui possède certainement une riche expérience sur l'exploitation des machines de moyenne puissance, ni des États-Unis, qui, en dépit de l'expérience malheureuse et prématurée de Grandpa's Knob, ont commercialisé un certain nombre de petites machines intéressantes.

Problèmes principaux affectant la conception de la machine

Ce qui vient d'être vu, tant pour l'énergie du vent que pour son utilisation, permet d'établir une liste des problèmes principaux que soulève la construction d'une machine éolienne :

a) Économie de la construction imposée par l'extrême dilution de l'énergie éolienne;

b) Relativement grand diamètre de la roue, conséquence de la dilution de l'énergie;

c) En conséquence, vitesse de rotation de la roue assez faible, d'où nécessité d'un système multiplicateur de vitesse;

d) Construction particulièrement robuste des pales de la roue pour résister aux efforts de turbulence en combinaison avec les variations cycliques d'effort;

e) Système d'éclipsage des pales ou de la roue imposé par le grand écart existant entre le vent nominal et le vent maximum de tempête;

f) Régulation de vitesse ou adaptation des caractéristiques de la machine éolienne aux caractéristiques de la machine réceptrice.

A ces six points fondamentaux viennent s'ajouter d'autres points à caractères plus particulièrement économiques, tels que la détermination de la hauteur du pylone, de la puissance équipée, du point de rendement maximum en fonction des conditions de vent, et de la vitesse de rotation de régime normal.

Choix du type de machine

On peut dire qu'actuellement à peu près tous les types de machines susceptibles de transformer l'énergie cinétique du vent en énergie mécanique utilisable par un récepteur ont été essayés, en sorte qu'il est possible de se faire une opinion sur la valeur de ces différents types. Mis à part quelques fantaisies mécaniques sans lendemain, les machines utilisables se classent en deux grandes catégories :

a) Les machines dont l'axe du rotor est perpendiculaire à la direction du vent (et de préférence vertical);

b) Les machines dont l'axe du rotor est orienté suivant la direction du vent.

Dans la première catégorie, on rencontre les panémones et les rotors genre Savonius. Ces machines à axe vertical ont pour elles le grand avantage de ne pas nécessiter de dispositif d'orientation, pour les mettre dans le lit du vent. Le classique anémomètre à coupelles en est le type le plus simple et le plus connu. Cet avantage est toutefois lourdement payé par plusieurs inconvénients. La machine ne pouvant récupérer qu'une faible partie de l'énergie du vent traversant la surface balayée, le rotor sera grand pour une puissance faible. Les pales traversant deux fois le flux d'axe auront une vitesse spécifique plus faible que celles des autres machines. A égalité de puissance, la vitesse de rotation sera au moins deux fois plus faible que pour une machine de l'autre catégorie. Enfin, il est très difficile d'imaginer et de réaliser pour ces machines un dispositif d'éclipsage par grand vent. Toutes ces raisons ont fait abandonner les machines du type panémone. Il est très probable qu'elles ne sont appelées à aucun développement important. Elles peuvent toutefois être retenues pour certaines applications simples de machine de petite puissance, du fait de l'absence de dispositif d'orientation.

Les machines à axe parallèle à la direction du vent sont donc les seules machines appelées à un grand développement et pratiquement les seules à être construites actuellement. Il en existe de différentes vitesses spécifiques, comme nous le verrons.

Avant d'aller plus loin, il faut faire état de certains dispositifs préconisés pour améliorer les machines précédentes en augmentant leur vitesse de rotation. Parmi ces dispositifs citons les suivants.

Machine dont le rotor tourne au col d'une tuyère de venturi

Ce dispositif a été essayé à plusieurs reprises; il est efficace pour l'augmentation de vitesse, mais irréalisable économiquement, par suite de la nécessité d'orienter dans le vent l'ensemble de la tuyère et du rotor.

Éoliennes en série

Selon cette disposition, l'hélice principale comporte à l'extrémité de ses pales des moulinets de petit diamètre entraînant directement des génératrices. Ces moulinets étant attaqués par le vent relatif, dont la vitesse est plusieurs fois supérieure à celle du vent principal, il suffit de leur donner un faible diamètre pour absorber toute la puissance disponible. Ce dispositif ingénieux constitue en somme un multiplicateur de vitesse aérodynamique, mais on se heurte alors à une grande difficulté de réalisation par suite de la présence de masses tournantes à l'extrémité des pales principales.

Éolienne à dépression

L'emploi d'une hélice à pales creuses servant de ventilateur aspirant l'air à travers une turbine à air directement reliée à la machine réceptrice constitue également un moyen d'accroître la vitesse d'utilisation sans multiplicateur par une voie purement aérodynamique. Ce dispositif ingénieux a donné lieu à plusieurs réalisations dont la dernière en date est sans doute la machine Andreau de 100 kW actuellement installée à Alger (Delafond, W/8 et W/9). L'inconvénient grave de cette solution réside dans son très faible rendement. Le rendement global est en effet le produit des rendements de l'hélice, du ventilateur, de la turbine à air et de la génératrice. Le rendement propre de l'hélice est ici plus mauvais que pour une machine normale, par suite de l'obligation d'épaissir les profils pour obtenir une pale creuse de section suffisante. Le rendement de l'ensemble ventilateur-turbine à air doit être comparé au rendement d'un multiplicateur classique à engrenages. Alors que ce dernier

présente normalement un rendement de l'ordre de 95 p. 100 et plus, par contre l'ensemble ventilateur-turbine à air a un rendement médiocre. Les pertes les plus grandes se produisent à la sortie des pales creuses à la périphérie; toute l'énergie cinétique de l'air étant pratiquement perdue, le rendement d'une telle machine est environ deux fois plus faible que celui d'une machine normale à entraînement mécanique. Il en résulte une importante augmentation du diamètre de la roue pour une puissance donnée, ce qui fait perdre très largement l'avantage de la simplicité de la transmission.

D'autres dispositions ont également été envisagées, telles que machines contra-rotatives, machines à jante et transmission par courroies, etc.

Toutes ces conceptions, parfois très ingénieuses, doivent être considérées comme des curiosités; les réalisations qui en ont été faites prouvent largement leur manque d'économie. Dès lors, la seule machine susceptible de développement et qui a été suffisamment éprouvée par l'expérience est la machine du genre hélice orientée dans le vent et attaquant son récepteur soit directement soit par l'intermédiaire d'un multiplicateur. C'est uniquement de ce type de machine qu'il sera question dans la suite de cet exposé.

Choix du type de roue

De même que dans le domaine des turbines hydrauliques il est possible de réaliser des roues correspondant à toute une gamme de vitesses spécifiques, on caractérise en général la vitesse spécifique d'une roue par le rapport u/v de sa vitesse périphérique à la vitesse du vent.

Il est possible actuellement de pousser la vitesse spécifique des roues jusqu'à des valeurs u/v pouvant atteindre 10. Il ne semble pas qu'une telle valeur puisse être utilement dépassée sans mettre en œuvre des moyens aérodynamiques vraisemblablement coûteux, tels que le contrôle de la couche limite sur les pales. Il faut noter d'ailleurs qu'un accroissement exagéré du rapport u/v entraîne une diminution du rendement par augmentation des pertes relatives par frottement.

Les caractéristiques des roues sont telles que le couple moteur diminue, toutes choses égales d'ailleurs, quand on augmente la vitesse spécifique; en particulier, le couple de démarrage diminue très vite quand la vitesse spécifique augmente. Pour cette raison, on préfère les roues à faible vitesse spécifique pour l'entraînement des pompes de type à piston qui nécessitent un fort couple de démarrage et de faibles vitesses de rotation.

Mis à part le cas des récepteurs nécessitant un fort couple de démarrage, pour toutes les applications où il y a un récepteur entraîné à vitesse élevée, on choisira des roues à grande vitesse spécifique. Plusieurs tendances se manifestent dans cette voie. Il ne faut en effet pas perdre de vue que le point essentiel est la réalisation d'une machine économique; il convient donc de déterminer tous les facteurs affectant l'économie de la construction, et la vitesse de la roue n'est pas le seul. On peut ainsi être amené à choisir entre les deux cas extrêmes suivants :

a) Roue à très grande vitesse spécifique, amenant une réduction du prix du multiplicateur, mais d'une réalisation plus coûteuse par suite du fini d'exécution des pales et de la qualité des matériaux exigés pour leur fabrication;

b) Roue de vitesse spécifique moyenne, alourdissant par conséquent le multiplicateur, mais d'une réalisation plus rustique et par conséquent moins coûteuse.

On ne peut donc pas dire qu'il existe une solution aérodynamique optimum, et le choix de la vitesse spécifique de la roue doit rester lié aux possibilités de fabrication et à l'économie du mode de construction. Les mémoires reçus présentent deux machines : machine de la StudienGesellschaft Windkraft, d'une part (Armkrust, W/34), et machine danoise de Gedser d'autre part (Askegaard, W/15, et Juul, W/17), illustrant assez bien les deux tendances que nous venons d'indiquer. L'avantage d'un type par rapport à l'autre dépend du cadre économique dans lequel il se situe (moyens de production du pays constructeur, importance des séries, etc.).

Dans tous les cas, pour les applications mettant en jeu des récepteurs à grande vitesse de rotation, il ne semble pas qu'il y ait intérêt à adopter des vitesses spécifiques u/v inférieures à 4, et les procédés nouveaux de construction dont on parlera plus loin semblent indiquer que cette limite peut être plus élevée.

Nous allons examiner maintenant les différents éléments constituant la machine et les solutions généralement adoptées.

Construction des pales

Étant donné les vitesses spécifiques élevées, le nombre de pales est réduit. On a réalisé en Allemagne pour de très petites machines, des roues à une pale. La nécessité d'un équilibrage constituant un poids mort fait perdre beaucoup de son intérêt à cette solution. A titre de curiosité, indiquons le cas d'une petite machine à une pale creuse fonctionnant suivant le principe de l'aspiration d'air et entraînant une petite turbine air avec génératrice électrique constituant le contrepoids de la pale unique.

Le plus généralement, les roues comportent deux ou trois pales. Ici encore, le débat n'est pas tranché entre deux et trois pales. En effet, si deux pales conduisent à une réalisation plus économique de la roue et à une vitesse spécifique plus élevée, par contre des difficultés de vibration apparaissent complètement pour trois pales et au-delà, en sorte que les roues à trois pales paraissent d'un fonctionnement plus sûr et autorisent pour le reste de la machine une construction plus rustique.

Le tracé des pales a fait de grands progrès, tant grâce aux essais en soufflerie qu'aux développements des méthodes mathématiques de calcul. Les travaux de Hutter (W/31), entre autres, donnent à ce problème une solution très satisfaisante.

Les pales subissent des efforts tant du fait de la marche normale que du fait des irrégularités de turbulence et principalement des écarts en orientation. Des efforts alternés importants prennent naissance; aussi tous les matériaux utilisés pour la construction doivent-ils être capables de résister à un grand nombre d'alternances, de flexion et de torsion.

Les efforts subis par les pales en marche sont maintenant mieux connus (Morrison, W/24; Askegaard, W/15; Juul, W/17). Mais la difficulté des mesures est telle qu'il y a encore beaucoup à faire dans ce domaine, principalement en vue de la réalisation des machines de grande puissance.

La construction des pales est influencée par le montage au moyeu (pales fixes, pales orientables) dont il sera question plus loin à propos de la régulation. Plusieurs types de structure et plusieurs matériaux sont utilisés. Pour les petites machines rapides, le bois est encore assez utilisé; c'est d'ailleurs un matériau qui, convenablement traité, est très intéressant, par suite de son excellent rapport résistance/densité (Havinga, W/32).

Pour les machines plus importantes le métal est très employé (métal coulé pour petites pales; métal embouti et structures composites pour longerons, nervures et revêtements), suivant un mode d'utilisation dérivant de la technique aéronautique. Il faut bien reconnaître que les constructions entièrement métalliques ne s'adaptent pas toujours aisément aux difficultés de la réalisation des pales.

Parmi les matériaux nouveaux, les plastiques et principalement les plastiques armés au verre apportent des possibilités extrêmement intéressantes pour la réalisation des pales (Villinger, W/27). Ces matériaux, en effet, présentent un bon rapport résistance/densité, tiennent bien aux intempéries, résistent convenablement aux efforts alternés, et surtout possèdent d'excellentes qualités de mise en œuvre. Avec ces matériaux, il est possible de réaliser sans difficulté particulière les formes imposées par l'aérodynamique et de les combiner avec les besoins de la résistance. Enfin, et ceci est important, ils n'exigent pas d'outillage compliqué ni de personnel très spécialisé. Il semble bien que ces matériaux soient appelés à modifier complètement la technique des éoliennes. Dans le domaine des grandes machines, une éolienne de 100 kW a été réalisée et fonctionne en Allemagne, grâce aux travaux de la StudienGesellschaft Windkraft (W/34). En France, une machine de 150 kW a été réalisée par Neyrpic et fonctionne de façon satisfaisante suivant cette technique. Dans le domaine des machines de moyenne puissance, Neyrpic en France, a mis au point et construit depuis plusieurs années une série de machines pour production d'énergie électrique et pour pompage d'eau, machines dont les pales réalisées entièrement en plastique armé au verre ont donné d'excellents résultats.

L'emploi des pales en matière plastique facilite considérablement la réalisation des machines de grande puissance; en outre, par suite de la simplicité des moyens de fabrication, sa mise en œuvre peut être entreprise même dans des pays à faible industrialisation.

Mention particulière doit être faite des roues à faible vitesse spécifique pour machines lentes. Ces roues à grand nombre de pales sont généralement entièrement métalliques, et démontables pour le transport. Les pales sont en tôle galvanisée emboutie ou cintrée. Des essais ont été faits en Inde pour remplacer la tôle par des produits locaux d'origine végétale.

Parmi les solutions avantageuses empruntées au passé, il y a lieu de signaler la possibilité non suffisamment étudiée des roues à voiles (moulins grecs et portugais). Ces machines joignent à une grande simplicité de construction la possibilité d'un réglage et d'un éclipsage efficaces par grand vent en relachant la tension des voiles.

Type d'orientation

Deux solutions sont en présence : l'orientation en girouette, avec soit roue en amont du pylone et empennage, soit roue en aval du pylone; l'orientation commandée (détecteur de direction, rose des vents, démultiplication, etc.), qui peut être utilisée avec roue en amont ou en aval du pylone.

La mesure des efforts sur les pales du fait du sillage du pylone montre que les roues en amont du pylone sont plus favorables du point de vue fatigue de la pale, mais plus compliquées du fait de la nécessité d'un mécanisme d'orientation et de l'augmentation des efforts d'orientation. Pour les machines de petite puissance, qui doivent être très économiques, l'orientation en girouette avec ou sans empennage s'impose. Pour les grandes machines, l'empennage devient trop lourd et trop coûteux, mais on utilisera indifféremment les roues amont et aval. La question des oscillations d'orientation avec roue aval montée en girouette pure n'est pas encore suffisamment éclaircie pour qu'il soit possible de se prononcer en faveur de l'une ou l'autre solution.

Dispositifs de régulation

Ce dispositif peut avoir deux fonctions à remplir : il peut être utilisé comme régulateur de vitesse si la machine réceptrice l'exige; il sera utilisé comme limiteur de puissance et limiteur d'effort sur les pales en cas de grand vent.

Le nombre des solutions adoptées est assez grand. A part les machines lentes à grand nombre de pales, pour lesquelles le principe de l'éclipsage de l'ensemble de la roue s'est généralisé, on rencontre deux grandes classes de solutions : la régulation à pales orientables et la régulation à pales fixes.

La première solution utilise une technique analogue à celle des hélices d'avion à pas variable et des tur-

bines hydrauliques Kaplan. Elle permet l'adaptation de la roue à différentes conditions de vent, et en particulier autorise la mise en drapeau par grand vent, avec effort minime sur les pales.

C'est une solution qui présente évidemment une certaine complexité mécanique mais donne une grande souplesse de manœuvre. La commande des pales dans ce cas peut être faite de différentes manières suivant la qualité du réglage. Elle peut être automatique grâce à des systèmes de ressort (machines Neyrpic) ou à volets Flettner (en URSS) ; elle peut être sous la dépendance de régulateurs classiques de puissance ou de vitesse (mémoire Armbrust, W/34).

La deuxième solution est généralement utilisée en combinaison avec des profils autorégulants dont les caractéristiques présentent un décrochement pour une certaine vitesse. Elle peut également être utilisée en combinaison avec des freins aérodynamiques commandés par un réglage de vitesse ou de puissance (machine danoise de Gedser, voir mémoires W/15 et W/17).

Dans les deux solutions, le réglage résulte d'une bonne combinaison des caractéristiques de l'éolienne avec celles de la machine réceptrice. A ce sujet, il faut signaler l'excellente conjugaison qui existe entre éolienne et pompe du type centrifuge ou hélice, l'emploi d'une telle pompe constituant en soi un système de régulation avec conjugaison optimum des rendements (l'emploi d'un frein hydraulique pour production d'eau chaude jouit des mêmes propriétés). On peut donc dire que le pompage est une utilisation remarquablement intéressante de l'éolienne si la combinaison des caractéristiques a été convenablement étudiée.

Dans le cas d'emploi avec génératrice débitant sur un réseau, les échanges de courant magnétisant assurent automatiquement le maintien de la vitesse constante, en sorte que le dispositif de régulation se ramène essentiellement à un limiteur de puissance pour grand vent.

Multiplicateur de vitesse

Dans la grande majorité des cas, le multiplicateur interposé entre la roue et la machine réceptrice est du type à engrenages à un ou plusieurs trains. La technique du multiplicateur à engrenages est maintenant tout à fait au point et permet d'utiliser des appareils d'un rendement excellent et d'une grande sécurité de marche. Ces appareils peuvent être utilisés jusqu'à des puissances élevées dépassant nettement le millier de kW.

Les transmissions par chaînes ou par courroies essayées dans certains cas pour leur rusticité ne bénéficient pas encore d'une expérience suffisante dans le domaine des éoliennes pour qu'on puisse les considérer comme des concurrents sérieux des multiplicateurs à engrenages.

A part les machines à aspiration d'air, il n'a pas été fait usage de transmission fluide qui puisse être considérée comme d'un intérêt industriel.

Dans le cas de l'entraînement de génératrices à courant alternatif, on peut envisager l'absence de multiplicateurs par l'emploi d'alternateurs à très grand nombre de pales (Kiss, W/36). L'examen de cette question ne peut être abordé que par les constructeurs de matériel électrique. Il ne faut toutefois pas oublier que l'emploi d'un multiplicateur permet d'utiliser pour la génératrice un matériel de caractéristiques classiques pouvant généralement être pris sur catalogue, donc d'un prix assez réduit, alors que l'alternateur à grand nombre de pales sera obligatoirement une machine spéciale coûteuse.

Pylones

Le choix du pylone est intimement lié, quant à la hauteur, au problème de la production d'énergie éolienne et au prix de revient de cette énergie, et quant à la structure, au problème délicat des vibrations.

L'intérêt économique qu'il y a à augmenter la hauteur d'implantation de la roue, c'est-à-dire la hauteur du pylone, est dû à l'existence d'un gradient de vitesse du vent en fonction de la hauteur au-dessus du sol. Ce gradient dépend principalement de la nature du sol de la région. Une détermination précise de la valeur moyenne de ce gradient peut seule justifier l'emploi d'un pylone de grande hauteur.

Normalement, le principal souci est d'élever la roue au-dessus de la couche très turbulente près du sol. Suivant les conditions de relief, cette couche présente une épaisseur plus ou moins grande. En moyenne, on peut considérer que la hauteur la plus favorable pour une machine d'une certaine puissance est de l'ordre de grandeur du diamètre de la roue. Au sommet d'une colline, l'épaisseur de la couche turbulente diminuant par effet de relief, on peut adopter une hauteur plus faible. Pour les très petites machines, la hauteur du pylone sera de l'ordre d'une dizaine de mètres, toujours dans le même but.

Le type de structure le plus courant est le pylone en treillis métallique de forme pyramidale à quatre côtés. L'emploi de fers de cornière est de beaucoup le plus économique; la construction en tubes, plus avantageuse au point de vue de la traînée dans le vent et du sillage, est nettement plus coûteuse.

Toujours en partant de la structure en treillis métallique, d'autres combinaisons sont possibles, telles qu'un mât avec plusieurs pieds. Une solution un peu moins fréquente est constituée par un mât haubané, le mât lui-même pouvant être soit en treillis métallique, soit en tube d'un seul élément.

Qu'il s'agisse d'une solution ou d'une autre, une étude sérieuse des vibrations doit être faite, surtout pour les machines d'une certaine importance. Cette étude nécessite la détermination des fréquences propres de flexion et de torsion du pylone, étude pouvant entraîner des renforcements pour éviter la mise en résonance du pylone sous l'influence des efforts alternés dus à la rotation de la roue.

Une question importante peut être soulevée à propos du pylone : c'est celle du montage de l'ensemble de la machine. Il peut être d'un grand intérêt d'utiliser le pylone lui-même ou certaines de ses parties comme moyen de montage. Pour les machines de petites et moyennes puissances, le procédé de montage le plus simple consiste à assembler toute la machine au sol, puis à la dresser au moyen d'une chèvre en faisant pivoter le pylone autour de deux de ses pieds.

Essais

On considérera, d'une part, les essais ayant pour but d'étudier certains éléments de la machine ou de déterminer les efforts auxquels elle est soumise, d'autre part, les essais de puissance et de fonctionnement proprement dit. La première catégorie d'essais (mémoires de Morrison, W/24, et de Askegaard, W/16) est d'un grand intérêt pour le constructeur ou pour l'aérodynamicien; la seconde catégorie (mémoires de Clausnizer, W/3, et de Delafond, W/9) intéresse plus particulièrement l'utilisateur.

La difficulté essentielle des essais de puissance réside dans la grande irrégularité de turbulence du vent, irrégularité qui oblige l'expérimentateur à faire un grand nombre de points de mesure, puis à interprêter ces résultats pour en déduire des valeurs de régime permanent. Indépendamment de l'irrégularité, la répartition aléatoire des vents moyens est un facteur qui contribue à augmenter considérablement la durée des essais.

Si la mesure d'une puissance sans cesse variable pose des problèmes assez sérieux, la plus grande difficulté réside bien dans la détermination du vent moyen traversant la surface balayée à l'instant où est faite la mesure de puissance.

Cette détermination est sujette à caution du fait que la mesure de vitesse de vent ne peut être faite sur toute l'étendue de la surface balayée et que, d'autre part, elle est faite à une certaine distance de l'emplacement de la roue. Ces considérations montrent que les résultats d'essais sont toujours critiquables. Il serait souhaitable, pour réduire la durée des essais, de pouvoir effectuer des mesures en régime variable. En outre, une meilleure connaissance de la turbulence du vent paraît nécessaire. Il n'est pas exclu, enfin, que l'on s'oriente, surtout pour les grosses machines, vers une détermination des caractéristiques uniquement à partir d'essais sur modèle en soufflerie, comme cela se fait déjà pour les turbines hydrauliques. Il est en effet beaucoup plus commode de fixer les caractéristiques du vent et d'opérer en régime permanent. Il est bien entendu, toutefois, que le passage des essais en soufflerie aux caractéristiques industrielles devra faire intervenir un coefficient d'échelle ou une formule de passage dans le genre des formules Moody ou Ackeret, utilisés en hydraulique.

Sujets de discussion proposés

1. Influence de la conception et du type de construction sur le prix de revient de l'énergie éolienne.

2. Influence du choix de la dimension et de la puissance de la machine sur le prix de revient.

3. Mode de fabrication, choix du nombre de machines pour une puissance donnée et influence de l'importance des séries de fabrication sur le prix de revient.

4. Possibilités offertes par l'emploi de matériaux nouveaux, principalement dans le domaine des plastiques, et possibilité de fabrication locale.

5. La méthode simple d'essai accéléré présentée par Clausnizer (W/3) comparée à l'enregistrement photographique presque continu du tableau d'instruments, de Delafond, comme base pour les calculs d'études techniques.

6. Les mesures des efforts subis par les pales en relation avec la vitesse du vent et la puissance obtenue, telles qu'elles ont été faites par Morrison (W/24) et la technique danoise, exposée notamment par Askegaard (W/15).

7. Comparaison des plans d'appareils très complexes avec des plans simples ou même primitifs : modèle allemand d'une part (W/31 et W/34) et modèles danois et japonais d'autre part (W/13, W/17, W/5). Application de l'aérodynamique au dessin des pales par Hütter, s'opposant à la machine de Gedser et au moteur japonais de 15 watts avec réglage automatique du pas.

8. Utilisation d'alternateurs synchrones avec prise directe dans l'installation expérimentale hongroise de 200 kW, en vue d'éliminer la transmission à engrenages. Avantages et inconvénients.

THE DESIGN AND TESTING OF WIND POWER PLANTS

(Translation of the foregoing report)

Louis Vadot *

Fundamental characteristics of wind power

The inherent characteristics of wind power must first of all be recalled, since they exert a basic influence on the design and utilization of the machines employed to convert it.

Two essential facts dominate the problem of the utilization of wind power: on the one hand, the great dilution of this energy in space, and on the other, its considerable and unpredictable irregularity.

We find ourselves here in the presence of one of those forms of energy that are apparently available without cost, thus making design economy of major importance, since the cost of generating useful energy depends entirely on the cost of the equipment and its maintenance, and on its service life.

The total power that exists in the kinetic form in a current of air 1 m² in cross section is given by the expression :

$$N_t = 0.000613\, v^3$$

where the power Nt is expressed in kW and the wind-speed in m/sec.

The Betz theorem indicates the part of this power that is theoretically recoverable — only 16/27 of the total power — so that we get :

$$N_b = 0.000364\, v^3$$

for the theoretically recoverable power per m² of wind section, using the same units as above.

Finally, the efficiency of the machine must also be taken into account. According to the type of equipment and the quality of its design, this efficiency will range from 80 per cent for excellent machines to 50 per cent for poor ones.

The figure of 70 per cent may reasonably be adopted for a preliminary estimation, giving the following value for the effectively useful power per m².

$$N_{eff} = 0.000255\, v^3$$

Under these conditions, for a wind-speed of 10 m/sec, only 0.25 kW can effectively be collected per m² of swept surface. But wind-speeds of 10 m/sec occur only a few hours in the year, which further decreases the mean annual available power. Depending on the local wind conditions, the annual available energy per m² of swept surface may vary between 100 kWh for calm areas and 500 kWh for very windy areas. These figures show that plant construction cost must be studied with particular care to make the use of wind power competitive.

The irregularity of the quantity of available energy in the wind is another factor playing a very important part in the design of a wind power plant. The irregularity of the available wind-speed manifests itself in different ways, according to the time scale under consideration, and also according to the size of the plant.

First of all we note great and very rapid variations of random nature, representing the effect of the atmospheric turbulence near the ground. Then, from records of sufficient length, we also observe variations in the mean wind-speed, which are more directly correlated to meteorological factors. The former type of irregularity has a considerable effect on the resistance of the wind power plant, and consequently on its design as well, while the latter type primarily affects the mode of utilization of wind power.

In addition to the irregularities due to turbulence and the irregularities of the mean values affecting the mode of utilization of the wind power, a fundamental and unfavourable characteristic of this form of energy resides in the substantial gap between the mean useful power of a plant and the accidental power it will deliver in a storm, unless special precautionary measures are adopted. Wind-speeds five times as great as the mean design wind-speed are not uncommon. Under these conditions, the stresses on the fixed structures are 25 times the design values, and the power available in the air current 125 times as great. The necessity of providing special devices to permit the plant to adjust to conditions so variable will thus be apparent.

It should, finally, be noted that the available wind energy is influenced by the relief, so that this factor must be taken into consideration in setting up any project.

In hilly country, only the ridge lines are freely available for extraction of wind power. The relief may cause concentration of the production zones at a few points, thus affecting the choice of the power to be generated per machine. Similarly, and for an analogous reason, the wind power plants may be

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concentrated at several points, while the machines using the power they deliver are distributed as needed. A typical case of this kind is the use of wind power to run mine-drainage pumps in very hilly country. The pumps must be installed in depressions, where the wind is gentle, while the wind power plants are placed on the ridges. The unavoidable separation, in this case, of the wind-driven energy producers and the energy-consuming machines, leads to the adoption of a means of transmitting this energy, and may encourage the grouping of several energy-consuming machines fed by the same generator.

Fundamental characteristics of the type of utilization of energy

This problem is dominated by the extreme irregularity of the wind power, which, to some extent, imposes the type of utilization. The special problems of energy storage, or of its combination with a different source of energy, will be discussed elsewhere. Nevertheless, we may say here that the only types of utilization that can be considered acceptable are those adapted to the irregularity of energy production. In an age when working hours were not fixed and not imposed by social interdependence, the utilization of wind power could adapt its operating rhythm to the caprices of the wind. This may be considered possible in certain cases and certain regions, but in the great majority of cases one must seek a type of utilization that will not oblige the worker to adapt himself to the rhythm of the wind. Under these conditions, the most important uses will be those that offer means of simple storage or means of compensating effects of the irregularities of production. The generation of electric energy and the pumping of water are most assuredly the two principal applications of wind power. It would not be unreasonable, either, to consider the direct generation of heat by braking the rotor as a domestic application of a certain interest, in view of the possibility of easily accumulating heat, although this type of utilization has not as yet been envisaged on an industrial scale.

The type of utilization of wind power affects plant design in two important respects. Depending on the operating speed of the driven machine, a step-up transmission between the windmill rotor and the driven machine may or may not be required (such transmission may occasionally be a reducer, for certain slow-acting pumps). Depending on whether or not the speed must be held constant, the plant design will be developed.

The major problems of wind power today

The technology of wind power plants is well developed. They are, however, not yet, as a rule, fully competitive with alternative sources of energy. They still must round the cape of economic utilization.

Some of the problems raised by the quest for a more favourable economic environment are :

Adaptation of wind plant features to the wind conditions and types of utilization.

Selection of optimum unit size and power output.

Whether one unit or more than one should be used to generate the total energy required.

Design selection; possible series production; use of new materials, especially plastics.

Design details appropriate to climatic conditions, incorporating ease of maintenance and corrosion resistance.

If plants are to be competitive, the test standards and procedures must be separately prescribed for small and large plants. Owing to their use in a grid, large plants as a rule present somewhat different features and problems.

The contributions to this section and the tasks before it

In view of the specific objective of this Conference, discussion of this entire complex of problems would have been eminently desirable. Some of them, however, have barely been touched; others, completely ignored. This is, of course, due to the relatively small attendance, and, unfortunately, to the very incomplete representation.

There are fourteen papers before this section, classified by general subject as follows :

1. General discussion and theoretical calculations (Sterne, W/30; Hütter, W/31; Santorini, W/37).

2. Description of large plants and experience with them (Juul, W/17; Armbrust, W/34; Kiss, W/36).

3. Description of small plants and experience with them (Moriya, W/5; Villinger, W/27; Havinga, W/32; Cambilargiu, W/39).

4. Tests to determine power (Clausnizer, W/3; Delafond, W/9; Morrison, W/24).

5. Tests to determine stresses (Morrison, W/24; Askegaard, W/15).

Unfortunately there are no papers from France, although large and intermediate-size plants are now undergoing testing and research; none from the USSR, which has had abundant experience in the operation of intermediate-size wind power plants; none from the United States, where several interesting small plants have been developed commercially, in spite of the unfortunate and premature experiment at Grandpa's Knob.

Principal problems related to plant design

What we have just seen with respect to wind energy and wind utilization allows us to formulate the following list of the principal problems that arise in designing a wind power plant.

Economy of design, imposed by the extreme dilution of wind power.

Relatively large rotor diameter, in consequence of that dilution. Rotor speed is therefore rather low, making a step-up transmission necessary.

Especially strong design of the rotor blades, to withstand the stresses of turbulence acting in conjunction with the cyclical variations of stress.

System of blanking out the blades or the rotor, imposed by the great gap between the rated wind-speed and the maximum wind-speed in a storm.

Speed control or adaptation of the characteristics of the wind power plant to the characteristics of the driven machine.

Other points, more specifically of economic nature, are added to these six fundamental points, such as :

Determination of the tower height;

Determination of installed power;

Determination of the point of maximum efficiency for varying wind conditions;

Determination of the normal operating rotor speed.

Choice of plant type

We may say today that almost all types of machines able to convert the kinetic energy of the wind into mechanical energy that can be used by a driven machine have now been tried out, so that an opinion on the value of these different types can be formulated. With the exception of several mechanical fantasies with no future, the machines that can be used fall into two main categories :

Machines with rotor axis perpendicular to the direction of the wind (and preferably vertical),

Machines with rotor axis kept oriented into the wind.

The first category includes panemones, or vertical-axis machines, especially those whose rotor elements run contrary to the wind for one-half revolution, and machines with Savonius-type rotors. These vertical-axis machines have the great advantage of needing no orientation system to hold them in the path of the wind. The conventional cup anemometer is the simplest and best-known example of this type. The advantage of such machines, however, is gained at heavy cost, for they also have several disadvantages. They can recover only a small part of the energy of the wind passing the swept surface, so that a large rotor will be required to deliver a small amount of power. The blades cross the flux of the axis twice, and their tip-speed ratio will thus be lower than in other machines. At equal power, the rotational speed will be at most half that for a machine of the other category. Finally, it is very difficult to design and build a practical furling device to protect these machines in high winds. All these reasons have led to the abandonment of the panemone type, and there will, in all probability, be no major development for them. But they may still be used for certain simple applications in low-power machines, since they need no orientation system.

The machines with axis parallel to the wind direction are thus the only machines due for large-scale development, and are practically the only machines being built today. As we shall see, there are various tip-speed ratios.

Before going on, we must mention certain systems used to improve the above wind machines by increasing their rotational speed. Such systems include :

Machine with rotor turning at the throat of a Venturi tube

This system has been tried a number of times It is effective enough in increasing the rotor speed, but is uneconomic, since the entire Venturi-rotor assembly must be kept oriented into the wind.

Wind turbines in series

In this system, the main propeller carries miniature windmills on its blade tips, and these drive generators directly. Since they are swept by the relative wind, which is several times as fast as the principal wind, they will be able to absorb all the power available even if their own diameter is small. This ingenious device amounts essentially to an aerodynamic step-up gear system, but is very difficult to realize, owing to the presence of rotating masses at the ends of the principal blades.

"Depression" wind turbine

The use of a propeller with hollow blades acting as a suction pump to draw air through an air turbine directly coupled to the driven machine is another way of increasing the operating speed by a purely aerodynamic method, without using mechanical gears. This ingenious system has engendered a number of embodiments, of which the most recent is without doubt the 100 kW Andreau installation now operating at Algiers (Delafond, W/8 and W/9). The serious disadvantage of this solution resides in its very low efficiency. The over-all efficiency is the product of the efficiencies of the propeller, the pump, the air turbine, and the generator. The efficiency of the propeller itself is lower than in a conventional machine, since thicker profiles must be used to obtain a hollow blade of adequate cross section. The efficiency of the combination suction pump-turbine should be compared to the efficiency of a conventional step-up gear drive, which is normally around 95 per cent or higher, while that of the combination is poor. The greatest losses take place at the outlets from the hollow blades, at their tips, and since all the kinetic energy of the air is practically lost, the efficiency of such an installation is about half that of a conventional assembly with a mechanical drive. This results in a great increase of rotor diameter for a given power, thus largely sacrificing the advantage gained by the simplicity of the transmission system.

Other systems have also been envisaged, such as contrary-rotation machines, machines with wheel-rim and belt transmission, etc.

All these ideas, sometimes very ingenious indeed, must be considered as curiosities. Those models that have actually been built show them to be, for the most part, uneconomic. Thus the only machine that can be developed, and has been sufficiently tried by experience, is the machine with a propeller oriented in the wind and driving its generator or other driven machine directly or through a step-up gear drive. During the rest of this report, we shall be concerned exclusively with this type of machine.

Selection of the rotor type

Just as it is possible, in the field of hydraulic turbines, to build rotors corresponding to a wide range of specific speeds, the specific speed, or tip-speed ratio of a windmill rotor, is characterized, in general, by the ratio u/v of its peripheral speed to the wind-speed.

The tip-speed ratio of rotors today can be brought up to values as high as 10. It does not seem that this value can be usefully exceeded without the employment of aerodynamic methods, which would probably be expensive, e.g., control of the boundary layer on the blades. It should also be noted that an excessive increase of the ratio u/v involves a fall in efficiency, owing to the increased relative losses by friction.

The characteristics of rotors are such that, other things being equal, the torque decreases with increasing tip-speed ratio; in particular, the starting torque decreases very rapidly when the tip-speed ratio increases. For this reason, rotors of low tip-speed ratio are preferred for driving piston pumps, which require a high starting torque and low rotational speeds.

Except for driven machines requiring a high starting torque, rotors of high tip-speed ratio will be chosen for all applications involving a machine driven at high speed. There are several trends in this general direction. One must not lose sight of the fact that the essential object is to realize an economic machine; all the factors affecting the economy of the design must therefore be determined, and the rotor speed is not the only such factor. We may thus have to choose, ultimately, between the following extreme cases:

Rotor of very high tip-speed ratio, decreasing the cost of the step-up gearing, but which itself will be more expensive to build, owing to the blade design and to the quality of the materials required for the blades.

Rotor of moderate tip-speed ratio, requiring a heavier step-up gearing, but simpler, and thus less costly to build.

Thus, no optimum aerodynamic solution may be said to exist, and the choice of the tip-speed ratio must remain linked to the manufacturing possibilities for the rotor, and to the economy of its mode of construction. The papers received by this section present two machines that are good illustrations of these two tendencies: the machine developed by Studiengesellschaft Windkraft (Armbrust, W/34) and the Danish machine at Gedser (Askegaard, W/15 and Juul, W/17). The advantage of one type over the other depends on the economic background of the situation (means of production of the country in question, number of units in a manufacturing series, etc.).

In all cases, for applications involving high-speed driven machines, there would appear to be no advantage in adopting tip-speed ratios u/v under 4, and the new design procedures to be discussed below seem to indicate that this limit might be set still higher.

We shall now examine the various elements composing the machine, and the solutions that have been generally adopted.

Blade design

In view of the high tip-speed ratios, the number of blades is small. Single-blade rotors have been built in Germany for very small machines. The need for a balancing element, which was a dead weight, considerably attenuated the initial interest in this solution. We may mention, as a curiosity, a small machine with a single hollow blade operating on the air-suction principle, and driving a small air turbine with electric generator, constituting the counter weight for the single blade.

In most cases rotors have two or three blades. Here again argument has not yet been settled between two-blade and three-blade partisans. While two blades improve the economy of rotor design and increase the tip-speed ratio, difficulties due to vibration do, by and large, appear during orientation. These difficulties disappear completely for three blades or more, so that three-blade rotors operate more reliably and allow a more primitive design for the rest of the machine.

The blade layout has registered great advances, owing to wind-tunnel tests and the development of mathematical methods of calculation. The work of Hütter, among others, has given a very satisfactory solution to this problem (Hütter, W/31).

The blades are subjected to stresses due to normal operation, to irregularities of turbulence, and, principally, to deviations from true orientation into the wind. Major alternating stresses also arise; and all the materials used must consequently be capable of withstanding a large number of alternating stresses in flexure and in torsion.

The stresses to which operating blades are subjected are better known today (Morrison, W/24; Askegaard, W/15; Juul, W/17). But the measurements are so difficult that much still remains to be accomplished in this field, primarily in view of the realization of high-power installations.

Blade design is affected by the hub mounting (fixed or orientable blades), which will be discussed later in connexion with the question of regulation. Various structural types and various materials are employed. Wood is still rather generally used for small, high-speed machines, and is a material which, if appropriately treated, is of great interest for this purpose, owing to its excellent strength/density ratio (Havinga, W/32).

Metal is very widely used for larger machines (castings for small blades; stampings; composite structure : spar-ribs-skin) according to a mode of utilization derived from the aircraft industry. It must be admitted frankly that all-metal designs are not always easily adapted to the difficulties of blade construction.

Among the new materials, the plastics, primarily the glass-reinforced plastics, afford extremely interesting possibilities for blade building, e.g., Villinger (W/27). These materials have a good strength/density ratio, they behave well in storms, have an appropriate resistance to alternating stresses, and, above all, possess excellent fabricating properties. With these materials, the intricate shapes dictated by aerodynamics can be formed with no particular trouble, and the strength requirements can at the same time be met. Finally, and this is important, they need neither complicated tooling nor particularly specialized personnel. They seem to be destined completely to modify the present wind-machine technology. In the field of large machines, a 100 kW wind power installation has been built in Germany ubder the sponsorship of Studiengesellschaft Windkraft (W/34), and is now operating. In France, Neyrpic has built a 150 kW plant by this technique, and it is now operating satisfactorily. In the medium power field, Neyrpic in France has also developed and built a series of machines, during the last few years, for generating electric power and for pumping water. In these medium-power plants, all-plastic blades, glass reinforced, have given excellent results.

The use of plastic blades considerably facilitates the construction of high-power installations. Further than that, the simplicity of the fabrication methods and equipment puts their installation within the reach of even the most unindustrialized countries.

The low-speed rotors specifically designed for slow wind machines should be particularly mentioned here. These rotors have a large number of blades, are usually of all-metal sectional construction, and can be disassembled for shipment. The blades are made of stamped or deep-drawn galvanized iron. Experiments have been made in the Indies with a view to replacing the sheet metal by local products of vegetable origin.

Among the advantageous solutions borrowed from the past, particular attention should be drawn to the possibility of using sail rotors (Greek and Portuguese windmills) — a possibility which has been nsufficiently studied. Such machines combine very simple design with the possibility of regulation and efficient furling in high winds by simply relaxing the tension of the sails.

Type of orientation

There are two solutions :

Orientation by means of a wind-vane, with the rotor either upwind of tower and empennage or downwind of the tower.

Orientation by automatic command (direction detector, wind rose stepdown device, etc.) which may be used with the rotor upwind or downwind of the tower.

Measurements of the blade stresses due to the shadow of the tower indicate that rotors upwind of the tower are located more favourably with respect to blade fatigue, but also involve more complications in connexion with the orienting mechanism required, and with the higher orienting stresses. Low-power machines must be very economical, and a wind-vane orientation system, with or without an empennage, must be used. The empennage becomes too heavy and too expensive in large machines, but rotors upwind and downwind of the tower are used indifferently in such cases. The question of oscillations in orientation with a downwind rotor mounted as a pure wind-vane has not yet been sufficiently elucidated to make a definite pronouncement in favour of either solution possible.

Regulating systems

This system may have two functions to perform :

It may be used as a speed control if the driven machine requires one.

It will be used as a power-output governor and a blade-stress limiter in high winds.

The number of different solutions adopted is rather large. Except for the slow multi-blade machines, for which the principle of blanking-off the entire rotor assembly has been generalized, we meet two great classes of solutions :

Regulation with orientable blades;

Regulation with fixed blades.

The former solution makes use of a technique analogous to that of variable-pitch aircraft propellers or of Kaplan hydraulic turbines. It permits adaptation of the rotor to various wind conditions, and, in particular, it allows feathering in a high wind, with minimum blade stress.

This is obviously a solution of a certain mechanical complexity, but it does give a high degree of flexibility. The blades may be controlled in various ways, according to the control system adopted. Control may be automatic, using spring systems (Neyrpic machines) or Flettner blinds (USSR machines); it may also depend on a conventional power governor or constant-speed governor (Armbrust, W/34).

The latter solution is generally employed in combination with auto-regulating profiles having charac-

teristics that cause disengagement of the system at a predetermined wind-speed. It may also be used in combination with aerodynamic brakes, actuated by a speed or power governor (Danish plant at Gedser, W/15 and W/17).

In both solutions, the regulation results from a good combination of the characteristics of the wind machine with those of the machine it drives. In this connexion, we must call attention to the excellent co-ordination between a wind power plant and a centrifugal or propeller pump, since the use of such a pump in itself constitutes a control system with optimum combination of efficiencies (the use of a hydraulic brake to produce hot water enjoys the same properties). Pumping may thus be said to be a remarkably interesting utilization of a wind machine, provided the combination of characteristics has first been properly studied.

If the wind power plant is used with a generator feeding a network, the exchanges of magnetizing current will automatically maintain constant speed, so that the regulating system reduces essentially to a power-output governor for high winds.

The step-up drive

In the great majority of cases, the step-up drive interposed between the rotor and the driven machine is of the gearing type, with one or several trains. The technique of step-up gearing is now completely developed, and permits the use of transmissions with an excellent efficiency and very great reliability of operation. These transmissions may be used up to high power levels, considerably in excess of 1 000 kW.

The chain or belt transmissions that have been tried in some cases for their simplicity have not yet been used sufficiently in wind power work to allow them to be considered serious competitors of step-up gear transmissions.

Except for air-suction, "depression" machines, there has been no use of hydraulic transmissions that could be considered of industrial interest.

In cases involving an a.c. generator, its use without step-up gearing may be envisaged if an alternator with a very large number of blades is used (Kiss, W/36). This question can be examined only by designers of electrical equipment. It should not be forgotten, however, that the use of step-up gearing permits the use of a generator with conventional characteristics that can generally be ordered from a catalogue, and is therefore priced rather low, while an alternator with a large number of blades is necessarily an expensive special-order machine.

Towers

The choice of the tower is intimately connected with two problems: its height, with the problem of the production of wind-generated energy and of the generating cost of that energy; its structure, with the delicate problem of vibration.

The economic advantage of increasing the height of the rotor, that is, the height of the tower, is due to the existence of a velocity gradient of the wind. This gradient depends primarily on the nature of the ground of the region. The use of a very high tower can be justified only by a precise determination of the mean value of this gradient.

Normally, the major concern is to elevate the rotor above the very turbulent layer close to the ground. The thickness of this layer varies with the relief. On the average, it may be considered that the most favourable height for a machine of a certain power is of the order of magnitude of the rotor diameter. At the top of a hill, where the thickness of the turbulent layer is decreased by the effect of the relief, the height chosen may be lower. For very small machines, the height of the tower will be of the order of ten or twelve metres or so, always with the same object.

The most usual type of structure today is the metal latticework tower, of four-sided pyramidal shape. The use of angle irons is much more economical, while the construction with metal tubing, which is more advantageous with respect to tower shadow in the wind, is distinctly more expensive.

On the basis of the metal latticework structure, other combinations are possible, such as a mast with several feet. A mast with guys is a solution somewhat less frequent. The mast itself may be of metal latticework or consist of a single-element tube.

Whatever the solution finally adopted, a serious vibration study must be made, especially for machines of a certain size. Such a study requires the determination of the natural frequencies of the tower in flexure and torsion, and may indicate the need for reinforcements to prevent resonant vibration of the tower under the action of the alternating stresses due to the rotation of the rotor.

An important question may be raised in relation to the tower : that of the installation of the assembled machine. It may be of great advantage to utilize the tower itself, or certain of its parts, as a means of mounting. For low and medium power machines, the simplest installation procedure is to assemble the whole machine on the ground, and then hoist it into place with a windlass, pivoting the tower about two of its feet.

Tests

We shall now consider tests performed to study certain machine elements or determine the stresses on the machine, and, on the other hand, power tests and operating tests proper. Tests of the former class — Morrison and Askegaard papers (W/24 and W/16) — are of great interest to the designer or aerodynamicist, while those of the latter class — Clausnizer and Delafond (W/3 and W/9) — are of more particular interest to the user.

The essential difficulty of the power tests resides in the great irregularity of the turbulence of the wind, which compels the experimenter to make a large number of measurements and then to interpret the results to infer the steady-state values. In addition to the irregularity, the random distribution of the mean wind is another factor that helps considerably to lengthen the required testing period.

While the measurement of a ceaselessly varying power itself poses rather serious problems, the greatest difficulty of all is in the determination of the mean wind crossing the swept surface at the instant the power is measured.

This determination can be accepted only with caution, since the wind speed cannot be measured over the entire swept surface, and, on the other hand, it is made at a certain distance from the rotor position. These considerations show that test results can always be criticized. To shorten the testing period, it would be desirable if measurements could be made under variable conditions. A better knowledge of the turbulence of the wind would likewise seem essential. Finally, it is not at all out of the question that a trend may develop, especially in the case of large machines, toward the determination of the characteristics on the exclusive basis of wind-tunnel model tests, as is already being done on hydraulic turbines. It is, indeed, far more convenient to fix the characteristics of the wind and to operate under constant conditions. It goes without saying, however, that in passing from wind-tunnel tests to industrial characteristics, one must use a scale factor or a formula like the Moody or Ackeret formulas now used in hydraulics.

Suggested topics for discussion

1. Effect of plant design and type on generating cost.

2. Effect of plant size and power on generating cost.

3. Effect on installed cost of method of manufacturing and installing plant, of the number of units used for a given power output, and of the number of machines in a factory series.

4. Possibilities afforded by using new materials, especially plastics; and possible local manufacture of plant components.

5. The simple accelerated test method presented by Clausnizer (W/3) as compared with the Delafond almost continuous photographic record of the instrument panel as a basis for engineering calculations.

6. Blade-stress measurements correlated to wind-speed and power output by Morrison (W/24) and the Danish technique— amongst others, Askegaard (W/15).

7. Highly sophisticated versus simple or even primitive design, as exemplified in the German model (W/31 and W/34) on the one hand, and the Danish and Japanese models (W/13, W/17 and W/5) on the other. Application of aerodynamics to blade design by Hütter contrasted with the Gedser mill and the 15 Watt Japanese development with automatic pitch adjustment.

8. Use of direct-driven synchronous alternators in the 200 kW Hungarian experimental plant to eliminate transmission gears. Advantages and disadvantages (W/36).

PLANS ET ESSAIS D'INSTALLATIONS ÉOLIENNES

Résumé du rapporteur

Si les problèmes ayant trait à la construction des machines éoliennes ont été groupés sous le même titre II.B.2 de l'ordre du jour, il faut préciser dès l'abord qu'ils débouchent en fait sur deux perspectives différentes.

La première est d'ordre physique et technique, la seconde d'ordre économique.

La première question qui se pose en effet au constructeur est bien une question de possibilité physique : « Est-il possible de prélever l'énergie cinétique du vent à des fins utilitaires? » La réponse, certes, nous est donnée depuis des siècles. Mais, allant plus avant, cette question se précise et devient : « Les connaissances de la physique et les moyens de la technique permettent-ils de construire des aéromoteurs pour répondre aux besoins énergétiques actuels dans leurs qualités et dans leurs quantités? »

La seconde question touche à l'économie, c'est encore un problème de possibilité non plus physique cette fois, mais financière. Dans le cas de l'énergie éolienne qui nous préoccupe ici, c'est en effet au constructeur que sera posé le problème puisqu'il possède les principaux éléments permettant de l'attaquer et éventuellement de le résoudre et que, de ce fait, il sera tenu pour principal responsable du prix de l'énergie éolienne, qu'il s'agisse du capital nécessaire à l'achat et à l'érection de l'appareil, ou de sa durée de vie et de ses frais d'entretien. Formulons donc la seconde question : « Est-il possible, dans l'état actuel des connaissances scientifiques et techniques, de construire des aéromoteurs dont l'emploi puisse être raisonnablement envisagé en concurrence avec les autres moyens de production d'énergie, et dans quels cas ces appareils peuvent-ils être utilisés? »

Voilà fixés quelques-uns des repères marquant le cadre dans lequel nous avons eu et nous aurons encore à travailler. Pour terminer la définition de ce cadre, quelques mots doivent être dits sur la dimension des appareils dans ses rapports avec les champs possibles d'application aux régions développées ou sous-développées. On sera peut-être surpris que ces mots soient pris comme conclusion et non comme introduction de nos travaux. Cependant, la nature d'une bonne partie des communications faites montre qu'il convient d'y revenir.

Une classification simple permet de répartir les appareils dans les groupes suivants :

1. Les grosses machines d'une puissance de l'ordre de la centaine de kW, pouvant aller jusqu'au millier de kW, machines utilisables seulement pour la production d'énergie électrique. (Qu'il s'agisse de la construction ou des essais, six communications traitaient de ces appareils.)

2. Les machines moyennes d'une puissance comprise entre 5 et 20 kW environ, puissance telle qu'elle nécessite certains organes de réglage apparentés à ceux du groupe précédent. Ces machines seront applicables à des usages multiples, mais principalement à la production d'énergie électrique et au pompage de l'eau. (Il n'y a pas eu de communications faites spécialement sur ce sujet, mais comme nous le verrons, certaines communications ont abordé des sujets techniques qui s'y rattachent.)

3. Les petites machines d'une puissance inférieure à 5 kW, ne comportant que des organes de réglage rudimentaires et dont les principales applications sont le pompage de l'eau et la production de petites quantités d'énergie électrique (trois communications avaient directement trait à ce sujet).

Les zones possibles d'application ont été clairement fixées. Mettons-les tout de suite en parallèle avec les groupes d'appareils que nous venons de définir.

Les zones possédant un réseau d'interconnexion ne seront intéressées que par les machines de grande puissance.

Les zones caractérisées par la présence de petites centrales locales ou de communautés à besoins moyens en énergie seront intéressées par les machines moyennes et éventuellement par les petites machines.

Les zones dépourvues de source d'énergie s'intéressent surtout aux petites machines et éventuellement aux moyennes, mais certainement pas aux grosses.

Or, les efforts de cette conférence doivent se porter surtout vers l'équipement des zones pauvres en énergie; il n'est donc pas inutile de reprendre à la fin de nos travaux des mots que la logique aurait placés à leur début.

Parmi les communications faites :

Deux portaient sur des questions d'ordre général relatives à la théorie et au calcul des aérogénérateurs, sous l'angle de la mécanique des fluides ou de l'application à la production d'énergie électrique;

Trois donnaient la description technique de machines de grande puissance ou de dispositifs de réglage appliqués à ces machines;

Deux traitaient des essais de puissance de ces machines, cependant que deux autres communications exposaient les méthodes ou les résultats d'essais de répartition d'efforts dans les pales ou dans le mécanisme d'orientation d'aérogénérateurs;

Une communication se rapportait à un problème technique et aérodynamique relatif à l'orientation;

Trois autres s'en tenaient aux petites machines : l'une rappelant que les techniques de nos ancêtres n'étaient peut-être pas dépourvues d'intérêt; les deux dernières, enfin, donnant des descriptions de petites machines présentant une expérience et des éléments originaux.

Les interventions au cours de la séance technique ont porté en grande partie sur des problèmes mécaniques ou aérodynamiques ayant trait à l'emploi de machines à grande vitesse spécifique; et sur les méthodes d'essais de puissance d'aérogénérateurs couplés sur un réseau. Des clichés projetés nous ont présenté certaines machines, dont l'une en particulier, à la limite entre moyenne et grande puissance, mérite par sa simplicité de conception de retenir l'attention. Un orateur, faisant appel aux liens de parenté qui unissent les différents membres de la grande famille des fluides, a proposé une application extra-éolienne des aérogénérateurs, ouvrant ainsi la voie à une source d'énergie hydraulique constituant en quelque sorte une étape préalable à l'équipement des grands fleuves ou des courants marins. Quelques interventions ont porté sur des problèmes relatifs aux petites machines ou sur leur utilisation. N'oublions pas de dire d'ailleurs que fort opportunément fut évoqué à plusieurs reprises la nécessité d'une orientation vers la simplicité. Une intervention enfin nous a fait connaître, avec clichés à l'appui, les grandes lignes de la technique et de l'emploi des matières plastiques armées au verre (fiberglass - plastic) pour la construction des pales d'hélice.

Que retenir de cet ensemble?

Tout d'abord, et pour répondre à la première question formulée au début de cet exposé, il est maintenant acquis que la construction d'aérogénérateurs des plus petites puissances jusqu'à des capacités dépassant largement la centaine de kW ne pose plus de problèmes fondamentaux.

Dans le domaine du calcul et de l'aérodynamique théorique, les connaissances acquises, si elles ne sont pas définitives (elles ne le sont d'ailleurs jamais), sont suffisamment avancées pour être utilisables d'une manière quasi-routinière et pour qu'il n'y ait plus de surprise à attendre.

Dans le domaine de l'aérodynamique expérimentale et des travaux de soufflerie, on est également suffisamment avancé pour dire que les progrès à attendre ne seront que tout à fait minimes et nullement de nature à bouleverser les données du problème.

Dans le domaine de la construction, le nombre des réalisations déjà effectuées montre bien que là aussi le terrain est solide. Bien entendu, pour les très grosses machines il existe encore de petites imperfections de détail, mais il est rare de rencontrer un domaine où un aussi faible nombre de prototypes (je parle de machines de plus de 100 kW et du point de vue constructif) ait conduit à aussi peu d'échecs. Ceci est très encourageant. En effet, il n'est pas douteux que la technique et l'expérience acquise sur les grosses machines profitent, non pas aux petites machines certes, mais aux moyennes, et on peut, de ce fait, envisager actuellement en toute sûreté la réalisation de ces dernières. En outre, il faut noter une circonstance favorable. Tout en restant bien entendu dans le cadre de la machine classique type hélice à axe horizontal, on rencontre des constructions de conception et de fabrication assez différentes, qui toutes paraissent présenter un égal succès. Ceci montre que la solution du problème n'est pas unique et qu'il existe une marge de sécurité assez grande autour de l'optimum. Ce fait caractéristique accompagne presque toujours les réalisations techniques viables.

Dans le domaine des machines rapides, qui seules ont été examinées en séance technique, la voie reste ouverte aux hélices à deux ou à trois pales, aux systèmes de réglage à pales fixes ou à pales orientables, aux roues placées devant ou derrière le pylone. Il faudra encore un certain temps pour que se dégage la meilleure solution; il y en aura d'ailleurs sans doute plusieurs suivant le type d'application.

La grosse nouveauté, tout au moins pour le profane, car les spécialistes depuis plusieurs années déjà se penchent sur le problème, est l'utilisation des matières plastiques armées au verre pour la construction des hélices. Deux communications font état de machines utilisant cette technique, et un orateur a exposé la question plus en détail en séance technique. Ce procédé a été utilisé jusqu'ici avec un plein succès pour des hélices de 2 m à 34 m de diamètre. Non seulement il permet d'obtenir des caractéristiques mécaniques et aérodynamiques exceptionnelles rendant possible des réalisations que l'emploi des seuls métaux laissait douteuses, mais encore, et ceci est capital, il ne demande pour sa mise en œuvre que des moyens extrêmement simples, un outillage des plus réduits, un personnel facile à former. Voilà donc une technique qui ouvre la voie aux fabrications locales dans des pays où l'industrialisation est faible.

J'en arrive enfin à la seconde question posée au début de l'exposé, celle qui a trait à la valeur économique de l'énergie éolienne.

On a souvent classé les différents pays suivant la quantité d'énergie disponible par habitant. Je voudrais, avant d'aller plus loin, dissiper certaines illusions que cette façon de procéder engendre. Le but final de notre action n'est pas tant de fabriquer de l'énergie mécanique ou électrique que de diminuer la peine de l'homme, c'est-à-dire, l'énergie physiologique qu'il dépense pour ses besoins vitaux. Or la relation qui existe entre la réduction de la peine de l'homme et l'énergie mise à sa disposition n'est pas une relation linéaire de proportionnalité. Qu'il nous suffise pour s'en convaincre de voir comment a varié au cours des années passées le nombre moyen annuel d'heures de travail de l'ouvrier dans nos pays en fonction de l'énergie par habitant. Une loi empirique veut que la consommation d'énergie double tous les 7 à 10 ans; il est bien évident que la durée du travail n'a pas été réduite de moitié dans le même temps. La relation existant entre la diminution de la peine de l'homme et l'énergie mise à sa disposition présente

plutôt un caractère logarithmique comme certaines lois physiologiques traduisant la réponse d'un organe à une excitation extérieure.

Ceci signifie que la diminution de la peine de l'homme est d'abord très forte pour les premiers kWh fournis, puis cette diminution va en décroissant au fur et à mesure que l'apport nouveau d'énergie se fait sur un capital énergétique préexistant plus grand. Il n'est pas question de s'étendre ici sur l'origine de ce phénomène, mais il faut retenir que, traduit en diminution de la peine humaine, un kWh présente une valeur très différente, suivant qu'il est apporté dans un pays à faible valeur énergétique par habitant ou dans un pays à forte valeur énergétique par habitant. Dans le premier cas, qui est celui des zones sous-développées, l'énergie fournie est immédiatement utilisée pour des besoins vitaux. La satisfaction de ceux-ci dépend directement de cette énergie, en sorte qu'il s'agit non pas tant d'un problème de prix que d'un problème d'existence.

Dans le seconde cas, qui est celui des pays très développés, l'apport énergétique se perd dans l'océan disponible. Les besoins vitaux étant satisfaits, la seule valeur de l'énergie éolienne sera sa valeur par rapport à celle des autres types d'énergie.

Ce dernier problème n'est pas le nôtre. Préoccupons-nous au contraire de rechercher des solutions aussi convenables que possible pour l'équipement des pays sous-développés, c'est-à-dire des aéromoteurs de petite et moyenne puissance. Aussi faut-il demander aux spécialistes de quitter l'Olympe où, tels les dieux, ils font de la géométrie, pour redescendre parmi les mortels. Loin de moi la pensée que leurs travaux ont été inutiles; bien au contraire, je les crois fructueux et nécessaires, mais qu'ils fassent maintenant le dur effort de synthèse qui conduira aux solutions simples.

Pour terminer, je voudrais faire deux suggestions dans le domaine des petites machines.

Premièrement, mettant à profit les connaissances techniques et aérodynamiques maintenant considérables, ne serait-il pas possible d'en dégager les idées qui permettraient de fournir aux artisans des pays sous-développés des directives ou des conseils leur facilitant la réalisation, sur place et avec leurs moyens locaux ou des moyens simples, d'appareils qui, tout en conservant un caractère primitif, bénéficieraient de l'acquis technique des machines évoluées? Ce travail, qui a d'ailleurs déjà été entrepris, devrait s'adapter aux besoins et aux moyens de chaque région et permettrait de faire un pas en avant, tout en facilitant l'éveil culturel dont un orateur a parlé en séance plénière.

Deuxièmement, étant donné qu'il existe déjà bon nombre de fabricants d'appareils de petite et moyenne puissance, et un plus grand nombre encore de types, ne serait-il pas possible de mettre de l'ordre dans cette confusion? Ceci en cherchant par un effort de systématisation et de normalisation de caractère international à limiter le nombre des types. Il convient dans une première étape de fixer et de limiter les types et les caractéristiques de ces types, de faire en somme un travail analogue à celui qui a été fait par nombre d'organismes de normalisation. Dans une deuxième étape, la normalisation serait poussée jusqu'à la conception et la fabrication, ce qui ouvrirait la voie à des réalisations en très grande série, seul moyen d'abaisser sérieusement le prix des aéromoteurs.

THE DESIGN AND TESTING OF WIND POWER PLANTS

Rapporteur's summation

Although the problems connected with the design of wind power plants have all been grouped together under agenda item II.B.2, it must be made clear from the beginning that they actually fall into two quite different categories — the first being physical and technical in character, and the second economic.

The first question that the designer has to ask himself is simply one of the physical possibility of harnessing the kinetic energy of the wind for practical purposes. The answer, of course, has been known for centuries. To go a little further, however, the question takes the more specific form of whether our knowledge of physics and our technical ability enable us to design wind power plants capable of meeting present power needs as regards both quality and quantity.

The second question brings in economics, for the problem becomes one of financial as well as physical possibility. In the case of wind power, with which we are concerned here, it is the designer who will be faced with the problem, since he more than anyone else has the means for tackling and possibly solving it and will consequently be the one held mainly responsible for the cost of the wind power, whether it is a matter of the capital necessary to buy and erect the equipment or of its useful life and upkeep. In formulating the second question, we may therefore ask whether, in the present state of scientific and technical knowledge, it is possible to design wind power plants which can reasonably be expected to be competitive with other means of power production, and in what circumstances such plants can be used.

These questions help to delimit the area in which we have had to work in the past and will have to work in the future. In order to provide details to fill in this area, something should be said about the size of the machines in relation to their possible applications in developed or under-developed regions.

A simple classification of the machines can be made as follows:

1. Large machines with a power of the order of 100 kW, in some cases rising as high as 1 000 kW, the only function of which is the production of electric power (six papers deal with such machines, from the point of view of design or of testing).

2. Medium-sized machines with a power roughly between 5 and 20 kW, requiring certain controls similar to those used with machines in the preceding group. These machines can be used for many purposes, but are mainly for the production of electric power and pumping of water (no papers deal specifically with this subject, but, as we shall see, some of them deal with related technical subjects).

3. Small machines with a capacity of less than 5 kW and with only rudimentary controls, their main uses being to pump water and to produce small quantities of electric power (three papers deal directly with this subject).

The kinds of area in which the machines can be used were clearly established; they may be matched up with the above categories of machine in the following way.

In areas with a network to which the machines can be connected, only machines of large capacity will be of interest.

In areas with small, local power stations and with communities whose power needs are moderate, medium-sized machines, and possibly small machines, will be of interest.

In areas with no sources of power, small machines will be of most interest, and possibly those of medium size, but certainly not large ones.

With regard to the papers submitted for this agenda item, two deal with general questions concerning the theory and the mathematics of wind power plants from the standpoint of fluid mechanics and the production of electric power; three give technical descriptions of high-power machines and their regulating systems; two are concerned with power tests of such machines, while two others describe methods of distributing the stresses in the blades and in the orienting mechanism of wind power plants and the results of tests carried out in that connexion; one deals with a technical and aerodynamic problem of orientation; and three others deal exclusively with small machines, one pointing out that the techniques of our ancestors might not be without interest, and the other two giving descriptions of small machines with new features and applications.

The statements made at the technical meetings were concerned largely with mechanical or aerodynamic problems relating to the use of machines with high tip-speed ratio and to methods of testing the power of plants coupled to a network. Slides were shown of some machines, one of which, of medium to large capacity, deserves particular attention by reason of the simplicity of its design. One speaker, noting the ties of kinship linking the different members of the great family of fluids, suggested that wind power plants might be used in other media, thus serving, for example, as a possible source of hydraulic power which might play a preliminary role

in the harnessing of large rivers and sea currents. Some statements dealt with the problems and uses of small machines. It must not, moreover, be overlooked that several references were quite rightly made to the need to seek greater simplicity. Finally, one speaker, using slides, gave us a general account of the technical aspects of fibre-glass plastic and its use in the manufacture of propeller blades.

What are the conclusions to be drawn from all of this?

First of all, in answer to the first of the questions that we asked in the beginning, it is now generally agreed that the design of wind power plants with capacities ranging from the lowest levels to far beyond 100 kW no longer presents any fundamental problems.

In the field of calculation and theoretical aerodynamics, our present knowledge is sufficient to be usable in a more or less routine way and without the need to be on guard against surprises.

In the field of experimental aerodynamics and wind-tunnel work, the progress made has also been such that further advances can be expected to be no more than marginal and certainly not of a nature to alter the substance of the problem.

In the field of engineering, the record of achievement shows that here too we are on firm ground. In the case of very large machines, there are, of course, still some small imperfections of detail, but it is rare to find any branch of activity in which such a small number of prototypes (I am speaking of machines of more than 100 kW and from the engineering point of view) have produced so few failures. This is very encouraging. There can be no doubt, moreover, that the technique and experience gained with large machines is of value for medium-sized machines, though admittedly not for small ones, so that the production of medium-sized machines can now be undertaken with complete assurance. One further favourable factor should be noted. Without going beyond the range of the traditional-type machine with a propeller on a horizontal axis, one can find machines of considerably varied design and manufacture which all seem to be equally successful. This shows that there is no single solution to the problem and that there is quite a wide safety margin around the optimum. This is a characteristic of almost all viable technical achievements.

In the realm of high-speed machines — the only ones considered at the technical meetings — the way remains open for two-blade or three-blade propellers, for regulating systems having fixed or orientable blades and for rotors placed before or behind the tower. Time is still needed for the best solution to emerge. Indeed, there will no doubt be several solutions, depending on the type of application.

The big innovation — at least for the layman, as specialists have been studying the matter for years now — is the use of glass-reinforced plastics in the construction of propellers. Two of the papers refer to machines using this technique, and one speaker went into the question in detail at one of the technical meetings. This process has thus far been used with complete success for propellers of 2 m to 34 m diameter. Not only is it a means of obtaining outstanding mechanical and aerodynamic characteristics that lend themselves to possibilities for which metals alone would be inadequate, but, what is even more important, it needs nothing more for its practical application than exceedingly simple equipment, very uncomplicated tooling and easily trained personnel. This is a technique, therefore, which opens the way to local manufacture in countries where industrialization is not far advanced.

I come now to the second question, namely, the economic value of wind power.

Countries have often been classified in terms of the quantity of available power *per caput*. I should like, before going any further, to dispel some illusions to which this approach has given rise. The ultimate objective of our work is not so much to produce mechanical or electrical energy as to reduce human toil, i.e., the energy that a man expends in satisfying his basic needs. It must be pointed out that the relation between the reduction of human toil and the availability of energy is not a linear one. To convince ourselves of this we need only consider the change, over past years, in the annual *per caput* working hours in our countries by comparison with *per caput* power availability. According to an empirical law, power consumption doubles every seven to ten years, but it is quite obvious that working hours have not been halved over the same period. The relation between the reduction of human toil and the availability of power is more logarithmic in nature, resembling in this respect certain physiological laws of stimulus and response.

This means that the reduction of human toil is very substantial in the beginning, i.e. for the first kilowatt-hours produced, and then declines as further energy is added to the larger supply already built up. It is unnecessary to dwell here on the origin of this phenomenon, but it is important to note that, when expressed in terms of a reduction in human toil, a kilowatt-hour has a very different value according to whether, in the country in which it is produced, the *per caput* energy production is small or large. In the former case, which is that of the under-developed areas, the new supply of energy is immediately put to use for basic needs. As the satisfaction of these needs is directly dependent on this energy, it is not so much a question of cost as of existence. In the latter case, i.e. in the highly developed countries, the additional energy is just another drop in the ocean of energy already available. Since basic needs have been satisfied, the sole value of wind power is its value by comparison with other types of energy.

The last-mentioned problem is not the one that demands our attention. What we should do is seek out the best possible solutions for the under-developed countries, that is, provide them with low and medium-power wind machines. I am far from thinking that the work of the specialists has been useless. On the

contrary, I consider it fruitful and necessary, but let the specialists now undertake the difficult task of reducing their knowledge to the level of simple solutions.

In conclusion, I would like to make two suggestions with respect to small machines.

First, could not the considerable advances that have been made in technology and aerodynamics be drawn upon to provide skilled persons in the underdeveloped countries with guidance or advice on how to use local or readily available materials to construct devices which, while remaining simple, would benefit from the technical refinements of the more complex machines? Such an effort, which has in fact already been started, should be geared to the needs and resources of each region. It would represent a further step forward and would at the same time promote the cultural awakening to which one speaker referred in plenary meeting.

Secondly, since there already are a large number of manufacturers of low and medium-power machines, and a still larger number of types of machines, would it not be possible to put some order into the existing confusion? This could be done by endeavouring, through some system of international standardization, to limit the number of types. In the first phase, the number of types would be reduced and their specifications made more uniform under a programme similar to those of a number of standardization agencies. In the second phase, standardization would be extended to design and manufacture. This in turn would pave the way for assembly line production, which is the only means of substantially lowering the price of wind power machines.

Agenda item II.B.2 (*a*)

REGULATING AND CONTROL SYSTEM OF AN EXPERIMENTAL 100-KW WIND ELECTRIC PLANT OPERATING PARALLEL WITH AN AC NETWORK

Sepp Armbrust *

Sponsored by the " Deutsche Studiengesellschaft Windkraft e. V. ", an experimental 100 kW windpower plant was designed and constructed between 1955 and 1957. After having been completed, the plant was erected on top of a barren hill at an altitude of 736 meters north of Stötten, which is situated about 80 km east of Stuttgart. The size of the plant is: tower height, 80 ft.; blade-swept area, 111 ft. diameter (figure 1).

The plant had been designed by a team under the direction of Professor Dr. Hütter. The following thoughts were given special attention in the design philosophy:

1. The various components should form self-contained assembly groups with regard to construction and fit other groups; they should also be independent to such an extent that they could be built in different workshops and still be connected with each other without rework.

2. In the design conception, special attention was paid to the large assembly groups — wing, machinery and tower — in order to assure that these groups would form entirely self-contained units to be connected with each other merely by attachment flanges. This division was made in recognition of the fact that these three main groups must be of totally different conception as to design and construction. The wings should contain no setting mechanisms whatsoever. They should merely be typically aerodynamic high-grade light-construction parts. The machinery was to enclose all necessary elements for energy conversion as well as for control and regulation as an integral unit. The tower itself only had to take over the function of the machinery foundation as an overground steel construction with the laws valid for such construction.

3. The specific power loading of the circular area swept by the wing blades was kept to a low level in order to assure an almost uniform energy output in places with relatively low mean wind speeds. Therefore, contrary to layouts of other teams in France, Denmark, England, United States, etc., we intentionally chose a design output of only 110 w/m² swept wheel area instead of the usual 300 to 400 w/m².

4. The governing system was devised to allow the possibility of studying a number of various control techniques and procedures during the tests with regard to their practical usefulness.

The windpower plant was created to examine the problems of energy conversion thoroughly from the free air stream to the feeding of electrical energy into the net.

The wings were designed without compromise according to aerodynamic optimum requirements. They consist of glass reinforced plastics, including the attachment flange, and are continuously set corresponding to operating conditions by a large hydraulic actuator.

The hydraulic actuator is operated by a working pressure of up to 20 atü, having to overcome the effect

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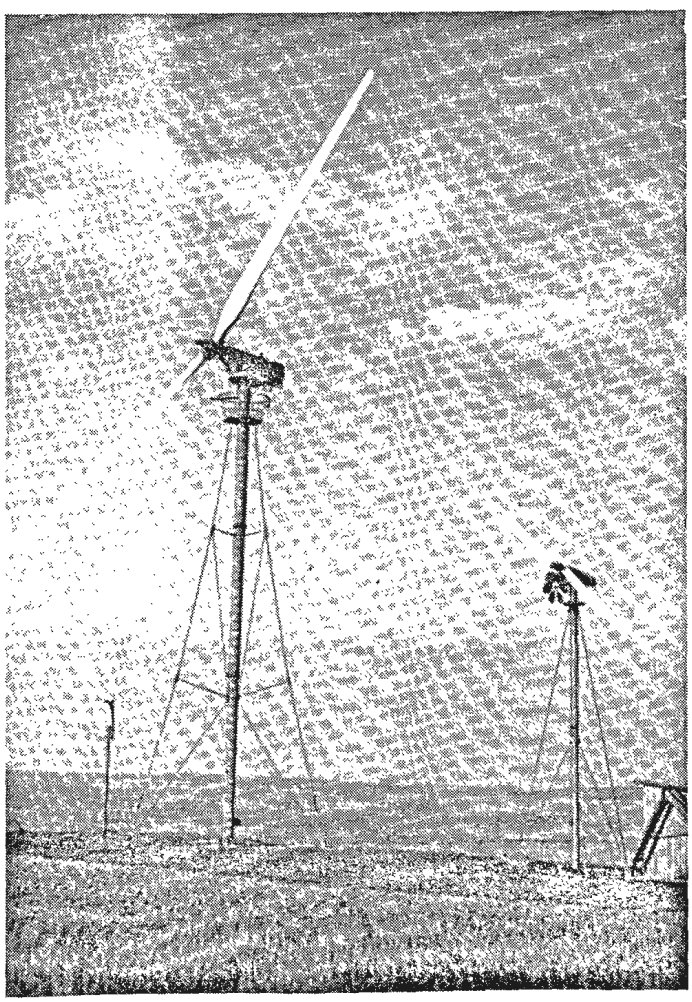

Figure 1

of aerodynamic and dynamic restoring moments of the wings and a bias spring.

The control and regulating system of this 100 kW experimental station is as follows (figure 2) :

The plant, being left to itself under automatic operation, registers the wind speed by means of an anemometer (pos. 1). As soon as the wind exceeds a mean speed of about 3 m/sec over a period of 16 minutes (variable) a solenoid value (pos. 2) will be closed. The oil delivered by the main pump (pos. 3) now does not return to the oil tank (pos. 4), but slowly begins to put the wings into operating position. The control slide (pos. 5) at first moves into a position leading the oil from the pump into the setting pipe (pos. 6), i.e., the propulsion wings (pos. 7) are adjusted in the direction of more revolutions. The control slide actuating rods are set in such a way that the restoring mechanism (pos. 8), working parallel with the pitch changing, resets the control slide over the intermediate lever (pos. 9) into the middle position at optimal blade setting. This occurs at a position of the power governor (pos. 10), still intending to raise the number of revolutions. The power governor does not stop to raise the revolutions until the desired power has been reached. Thus, the revolutions of the plant do not increase until the constant speed governor or the power governor start to respond, and the setting of the wind is being fixed or reduced by the control slide.

At parallel operation, the governing is carried out by the power governor only, and the constant-speed governor only serves as overspeed protection. The power governor, which may be adjusted between 30 and 120 kW, is set at 100 kW and will be kept within a tolerance of ± 5 per cent.

The power governor itself functions in such a way that a coil (Pos. 10a) is connected with the main current coming from generator over a transformer (Pos. 10b). At the nominal generator power setting, which may be adjusted by a slide resistance (Pos. 10c), a current flows through the coil sufficient to pull the iron core (Pos. 10d) against the return spring (Pos. 10e) to such an extent that the governing piston (Pos. 10f) moves into the middle position.

At the slightest change of the generator current, the force of attraction of the coil also changes (Pos. 10a), and the governing pistons are removed from the middle position. The oil coming from the servo pump consequently moves the actuating piston (Pos. 10h), and the propulsion wings (Pos. 7) are adjusted accordingly over the slide control

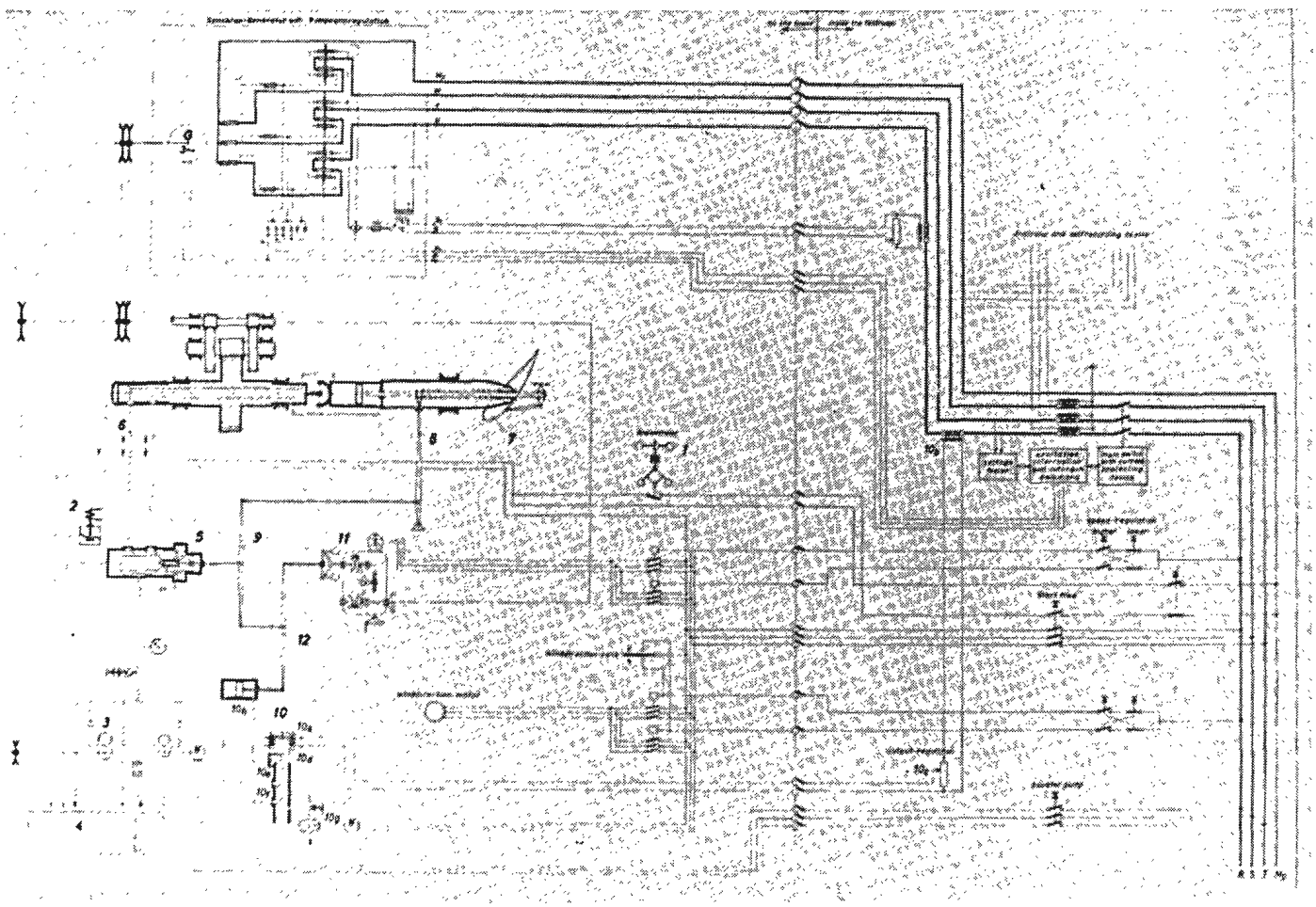

Figure 2. Regulating and control system

(Pos. 5). The larger the change of generator power, the faster the propulsion wings are adjusted.

The constant-speed governor (Pos. 11), at parallel operation, is set at 5 per cent above the nominal generator revolutions and practically responds only at an overspeed, i.e., at net failure.

At regulation by means of power governor (parallel operation), the bearing of the cross lever (Pos. 12) at the side of the constant-speed governor forms the fix point, about which the power governor actuates the cross lever (Pos. 12) and thereby the slide control (Pos. 5).

As soon as the constant-speed governor responds, the cross lever (Pos. 12) is moved about the bearing on the power governor side. By changing the transmission-ratio in the constant-speed governor, it is possible to obtain generator revolutions between 250 and 1 800 rpm. This possibility is of importance at solo-operation (not led by the net), whereby the revolutions as well as the power is governed. Outside the parallel operation, or below a generator power output, respectively, regulation is only possible by means of the constant-speed governor. In order to operate at 50 per cent nominal revolutions, for in instance, the transmission ratio (by hand or remotely controlled electric motor) has to be set on the corresponding value so that the flyball governor begins to respond at the desired plant revolutions.

The automatic start takes place in the following way: after having registered sufficient wind for a chosen period of time, the solenoid valve is closed and the revolutions rise higher and higher with the continuous wing adjustment. At 90 per cent nominal revolutions, the switching-in operation is initiated by the generator voltage over a sensing device. At first the exciting of the synchronous generator is interrupted, which fades away within 1.5 seconds. After about 2.5 seconds, asynchronous parallel circuits are closed by choke coils which absorb the switching-in impulse. After about three more seconds, the exciting again is switched on, and the choke coils are bridged. During these three seconds the generator was synchronized with the net.

As long as the wind stays calm and the generator does not reach the nominal power, the wings remain in the optimum position. If the wind speed rises, it will finally reach the nominal power (about 8 m/sec) at which the power governor begins to be engaged. Actuated by the hydraulic system, the propulsion wings are set back by the power governor to such an extent that the set nominal power is not surpassed. The governing range of the power governor is so large that even at top wind speeds the set power can be followed or not surpassed respectively, by turning back the setting of the wings.

If the wind abates so that in spite of optimum wing setting the power drops below 5 kW for three seconds, the cut-out operation will be released. The generator becomes separated from the net, the solenoid valve is opened, and by that the wings are reset into start position. At the same time the wind is registered again in order to introduce the new switching-in operation in time.

The plant is secured against all possible mishaps by various safety devices built in the parallel switch and governing automatic. An immediate cut-out is caused by the response of any one of these safety devices; in this case, however, without automatic re-start capability. Such an emergency cut-out takes place:

1. At break-down of the net (even at loss of one single phase);
2. At response of the generator high-voltage guard;
3. At response of the high-voltage guard at one of the electric motors; for instance, the wind direction motor, the servomotor at the power governor, the setting motor at the constant-speed governor and the booster oil-pump motor;
4. At response of the constant-speed governor because of over-speed.

To point 1 it may be added that the solenoid valve closes under voltage. Therefore, it will be opened automatically in case of net failure causing the return spring in the main shaft to draw back the piston and the setting of the wings into cut-out position. At failure or disturbance of the hydraulic system, this spring also acts upon the wings in such a manner that these are reset into the start position. At optimum working position, this return spring carries a load of approximately two tons.

As for the figure " Regulating and control system W 34/100 " it must be remarked that every simplified presentation was chosen in favour of a clear general view. Many complicated details have been omitted, e.g. the emergency cut-out or protective measures, the de-exciting of the generator and the parallel circuit by choke coils, the different time relays, the cut-out apparatus below 5 kW, the exact functioning of the wind registration with start order, etc.

Turning the plant into the wind is managed by a wind direction vane, which commands an electric motor and a worm gearing. If the wind turns into another direction, an electric motor is actuated by the wind direction vane by means of a relay, and the complete plant on the tower is moved in the proper direction of rotation, until the wind direction vane opens the contact.

This kind of wind-directional governing has proved to be sufficiently reliable in experimental operation, but for practical use a merely mechanical wind-directional governing by means of the often proved side-wheel above all is less likely to be malfunctioning during the winter months (with icing and hoar frost-accretion).

Figure 3 shows the indicating instruments and registration devices.

The indicating instruments are usually instruments (figure 4) built into the automatic container. In the upper left, there are 3 amperes among which there is one voltmeter as well as one 1 kW and cos φ indicator. At the right side there are the various

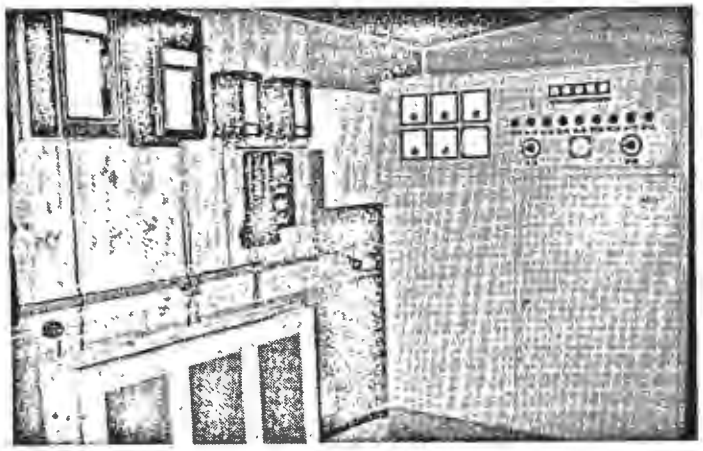

Figure 3

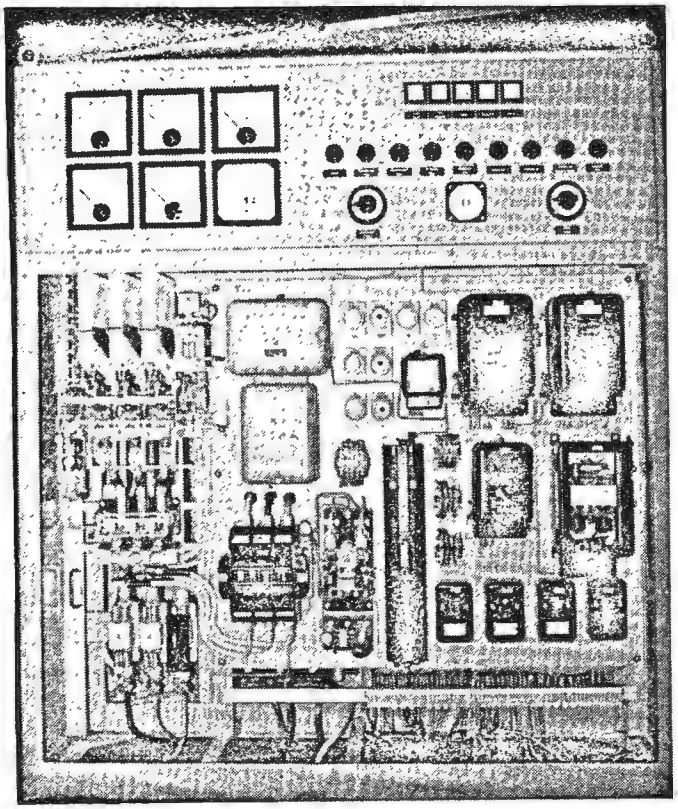

Figure 4

switches and in between a tachometer showing the revolutions of the generator and propulsion shaft. The control lamps are situated in the upper right, indicating the state of operations such as starting, automatic or manual working.

The measurement of wind and power is handled by impulse registration instruments (figure 5). The wind is given by an anemometer which yields an impulse every 20 meters covered by the wind. The electrical energy produced is measured by a three-phase current meter yielding an impulse every 0.033 kWh.

The registration instruments have been designed to transport a strip chart for 0.2 mm at each impulse. Every six minutes (measuring period) perforation takes place, which is released by the common clockwork, always ensuring synchronous run of both registration instruments (wind and power). Therefore, it is possible at the evaluation of the matching measurement periods to read directly the distance and the kWh from the distance between two perforations. From this, the mean values for each measurement period of six minutes may be obtained. Thus, we receive a time-duration curve from wind and power.

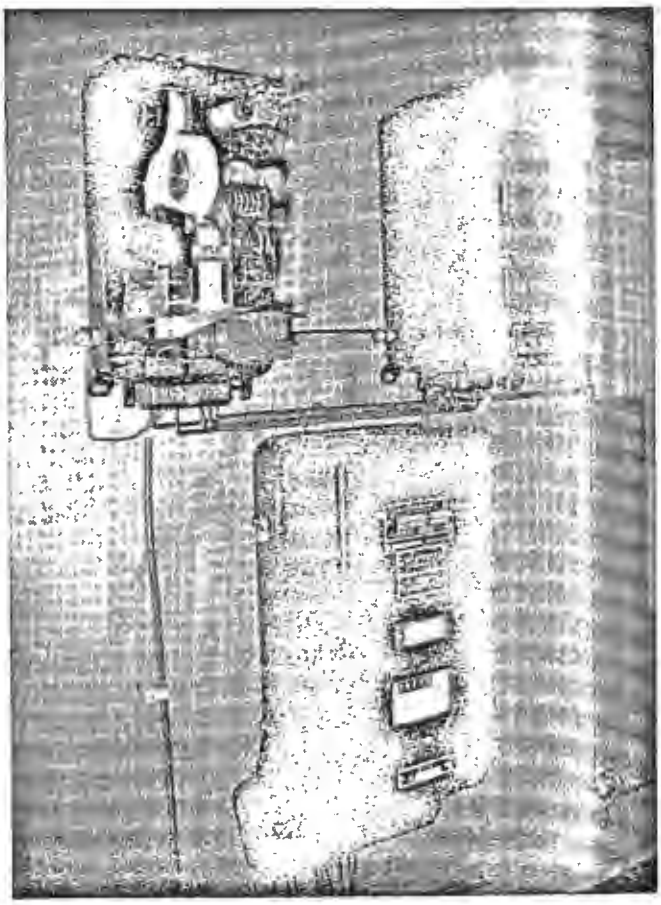

Figure 5

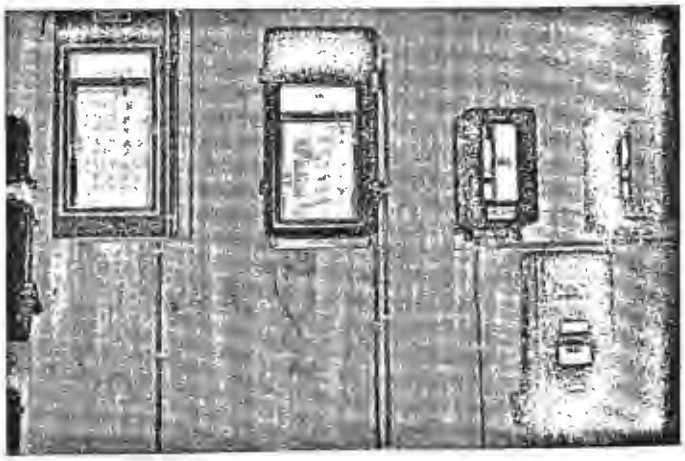

Figure 6

As additional registration instruments, a kilowatt recording apparatus and a net voltage recording apparatus were installed (figure 6). These instruments have the advantage that one can always gain a quick estimate of the power curve, etc., before having evaluated the more exact impulse figures. In conclusion, it may be remarked that the plant has been in operation since autumn 1957. The first parallel circuits were carried through in December 1957, but with simple parallel switching by hand only.

Since October 1959, the plant has been provided with the automatic start and governing device. The first measurements with the impulse registration instruments were carried out in autumn 1960.

EXPÉRIENCES FAITES AVEC GÉNÉRATRICES A AÉROMOTEUR DONT L'HÉLICE EST INSTALLÉE DERRIÈRE UNE TOUR A PROFIL AÉRODYNAMIQUE

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La conception d'éoliennes à rotor auto-orientable monté derrière la tour n'a rien de nouveau, car on a tenté, en diverses occasions, d'avoir recours à cette solution en vue des avantages qu'elle présente, et on a procédé à des études théoriques sur le comportement de ces dispositifs.

L'une des conditions essentielles d'exploitation des éoliennes réside dans la simplicité de leur construction, qui se répercute sur leur prix. En conséquence, dans les régions où le régime des vents s'y prête et où la densité de la population est faible — lesquelles se caractérisent le plus souvent par des moyens d'existence restreints et, en conséquence, par l'absence de tout réseau de distribution électrique — le fait d'avoir une source d'énergie située au lieu même de son utilisation et dont la consommation ne coûte rien, revêt une importance toute spéciale, surtout quant à la modicité des frais de premier établissement. Cette condition économique fondamentale est celle qui compense l'ennui de ne pouvoir compter sur la continuité de cet apport d'énergie et le besoin de devoir en adapter l'utilisation à l'intermittence.

Dans toute étude d'éolienne, il est fort important de songer à tous les moyens possibles de réduire les périodes d'intermittence et de limiter la capacité des accumulateurs d'énergie, lesquels augmentent notablement les frais d'installation et d'entretien.

La solution qui prévoit l'emploi d'une hélice auto-orientable montée sur l'arrière de la tour réduit les frais, car elle permet d'éliminer le gouvernail des éoliennes de petites dimensions, le rotor anti-couple des installations de moyenne puissance et les groupes avec moteur à auto-synchronisation du genre Selsyn et plan d'orientation des gros aéromoteurs.

La difficulté de leur emploi s'explique par les causes suivantes :

1) L'instabilité du régime d'écoulement de l'air dans le secteur circulaire où l'influence de la tour se fait sentir, laquelle fait apparaître, sous le vent, une zone de tourbillons de Karman provoquant des vibrations des pales de l'hélice, déjà chargée par les alternances des effets de masse cycliques.

Les coefficients de résistance aérodynamique des tours, soit C_x (pour les dimensions moyennes d'une éolienne de 100 kW et un vent de 10 m/sec) sont :

Tour à structure constituée par un treillis de cornières	C_x	1,7
Tour à structure cylindrique de section circulaire	C_x	1,2
Tour à structure cylindrique de section ovale $\lambda = 2:1$	C_x	0,6
Tour à structure cylindrique de section Navy Strut nº 1	C_x	0,06

L'existence même de la résistance limitée à un secteur circulaire d'une ouverture généralement inférieure à 10° impose une légère perte d'énergie qui influe sur le rendement, mais le facteur important est le passage des pales de l'hélice, une fois par tour, dans la zone à turbulence violente et à vitesse réduite du secteur en question.

Les expériences en cours avaient été précédées par des travaux dans lesquels le modèle d'hélice (2 m de diamètre) était soutenu par une tour de section cylindrique $d = 0{,}022\ D$ environ, mais malgré son faible diamètre relatif, on avait observé des vibrations qui restaient nettement perceptibles jusqu'à ce que le plan de l'hélice, par rapport à l'axe de la tour, soit éloigné de $x = 0{,}25$ à $0{,}30\ D$. Cette distance excessive rendait peu pratique l'installation d'un tel système.

2) L'augmentation des sollicitations gyroscopiques cycliques sur les pales, par rapport à la solution qui fait appel à une hélice située sur l'avant de la tour et à un gouvernail de direction ou, plus encore, par rapport au système à rotor anti-couple, qui permet de les réduire sensiblement.

3) L'augmentation de la charge aérodynamique qui agit sur l'hélice en cas de vents violents, lorsque les pales sont calées par rapport à l'arbre de rotation de l'hélice et la rotation du disque contre le vent est invariable (cas *a*) par rapport à celle que l'on observe lorsque les pales peuvent librement se mettre individuellement en drapeau (cas *b*) ou encore lorsque le disque de l'hélice peut se mettre en drapeau, les pales restant calées sur l'arbre (cas *c*).

Désignons par V_R la vitesse de régime de l'éolienne, V_m la vitesse à laquelle le système de régulation arrête toute rotation pour garantir la stabilité de l'ensemble de la machine, et V_s la vitesse maximum

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que le vent pourrait atteindre dans des conditions exceptionnelles. On pourra écrire : $V_s \gg V_m > V_R$.

Considérons par exemple le cas d'une éolienne ayant une solidité

$$\sigma_R = 0{,}113 \quad C_x\,(W = 0\ \text{m/s}) = 0{,}12$$
$$C_x\,(W = 15\ \text{m/s}) = 0{,}7$$
$$V_m = 15\ \text{m/s}\ (54\ \text{km/h}) \quad V_s = 62{,}6\ \text{m/s}\ (225\ \text{km/h})$$

Dans le cas *a*, nous observons que la charge frontale pour V_s ne dépasse pas 34,2 p. 100 de celle qui s'exercerait sur l'hélice en rotation à la vitesse V_m (c'est-à-dire qu'il n'y a pas une augmentation mais bien une diminution). Dans le cas *b*, la charge pour V_s est négligeable. Dans le cas *c*, la résultante due à la charge, lorsque le rotor est en drapeau, est pratiquement nulle, mais les pales perpendiculaires, ou presque, à la direction du vent dans le plan du disque ou rotor sont soumises à des charges qui pour V_s sont environ 3,4 fois plus grandes que pour V_m, la charge des pales supérieures étant dans une direction presque opposée à celles du bas. En conséquence, pour la stabilité de l'ensemble, la condition critique est donnée : *par la vitesse V_m et les pales en rotation* pour les hélices dont les pales sont calées sur l'arbre et dont l'orientation du disque est invariablement contre le vent (cas *a*) ou pour les hélices dont les pales peuvent individuellement se mettre en drapeau (cas *b*) et par *la vitesse V_s à hélice arrêtée* pour les hélices dont le disque peut se mettre en drapeau, les pales restant calées sur l'arbre (cas *c*).

La solution du cas *c* est évidemment exclue pour les éoliennes dont l'hélice se trouve derrière la tour, et ceci ne serait d'ailleurs pas indiqué, pour les raisons qui ont été mentionnées ci-dessus. On a observé de la sorte que les vents violents n'imposent pas de condition critique de charge pour les hélices situées derrière la tour.

4) La nécessité de construire la partie supérieure de la tour sur une hauteur un peu plus grande que le rayon de l'hélice ($L = 0{,}6\ D$), de telle sorte qu'elle soit orientable avec le vent.

Si on analyse en détail le problème d'ensemble des frais de construction, on notera que ceci ne provoque aucune augmentation des frais de fabrication en grande série, et, au contraire, présente l'avantage d'éliminer l'organe de direction et d'augmenter le rendement de l'éolienne.

Description du modèle et des expériences

Les essais ont été faits au départ avec une tour cylindrique tubulaire ayant une section circulaire de diamètre $d = 4{,}4$ cm. Par la suite on a réalisé une autre tour cylindrique à section aérodynamique au profil Navy Strut n° 1 (Hauban marine, n° 1) avec une articulation permettant d'assurer le déplacement progressif du plan de rotation de l'hélice par rapport à l'axe de la tour d'une manière plus compatible avec la solidité de l'ensemble, (figures 1 et 2).

La partie cylindrique de la tour est dotée, en sa partie inférieure, de deux paliers que sépare une distance $s = 0{,}2\ D$. Le palier de poussée supérieur, ou butée, qui est du type à billes, se trouve à une distance $s' = 0{,}7\ D$ de l'axe de rotation de l'hélice; celui qui est en bas est une simple butée en bronze. Juste au-dessus du palier supérieur, on trouve le boîtier des contacts électriques tournants de la génératrice et du compte-tours.

La section cylindrique de la tour peut tourner dans un logement cylindrique qui est fixé en ses extrémités à deux panneaux permettant de le boulonner au sommet du tronc de pyramide que représente une tour faite d'un treillis de cornières en fer. Cette seconde tour d'expérience a été construite après mise au point des études et exécution des calculs de stabilité d'une tour analogue pour une éolienne de 100 kW.

Les essais ont été faits en mettant la tourelle qui se voit aux figures 1 et 2 sur un corps surélevé du toit de la Faculté du génie civil et de l'arpentage de Montevideo, qui se trouve à une hauteur de 36 m au-dessus du sol. On a fait les mesures de contrôle voulues avec les instruments suivants :

a) Un anémographe de Lambrecht, capable d'enregistrer la vitesse et la direction du vent. Ce double

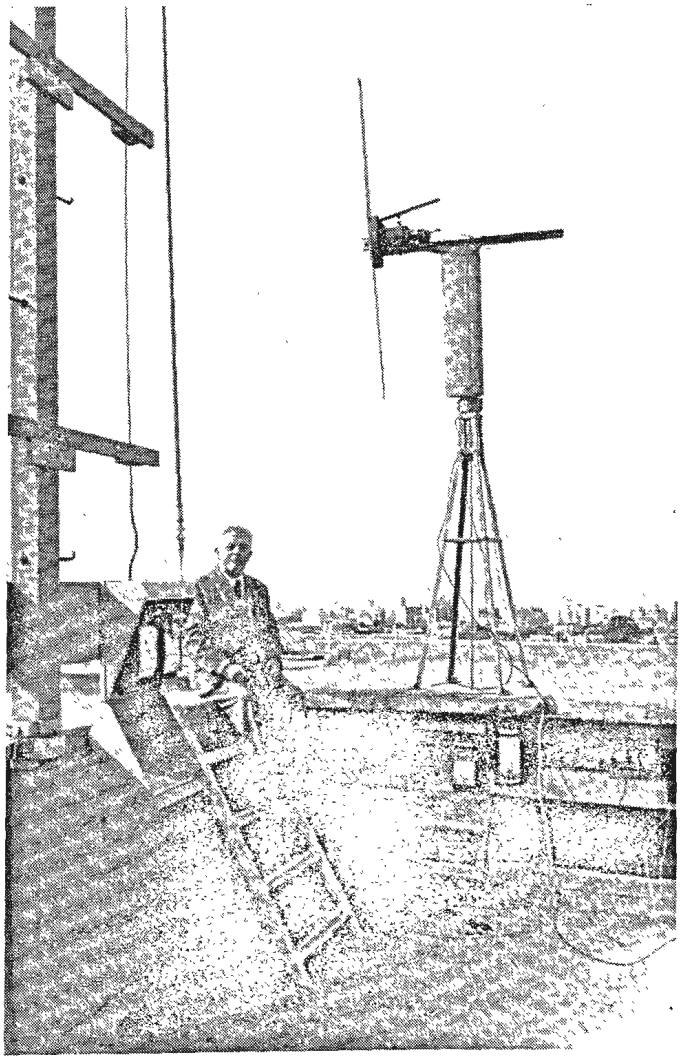

Figure 1

enregistrement est habituellement commandé par un mouvement d'horlogerie qui permet des avances de 1,4 et 8 cm à l'heure. Ce mécanisme a été remplacé par deux enregistreurs Westinghouse du type G-40, lesquels autorisent des vitesses d'enregistrement de 3/4, 1 1/2, 3 ou 6 pouces à l'heure ou à la minute. Le même type d'enregistreur, avec ces mêmes vitesses d'avance, a été utilisé avec tous les autres instruments.

b) Un deuxième anémographe de Lambrecht qui n'est doté que du mécanisme voulu pour enregistrer la direction; il est relié par une bielle au cylindre mobile de la tour, de manière à enregistrer les déplacements en azimut de l'éolienne à la même vitesse d'enregistrement que celle qui s'emploie pour la vitesse du vent.

c) Un compte-tours électrique relié à l'arbre du générateur électrique derrière l'hélice et à un enregistreur.

d) Un voltmètre et un ampèremètre enregistreurs du courant produit par la génératrice, ayant chacun son dispositif d'enregistrement.

e) Un vibromètre de Westinghouse.

Si on compare les courbes chronographiques synchrones des enregistrements des divers instruments, on peut en déduire toutes les données relatives aux essais. En particulier, en comparant les courbes qu'a donné l'enregistrement de la direction avec l'anémographe à celle de l'enregistrement direct des positions de l'éolienne, on peut mesurer, sur les intervalles voulus, les vitesses et les accélérations angulaires.

Avec les possibilités offertes par les conditions atmosphériques et l'existence de vents de diverses vitesses, on procède actuellement aux essais de fonctionnement du groupe hélice-tour-génératrice, de manière à réaliser les conditions les plus dures et à dresser des tables des résultats. Il ressort des comparaisons effectuées qu'il est opportun de construire et d'essayer divers types de paliers amortisseurs de rotation en vue de les monter à la partie cylindrique de la tour et de réduire ainsi la valeur admissible des accélérations angulaires du groupe hélice-porte-hélice, quand il est indiqué de le faire, pour les éoliennes de moyennes et grandes dimensions.

Jusqu'à présent, dans la première série d'essais réalisés avec une tour cylindrique de section circulaire, on a observé que cette solution n'était pas très satisfaisante, car, pour amortir d'une manière appréciable les vibrations produites par le dérangement de l'écoulement que provoque la tour avec l'hélice à deux pales utilisée, on a jugé nécessaire d'éloigner le plan de rotation de cette hélice de $x = 0{,}25\ D$ (avec $d = 0{,}022\ D$) de l'axe de la tour, ce qui est excessif au point de vue pratique.

Les expériences de la deuxième série avec une colonne cylindrique de section aérodynamique ayant un coefficient d'allongement $\lambda = 3 : 1$ (Navy Strut n° 1) ont démontré qu'un amortissement complètement satisfaisant des vibrations pouvait se réaliser pour $x = 0{,}13\ D$, quand on prend $d = 0{,}035\ D$. Ces résultats, obtenus avec une hélice à deux pales, seront certainement réduits avec une hélice à trois pales et constituent une démonstration fondamentale à l'appui des éoliennes à hélice située derrière une tour de section aérodynamique orientable avec le vent.

Comparaison des systèmes d'orientation des éoliennes contre le vent

Comme on le sait, l'orientation automatique des éoliennes contre le vent peut être réalisée des manières suivantes :

1) Au moyen d'un gouvernail arrière, qui fonctionne comme un plan directionnel;

2) Au moyen d'une petite hélice supplémentaire qui tourne dans un plan normal à celui de l'hélice principale et s'appelle l'hélice compensatrice de couple;

3) En situant le rotor derrière la tour;

4) Au moyen de moteurs électriques d'orientation dont l'un transmet l'orientation dans le vent d'un plan directionnel à un autre moteur qui oriente l'hélice de la même manière.

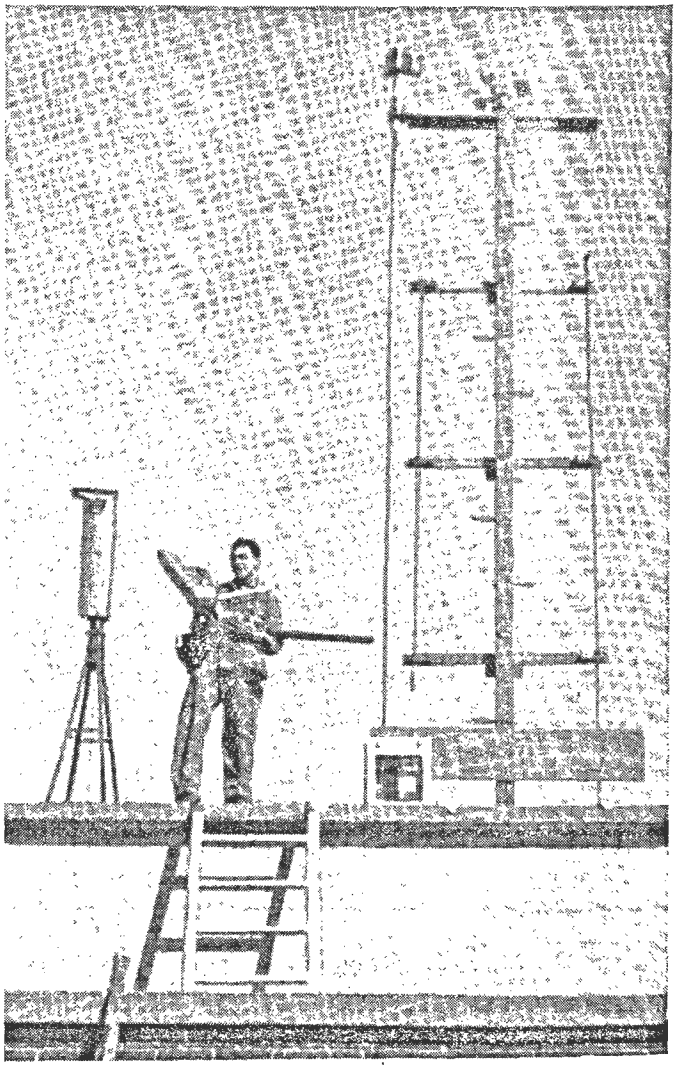

Figure 2

Les solutions 2 et 4 s'emploient pour les éoliennes de dimensions moyennes et grandes, la formule 1 restant limitée aux petites, d'une puissance comprise entre 1 et 10 CV à rotation lente, dont les pales ont un faible moment d'inertie.

Orientation au moyen d'un gouvernail monté à l'arrière

Pour le calcul de l'orientation contre le vent des éoliennes dotées d'un gouvernail, il faut disposer de courbes expérimentales (déduites d'essais faits au tunnel aérodynamique) relatives aux composantes des forces aérodynamiques qui agissent sur l'hélice, C_x (parallèle à l'axe de rotation de l'hélice) et C_y (située dans le plan de l'hélice) en fonction de l'angle γ que le plan du disque forme avec la direction du vent. Il est nécessaire, en outre, de disposer des courbes de la distance relative $\frac{x}{R}$ du centre de pression à C_x en fonction de γ.

Si l'on écrit l'équation des moments par rapport à l'axe de rotation vertical de l'éolienne, on peut en déduire la grandeur de la force aérodynamique qui doit être exercée sur le gouvernail et, par conséquent, sa surface, ou la distance entre l'axe de rotation et le centre de pression d'une surface de gouvernail donnée.

Si l'éolienne est dotée d'un axe de transmission vertical, relié par des engrenages coniques à l'arbre de l'hélice, il faut introduire, dans l'équation mentionnée ci-dessus, un terme qui représente le moment de réaction.

Certaines éoliennes sont construites de manière à réaliser une régulation approchée de la vitesse de rotation dans le cas où le vent est plus fort que celui qui correspond à la puissance nominale et à la mise en drapeau du disque de l'hélice, en faisant tourner le gouvernail de 90°. Dans ce cas, l'axe de rotation de l'hélice doit avoir une excentricité e par rapport à l'axe vertical de la tour. Cette excentricité fait apparaître un moment qui doit également être introduit dans l'équation d'équilibre mentionnée ci-dessus.

Dans le système à orientation par gouvernail, ce dernier se déplace rapidement en raison des variations continues de la direction du vent et maintient l'hélice perpendiculaire à cette brise. Mais les rotations rapides du groupe hélice-porte-hélice-gouvernail, compte tenu de toutes les sautes de la direction du vent, font apparaître un moment gyroscopique dans les pales en rotation, moment qui a tendance à les faire fléchir ainsi que l'arbre de l'hélice. Pour des rotations positives, à la fois pour les pales et pour les déplacements autour de l'axe vertical de l'éolienne, le moment gyroscopique ainsi réalisé est positif : c'est dire que la tendance est à la courbure de l'arbre de l'hélice vers le haut et de la pale supérieure vers l'arrière.

Le moment gyroscopique qui s'exerce sur l'arbre des hélices à deux pales varie entre 0 et un maximum deux fois par tour. Les variations harmoniques de ce moment peuvent provoquer des vibrations, particulièrement si elles entrent en résonance avec un élément quelconque de la structure.

Pour les hélices à trois pales et à quatre pales, le moment gyroscopique est constant. Le moment gyroscopique par rapport au pivot de chaque pale est doublement nul lorsque les pales passent à l'horizontale et doublement maximum quand elles passent par la verticale, le maximum étant égal à :

$$M_g = 2\, I\, \omega\, \omega_1$$

expression dans laquelle

I = moment d'inertie de masse de la pale de l'hélice par rapport au centre de rotation en kg/m/sec²;

ω = vitesse angulaire de l'hélice en radians par seconde;

ω_1 = vitesse angulaire du groupe hélice-porte-hélice en radians par seconde.

Pour une hélice massive de section trapézoïdale, comme celle du modèle, le rayon de rotation est égal à 53 p. 100 environ de celui de l'hélice. En conséquence, si l'on considère qu'une hélice de 2 m de diamètre pèse 1,6 kg (0,8 kg par pale) et tourne à 800 t/min, en admettant que la vitesse angulaire maximum ω_1 soit de 0,5 radian par seconde, on a un rayon de rotation :

$$0{,}53 \cdot 1 = 0{,}53 \text{ m}$$
$$I = (0{,}8/9{,}81) \cdot 0{,}53^2 = 0{,}0416 \text{ kg/m/sec}^2$$
$$\omega = 800 \cdot 2\,\pi/60 = 83{,}7 \text{ rad/sec}$$

On a d'autre part

$$M_g = 2 \cdot 0{,}0416 \cdot 83{,}7 \cdot 0{,}5 = 3{,}49 \text{ m/kg}$$

Ce moment doit être ajouté à celui qui est produit par les forces aérodynamiques. L'arbre de l'hélice fléchit sous l'action du moment gyroscopique de toute l'hélice.

Pour une hélice à deux pales on aura :

$$M_g = 2\, I_0\, \omega\, \omega_1 \sin 2\, \omega_t$$

expression dans laquelle

I_0 = moment d'inertie de toute l'hélice par rapport à son axe de rotation,

ω_t = angle de rotation de la pale compté depuis sa position horizontale à l'instant t.

Pour une hélice à trois pales on aura :

$$M_g = I_0\, \omega\, \omega_1$$

La vélocité angulaire ω_1 dépend de la longueur du gouvernail et se calcule en comparant l'énergie utilisée à celle qui est disponible pour chaque surface, ce qui donne son rendement maximum quand $\omega_1\, L = \frac{1}{3}\, V$, L étant la distance entre l'axe vertical de rotation et le centre de pression du gouvernail. Le rendement maximum est donc égal à :

$$\omega_1 = \frac{1}{3}\frac{V}{L}$$

Cette expression indique que ω_1 est inversement proportionnel à L.

Orientation en disposant l'hélice derrière la tour

Pour les fins du présent mémoire, il n'est pas nécessaire de s'intéresser à l'orientation au moyen de l'hélice auxiliaire anti-couple, car ce système d'orientation, caractérisé par les petites valeurs de ω_1 qu'on peut faire varier à plaisir avec le rapport de réduction du train de commande de la rotation, ne présente pas les caractéristiques d'orientation au moyen du gouvernail et de l'installation de l'hélice derrière la tour, qui sont analogues les unes aux autres.

Dans ce dernier cas qui nous intéresse, on utilise, pour le calcul, les courbes donnant le moment du rotor en fonction de l'angle γ avec $1/D$ comme paramètre, déterminées expérimentalement au tunnel aérodynamique (1 est la distance entre le disque ou rotor de l'hélice et l'axe vertical de la tour). Cette distance 1 qui, dans le cas de l'hélice située derrière la tour, correspond à L avec gouvernail, doit être, pour des raisons de construction, aussi réduite que possible pour donner un moment suffisant pour maintenir l'hélice contre le vent, soit :

$$1 \ll L$$

En conséquence, on emploie l'équation précédente, en remplaçant L par 1, ce qui démontre que ω_1 sera plus grand que dans le cas de l'emploi d'un gouvernail. C'est dire que les conditions que nous avons examinées, en ce qui concerne le moment gyroscopique des éoliennes orientées par un gouvernail, se retrouvent pour le cas de l'hélice montée derrière la tour, avec cette aggravation que $1 \ll L$.

Dans les expériences faites, l'accélération angulaire $d\omega/dt$ a pu être tenue faible en raison de l'amortissement dû aux deux paliers de la tour cylindrique.

Pour tous détails supplémentaires, voir la bibliographie.

Il ressort de ce qui précède que, dans la pratique, la possibilité d'application de l'orientation par l'emploi d'une hélice montée derrière la tour, si attrayante en raison de son esthétique et de son économie, est conditionnée par les observations suivantes :

a) Tour cylindrique à section aérodynamique qui dérange au minimum l'écoulement intéressant l'hélice ;

b) Réduction, dans les éoliennes de moyennes et grandes dimensions, de l'accélération angulaire du groupe hélice-porte-hélice dans ses mouvements autour de l'axe de la tour grâce, particulièrement, à des amortisseurs de rotation qui, fort heureusement, sont peu coûteux.

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Résumé

L'auteur fait observer, dans la première partie du mémoire, que l'une des conditions essentielles dont dépend le judicieux emploi des éoliennes est la réduction des frais de premier établissement afférents aux machines. Ceci veut dire que, dans toute étude des aéromoteurs, il faut tout mettre en œuvre pour en simplifier la conception et comprimer les frais.

En conformité avec ce besoin, on a envisagé l'élimination de l'organe qui sert à l'orientation automatique de l'éolienne contre le vent en exploitant les propriétés auto-directionnelles des hélices installées derrière la tour.

Les recherches dont le compte rendu suit se rapportent à des essais faits sur deux modèles d'hélice à deux pales ayant un diamètre $D = 2$ m, l'un avec une tour cylindrique à section circulaire, l'autre avec une tour également cylindrique, mais présentant une section aérodynamique caractérisée par un coefficient de 3 : 1.

On observera que les tours en treillis d'emploi généralisé présentent un coefficient de résistance $C_x = 1{,}7$, celles qui sont constituées par une structure cylindrique à section circulaire $C_x = 1{,}2$, et celles dont la section est aérodynamique le coefficient $C_x = 0{,}06$.

Pour utiliser une tour cylindrique à section aérodynamique qui peut tourner autour d'un axe vertical de manière à s'orienter automatiquement dans la direction du vent, il faut décaler les paliers autour desquels s'effectue sa rotation à 0,6 D au-dessous de l'axe de l'hélice. On analyse donc la condition critique de stabilité pour la tour et les pales. On donne pour $V_s \gg V_m > V_r$, respectivement, la vitesse maximum acceptable du vent (225 km/h), la vitesse maximum du vent qui reste compatible

avec la stabilité du système quand l'aéromoteur fonctionne (54 km/h), et la vitesse nominale choisie. On montre que, pour le cas où l'hélice se trouve derrière la tour, la condition critique correspond à V_m et non pas à V_s, dont la valeur est largement supérieure. Au contraire, dans le cas des aéromoteurs dont le plan de rotation de l'hélice peut se mettre en drapeau, les sollicitations auxquelles les pales sont soumises à la vitesse V_s sont 3,4 fois plus grandes que pour V_m.

On décrit ensuite, les modèles et les deux séries d'expériences, dont la seconde est encore en cours, en donnant une indication des instruments utilisés, et on souligne l'opportunité de faire usage de certains paliers amortisseurs des accélérations angulaires.

On examine enfin, les divers systèmes d'orientation automatique en usage, particulièrement celui qui emploie un gouvernail arrière et celui qui prévoit l'installation de l'hélice derrière la tour, lesquels sont analogues l'un à l'autre.

Les expériences de la première série ont donné des résultats qui, du point de vue pratique, étaient négatifs. Celles de la seconde série ont donné des résultats positifs, car, avec une tour ayant un diamètre $d = 0{,}035\ D$, il ne se produit pas de vibrations dans l'hélice quand le plan de cette dernière se trouve à $x = 0{,}13\ D$ de l'axe de la colonne.

Les accélérations angulaires relevées à l'occasion des essais réalisés avec le modèle ont été minimes et entièrement acceptables; mais on prévoit que, pour les aéromoteurs de moyenne et grande puissance, il sera nécessaire de faire usage de paliers amortisseurs d'accélération angulaire, lesquels, fort heureusement, sont très économiques. On estime donc que la simplification à l'étude est généralement réalisable, ce qui permettra une sensible réduction du prix de revient des aéromoteurs pour leur production en grande série.

EXPERIENCES WITH WIND-DRIVEN GENERATORS WITH PROPELLER BEHIND A MAST OF STREAMLINE SECTION

Summary

In the first part of this paper, the author notes that one of the fundamental conditions for wind energy utilization at low cost is the low cost of the equipment; for this reason, the utmost effort should be made to simplify design and reduce the cost.

We have therefore studied the possibilities of eliminating the automatic orientation system of the windmill, and utilizing instead, the auto-orientation property of a propeller placed behind the tower.

This paper reports tests in natural wind of two models, $D = 2$ m, both with a cylindrical tower, one of circular section, the other with streamline section, and aspect ratio 3 : 1.

The drag coefficient C_x of the lattice towers usually employed is 1.7; that of cylindrical towers of circular section is 1.2, and that of the streamlined towers is 0.06.

The choice of a cylindrical tower of streamline section which turns automatically in the wind direction compels us to set the shaft bearings for its rotation at distance 0.6 D below the propeller shaft. This is why we must analyse the critical condition of stability of the tower and of the blades. We state that $V_s \gg V_m > V_r$, where V_s is the maximum possible wind speed under exceptional circumstances (225 km 1 h). V_m is the cut-off wind speed required for stability (54 km) and V_r is the rated operating wind speed. For windmills with propeller behind the tower the critical condition can be proved to respond to V_m, and not to the higher speed V_s. On the other hand, for windmills that can be feathered without turning the blades, at V_s the load on the blades is 3.4 times greater than at V_m.

The second part of the paper describes the models used in the two test series, as well as the instruments used.

In the third part we examine various automatic orientation systems, especially those with tail rudder and with the propeller behind the tower, which are similar.

The first series of experiments gave negative results from the practical point of view. The second series gave positive results, because with a tower of diameter $d = 0.035\ D$, no vibration was produced in the propeller at a distance $x = 0.13\ D$ from the centre of the column.

The angular accelerations obtained in the tests were small and entirely acceptable, but it may be predicted that in medium-power and high-power windmills oil rotation dampers will be necessary. Fortunately such dampers are very inexpensive. The proposed simplification seems practicable, if cylindrical streamlined towers are used, and it reduces the cost of mass production of windmills.

CLASSICAL DESIGNS OF SMALL DRAINAGE WINDMILLS IN HOLLAND, WITH CONSIDERATIONS ON THE POSSIBILITIES OF THEIR IMPROVEMENT AND ADAPTATION IN LESS DEVELOPED COUNTRIES

A. Havinga *

It is not so very long ago since windmills in Holland were entirely hand-made from wood, with some minor parts only for joining and reinforcement. Wooden shafts ran on stones, but were provided with hardened steel bars at the spots where friction occurred. Building and repairing a full-sized Dutch windmill requires highly specialized tradesmen, who are difficult to find today, even in the Low Countries. In former centuries, however, there were in Holland numerous small pumping windmills (1), which served the purpose of draining small areas of land. As they were of simple design, they could be made by local carpenters and maintained by the farmers, who carried out minor repairs themselves. Under bad weather conditions, winds are very variable in Holland, both in direction and in force, and consequently a Dutch windmill of classical design requires much attendance when in operation. Nowadays, this is not economic when the windmill is small and of limited capacity. This explains why small wooden windmills have practically all disappeared from Holland and why they have been replaced by metal structures, which incorporate devices for automatic adaptation to variable wind-direction and wind-force. Thus, the appearance of the metal windmills indicates the raised standard of living in Holland. In other countries, where the standard of living is not so high, there is perhaps still a future for simple wooden windmills which can be made by tradesmen with only simple tools at their disposal. Suitable designs, however, are not immediately available, and it is an undeniable fact that designing a very simple structure offers its special problems. Inspiration for the design of a small windmill may be found in the classical Dutch designs, because they are based on the experience of many centuries and have proved their usefulness under severe working conditions.

Generally speaking, small Dutch drainage mills fall into two categories, those *with* and those *without* bevel gears. Those *without* gears have the Archimedean screw as a water-raising device. In former centuries, numerous mills of this kind were to be found in the province of Frisia, in the north-eastern part of the Netherlands, where they are named "tjask-mills". The screw and the sails of a tjask-mill have one long inclined shaft in common. The simplest mills *with* gears are provided with two shafts: first, the horizontai mainshaft with the sails and, secondly, a vertical shaft in the centre of the mill, which is nothing but the lengthened shaft of a wooden centrifugal pump.

Figure 1 shows the design of a small windmill with centrifugal pump, as it was made formerly in the western parts of the Netherlands. The plate is reproduced from a rather old Dutch handbook on hydraulic architecture (2). A mill of this kind is to be erected on a small spot of land — rather more than a dam — between the ditches leading to and from the mill. Its intake is an open culvert with a circular hole in the bottom, the centre of the hole coincides with the centre of the mill. The vertical shaft passes through this hole. It rests on a step bearing and is provided with four wooden blades of slightly curved shape, thus making a bladewheel with a diameter of 1.00 m. The bladewheel moves with very little clearance in a wooden housing. As the plate shows, the bottom of the intake is at the same time the cover of the housing. A discharge tube of rectangular section joins the housing more or less tangentially, completing the centrifugal pump. When the mill is in operation, the water enters the pump from above; it is brought into a circular motion and forced through the tube. Of course, a valve at the mouth of the discharge tube is necessary to prevent a reflow when the mill ceases to run with sufficient speed.

The figure shows the wooden tower, consisting of a fixed lower part and an upper part which may be adjusted to the wind direction and therefore rests upon a seat. Turning the mill into the right direction is made easier by a vane, but with a classical Dutch small windmill the friction at the seat is appreciable and cannot be overcome by the pressure of a moderate wind on the vane alone. This is not a disadvantage in every respect : the rather high friction adds to the stability of the mill, which is of value in stormy weather when storm-damage is to be feared.

The vertical pumpshaft is driven from the windshaft by means of a wooden bevel gear, ratio 29 : 13. The wheel with the 29 wooden cogs on the windshaft serves as the brakewheel too; when the mill must be brought to a standstill, a rather powerful brake is applied to it. The sails, with a span of 6.40 m, are made of wood and covered with planking. At the trailing side of each sail the planking can be removed, but in stormy weather this is a task of a dangerous nature. Experience has shown the advantage of sails of heavy construction, and this advantage is not

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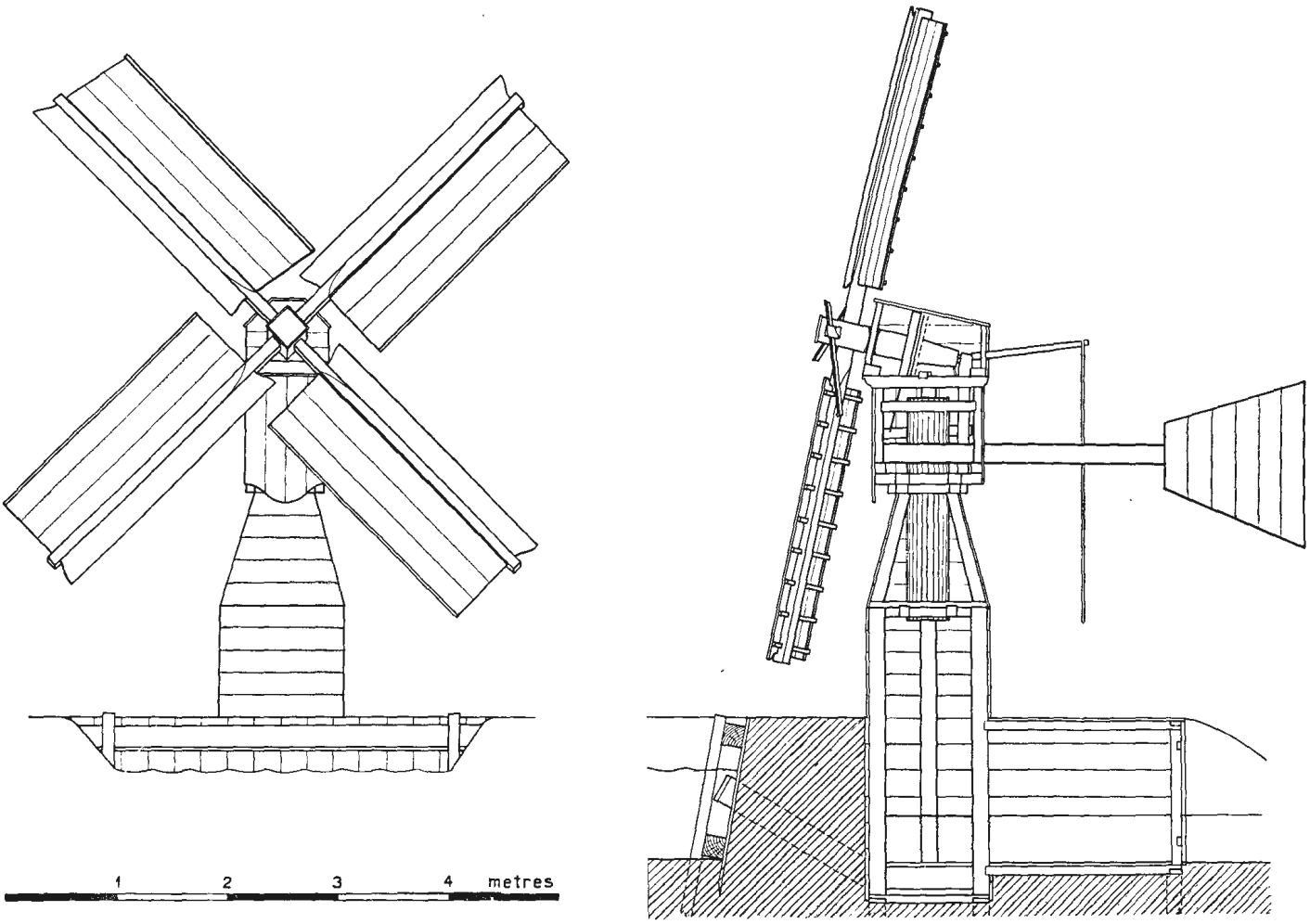

Figure 1. Design of small Dutch pumping windmill with centrifugal pump

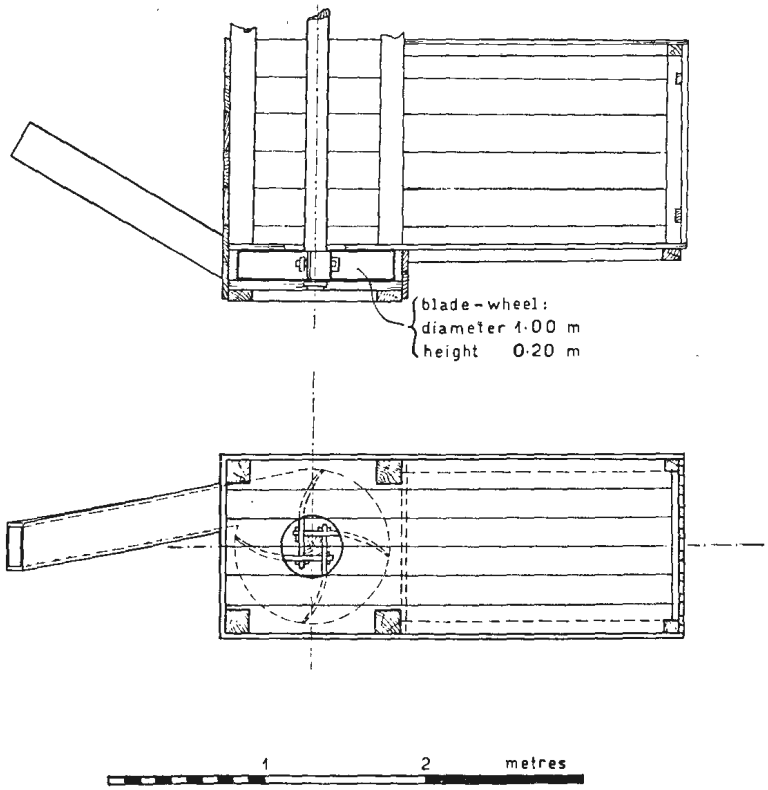

Figure 1 (supplement). Details of wooden centrifugal pump and intake

only to give sufficient strength. Recent scientific research in Holland (3) has shown that an appreciable moment of inertia in windmill sails is a factor of great importance when a reasonable efficiency is desired. Lack of inertia in the sails may result in very irregular running of the whole machinery, which is not conducive to high efficiency of either the sails or the pump.

The second plate is based on comparatively recent measurements, carried out at one of the last-surviving tjask-mills, standing in Frisia in the municipality of Blessum. A tjask-mill is simpler in construction than the mill shown in figure 1, but it requires a rather large amount of space and a somewhat complicated system of water-courses is necessary. The Blessum mill occupies a piece of land of about 18 metres square. In the centre is a circular pond, which is connected with the low level ditch by a wooden tube nearly 8 metres long, and the pond is surrounded by a narrow circular ditch at the high-water level. The water is lifted from the pond into this ditch by an Archimedean screw. In the Blessum mill, the screw has a length of 2.69 m over the threads, with 0.50 m diameter. Planks are nailed to the three threads of the screw, so that it looks like a long revolving coop, and three hoops of iron add to the strength and rigidity of the construction.

The shaft of the screw is rather long : 6.90 m. The top-end of the shaft is raised 3 metres above ground level and is provided with a set of four conventional Dutch windmill sails, the span being 5.70 m. The shaft with the screw and the sails is supported by a wooden frame, inclined at about 30°, which, in its turn, is supported at the top-end by a jack, made of wood and resting upon a circular track, and at the bottom-end by a wooden pile, standing in the centre of the pond and rammed into the soil. By moving the jack over the circular track, the mill can be set into the right wind-direction. Adaptation to the wind-force must be achieved by furling or unfurling sail-cloths at the windmill-sails. When the mill is in operation with irregular winds, it demands much time and labour, which is the main disadvantage of this — otherwise very attractive — design. Indeed, it is difficult to imagine a pumping windmill which is less complicated.

Several details of the shaft with its accessories need further attention. The bottom-end of it is provided

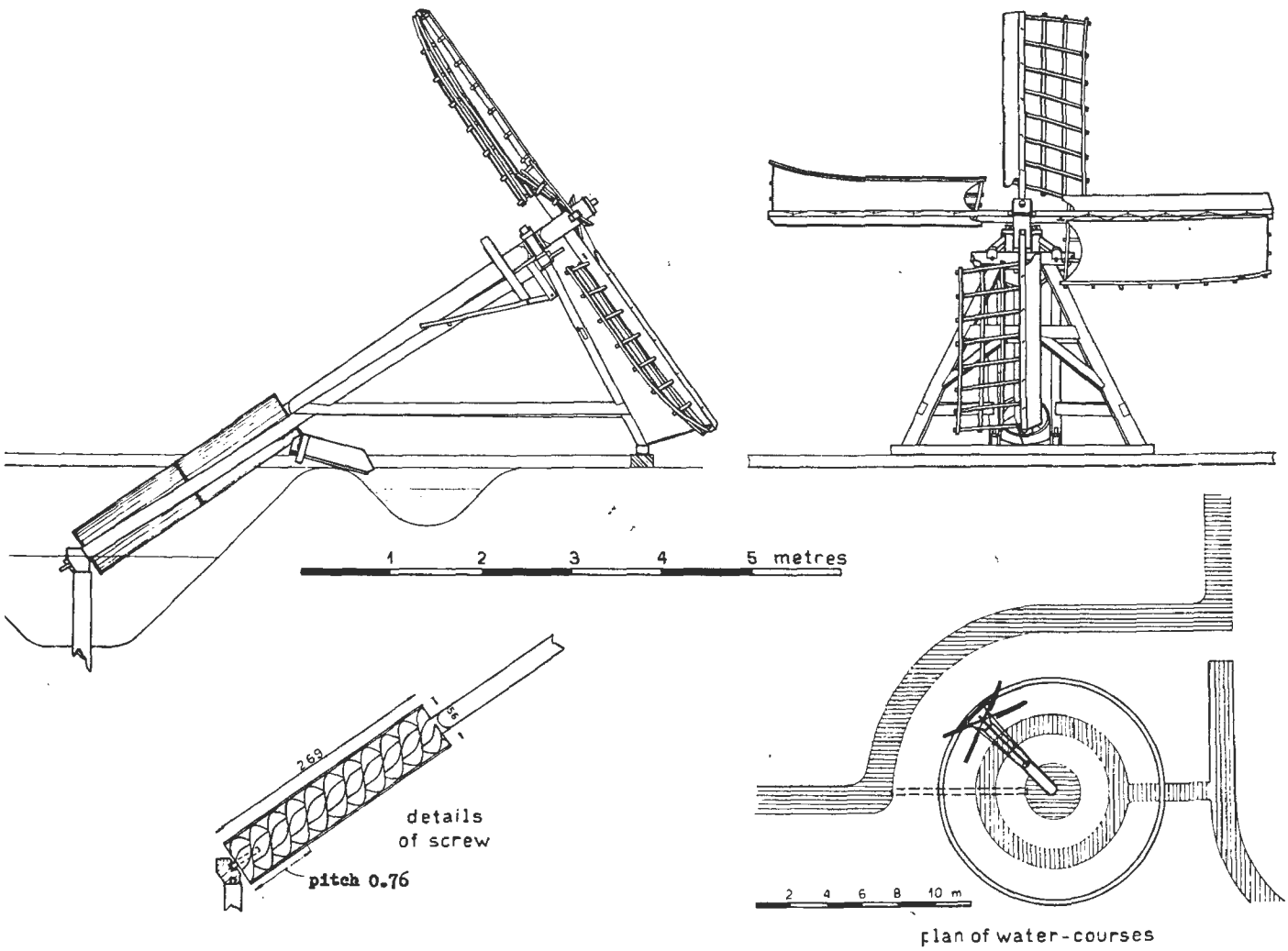

Figure 2. Design of small pumping windmill (tjask-mill) with Archimedean water-screw

with a gudgeon-pin, which turns in a steel cup. As more than half the weight of the shaft with the sails, the screw, etc., must be supported by the cup, high-quality materials are required. At a few decimetres behind the sails, the shaft is provided with a disk, to which the brake can be applied. In really bad weather conditions, the brake is not powerful enough; when the mill has to be stopped, it is necessary to wait for a quiet moment and, as soon as the sails are brought to a standstill, one of them must be fixed by means of a chain, as indicated in the figure.

Another weak point in the design is the small moment of inertia. Tjask-mills turn very irregularly. Evidently, the carpenters in Frisia never recognised the advantages of heavy sail construction.

Possibilities of development

The design of figure 1 offers many possibilities of development, which indeed have been put into effect in Holland. The pump may be modernized and refined in the design of both the blades and the housing, and the mill can be made self-adjusting to wind-direction and force. Moreover, the sails can be improved by adding sheets to reduce air-resistance (3). Every improvement adds to the difficulty of building and repairing the mill, especially when only simple tools are available, and the end of all improvements is a factory-made modern structure.

Possibilities for improving tjask-mills are more limited. At first glance, the sails seem subject to refinement in the design. Moreover, they can be improved by adding weights at their tips in order to raise the moment of inertia. But even this would make it necessary to provide the mill with a more powerful brake.

Performance of small Dutch pumping windmills

About ten years ago, two small Dutch drainage mills with centrifugal pump were tested in Holland under actual working conditions (4). They were not of purely classical design. One of them still had a wooden centrifugal pump, and the efficiency of this water-raising engine proved to be hardly 30 per cent. It was estimated that about 60 per cent of the power transmitted by the vertical shaft was lost in producing turbulence in the water. The other windmill was provided with a modern pump of advanced design, with a blade-wheel of brass and a housing of concrete. In spite of the fact that it was carefully made, its efficiency was no higher than that of the wooden pump. The present writer is of the opinion that it is very difficult, if not impossible, to design a small centrifugal pump with an appreciable high efficiency *when it is running irregularly*, especially when the pumping height is limited.

Generally, the head against which the water must be lifted by the small Dutch drainage-mills is no more than 0.8 m. When a sufficiently strong wind is blowing, the output may amount to an average of a hundred cubic metres per hour. This suffices for the drainage of 15 to 20 hectares of land.

Adaptation of small pumping windmills

It must be stated that the small Dutch drainage windmills are well adapted to the climatic and other conditions of the coastal districts of the Low Countries, but there is no doubt that the process of adaptation has required a very long span of time. When a trial of adapting such a small windmill to another country is considered, calculations for accelerating the adaptation may seem desirable. Unfortunately, calculations relating to pumping windmills are complicated, because many factors which have to be taken into consideration (wind-direction, wind-force, speed of rotation, water levels, etc.) are variable. It is possible to calculate the horsepower of Dutch windmill-sails with various wind-forces, but these sails do not seem the most suitable for other countries, where strong winds and gales are less frequent. Triangular cloth-sails, as they are used on the classical windmills of Mediterranean countries, are attractive. Perhaps, a basis for calculating their performance exists, but it is unknown to the author of this paper.

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4. Results of these windmill tests have been published in the yearly reports of the Dutch Government Service for land and water-use at Utrecht, 1947 and 1949.

Summary

The paper contains a description — with accurate plans — of two small drainage windmills according to classical Dutch designs. One of them has a wooden centrifugal pump as a water-raising engine; the other is provided with an Archimedean water-screw.

Windmills of this kind were made in former centuries by local carpenters and were maintained by the farmers. Since the Netherlands have been highly industrialized, practically all wooden small windmills have disappeared. Gradually they have been replaced by factory-made metal structures, which do not require much attendance, but which, however, are more complicated to make and to maintain.

In other countries, which are not yet industrialized, there is perhaps still a future for small pumping windmills, to be made by the local tradesmen with simple tools. When a trial of designing windmills for these countries is considered, inspiration may be found in the classical Dutch designs, because they are based on the experience of many centuries and have fully proved their usefulness.

LES TYPES CLASSIQUES DES PETITS MOULINS À VENT DESTINÉS À SERVIR AU DRAINAGE AUX PAYS-BAS; CONSIDÉRATIONS SUR LA POSSIBILITÉ DE LES PERFECTIONNER ET DE LES ADAPTER AUX PAYS PEU DÉVELOPPÉS

Résumé

On donne, dans le mémoire, une description de deux petits moulins à vent servant au drainage, complétée par des plans exacts à l'échelle, conçus conformément aux formules néerlandaises classiques. L'engin servant à élever l'eau utilisé en liaison avec l'un d'eux est une pompe centrifuge et il est fait usage d'une vis d'Archimède pour l'autre.

Au cours des siècles passés, ces moulins étaient construits par les charpentiers de village et leur entretien était assuré par les agriculteurs. Depuis que les Pays-Bas sont très industrialisés, la presque totalité des petits moulins à vent en bois a disparu. Ils ont été remplacés peu à peu par des constructions métalliques faites en usine, qui n'exigent pas beaucoup de soins mais dont la réalisation et l'entretien sont plus compliqués.

Dans d'autres pays qui ne sont pas encore industrialisés, il y a peut-être encore un certain avenir pour les petits moulins à vent servant au pompage, à construire par des artisans de village dotés d'outils simples. Si on songe à la mise au point de moulins à vent pour ces pays, il serait peut-être indiqué de chercher une inspiration dans les formules néerlandaises classiques, car elles reposent sur l'expérience accumulée au cours de nombre de siècles et elles ont certainement fait leurs preuves.

THE AERODYNAMIC LAYOUT OF WING BLADES OF WIND-TURBINES WITH HIGH TIP-SPEED RATIO

Ulrich Hütter *

Operating behaviour of high-speed blades

The blades of modern wind power stations are freewheeling axial-flow turbines with high tip-speed ratio and large flow loading.

If one imagines a wheel turning in the wind and surrounded by a wide control area, the principle of conservation of energy puts the useful work, which has been transferred from the wind wheel to the rotating blade shaft in the form of mechanical energy, into relation with the reduction of wind speed within the blade region.

By comparing the mechanical energy gained at the wheel shaft with the loss of kinetic energy of the air flow, it is not too difficult to define some kind of efficiency as a measure for the quality of conversion.

This efficiency, however, is of no interest to the power industrialist. Since the carrier of energy is at free disposal for wind power stations, only the expenditure for the establishment of the windpower stations besides the velocity frequency at the site has an essential influence upon the economic expenditure for the representation of the energy unit. This expenditure not only depends on the quality of conversion of the wind wheel, but also quite essentially on the principal construction of the station. A given principal construction of the station is about proportional to the square to cube of the wheel diameter.

Therefore, the losses which arise during the passage through the control space do not interest at first rate, but the degree of energetic exploitation of the air flow does, the amount of which is given by the size of the wheel area $F\,\phi$ (m²) swept by the blades, and by the free air wind speed v_o (m sec^{-1}).

In order to take into consideration these hastily mentioned relations, Betz (1) has established the conception of the power coefficient c_L in place of the usual efficiency conception.

This coefficient expresses the proportion of the effective power at the wheel shaft.

$$L\ (\text{mkp sec}^{-1}) = 102\ (\text{mkp sec}^{-1} \cdot \text{KW}^{-1}) \cdot N\ (\text{KW})$$

to the ideal energy input through the wheel area $F\,\phi$ swept by the blades in free air

$$c_L = \frac{204\,N}{V_o^3\,\rho\,F\phi} \tag{1}$$

(ρ [kg sec² m^{-4}] density of the air)

The rotational speed of the wind wheel and thus its circumferential speed u_o (m sec^{-1}) $= R \cdot \omega$ (R — blade tip radius of the wind wheel) at given free air wind speed v_o has a great influence on the technical expenditure of the apparatus for the conversion of energy (e.g. electricity), which is linked to the wind wheel shaft. The quotient from u_o and v_o is known as tip-speed ratio λ_o. The reciprocal value of the coefficient of propeller advance has been denoted as λ in the aeronautical literature.

$$\lambda_o = \frac{u_o}{v_o} = \frac{\pi}{30}\,\frac{Rn}{v_o} \tag{2}$$

(n [rpm] shaft revolutions per minute)

From (1) and (2) the equations immediately result for the shaft power in kilowatts

$$N\,[\text{KW}] = A_N\,C_L\,V_o^3 \qquad A_N = \rho\,F\,\phi\,/204 \tag{3}$$

and the revolutions per minute of the wind wheel

$$n\,[\text{rpm}] = B_N\,\lambda_o\,V_o \qquad B_N = \frac{30}{R\,\pi} \tag{4}$$

For a certain setting of the wing blades of the wind wheel, and thus for a certain gradient of the $c_a = 0$ line at a given radius defined by the angle β_r between $c_a = 0$ line and the plane of the turning wheel, the relation between the power coefficient c_L and the tip-speed ratio λ_o is unmistakable. For a given angle β_r a system of curves with parameter v_o may be obtained as relation between the shaft power N of the wheel and shaft revolutions n (figure 1).

These curves originate from the c_L, λ_o relation by linear distortion in abscissa (rotations) and by cubic distortion in ordinate (power) direction (revolutions n and power N are given by equations (3) and (4)).

For a certain point of the c_L, λ_o curve, perhaps for the vertex, a cubic parabola may be obtained at steady variation of the wind speed as relation between power and revolutions.

This coherence, however, is unimportant for the consideration of relations at the drive of electrical

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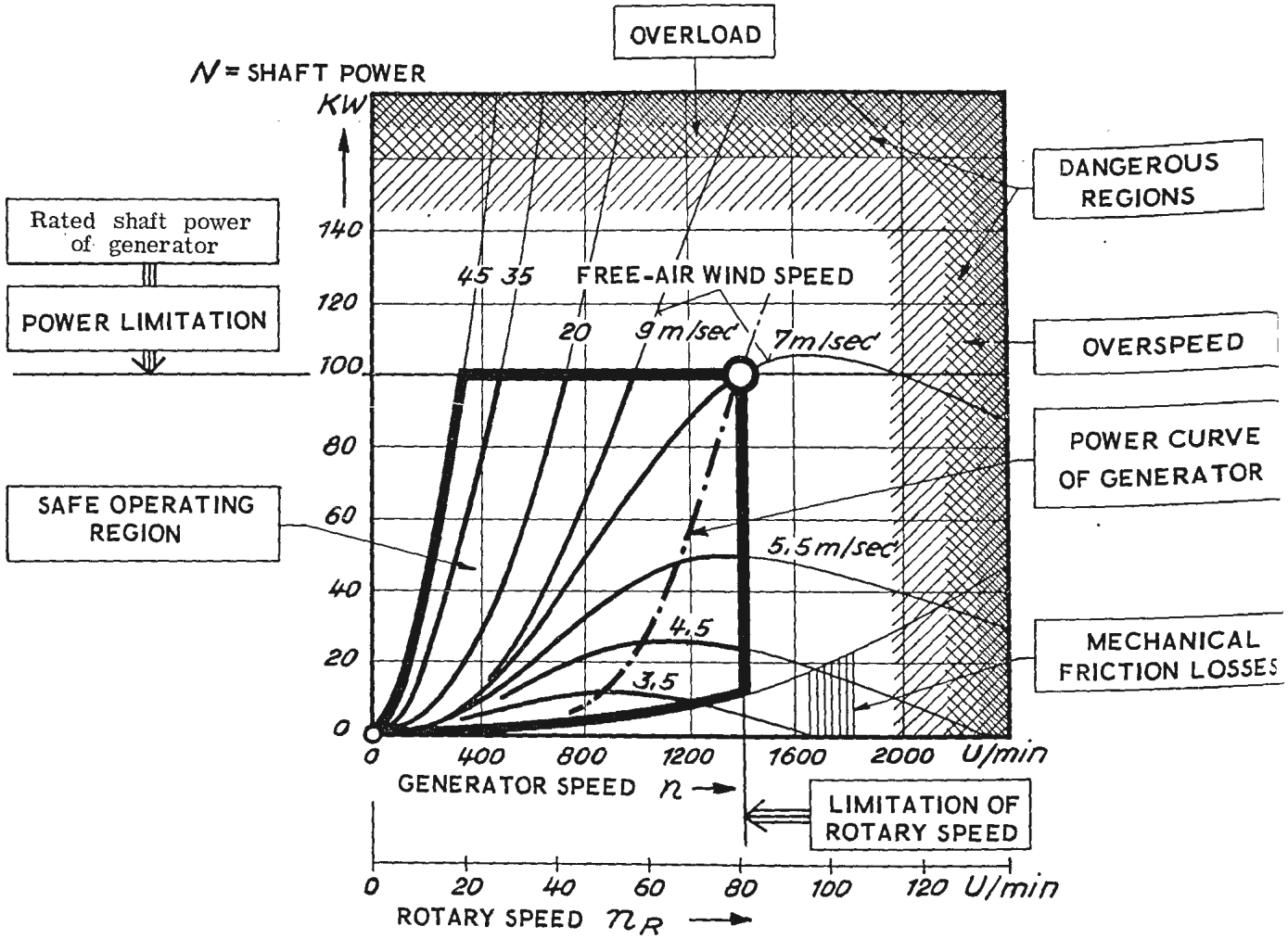


Figure 1

machines or pumps by wind power stations, and especially for delivering wind energy into a strong three-phase net. In such an operation, the revolutions of the wheel shaft, led by the net, remain constant (synchronous operation) or approximately constant (asynchronous operation), and the power-wind-speed-relation is defined by the location of the $n \approx$ constant-straight line in the N,n diagram (2).

It is in the nature of high-speed wheels that at small tip-speed ratios a power loss shows up because of separation of air flow at the blade, which represents itself as a distinct unsymmetry in the c_L, λ_o curve (figure 2).

Because of this mostly rapid power loss at tip-speed ratios $\lambda_o < \lambda_{o\ \text{from}\ c_{L\,\text{opt.}}}$, the relations between shaft power and wind speed at fixed revolutions already have a maximum at modest wind speeds, which cannot be surpassed by any increase of wind speed. The resulting curves, whose parameter is the number of revolutions n, each touch the cubic parabola, which represents the ideal case of the wind speed-power relation, in only one (design) point (figure 3). From the diagrams in figure 1 and figure 3 it may also be recognized that even by neglect of the

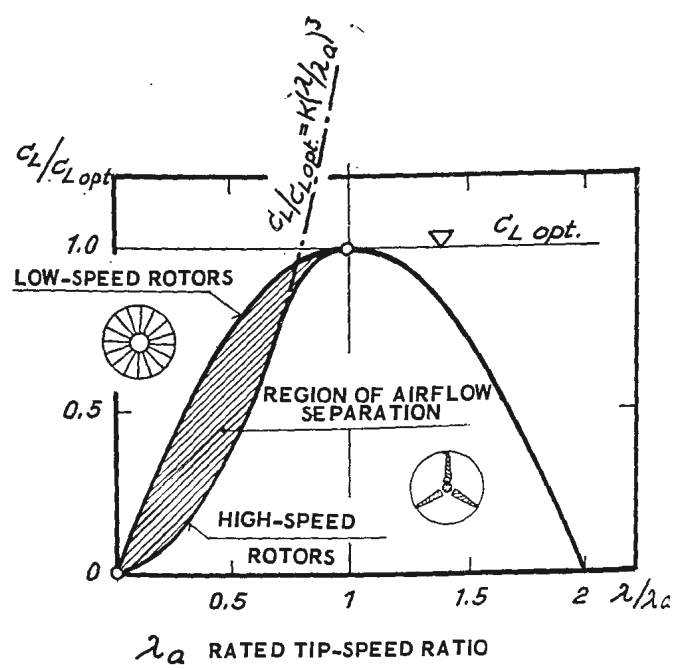


Figure 2

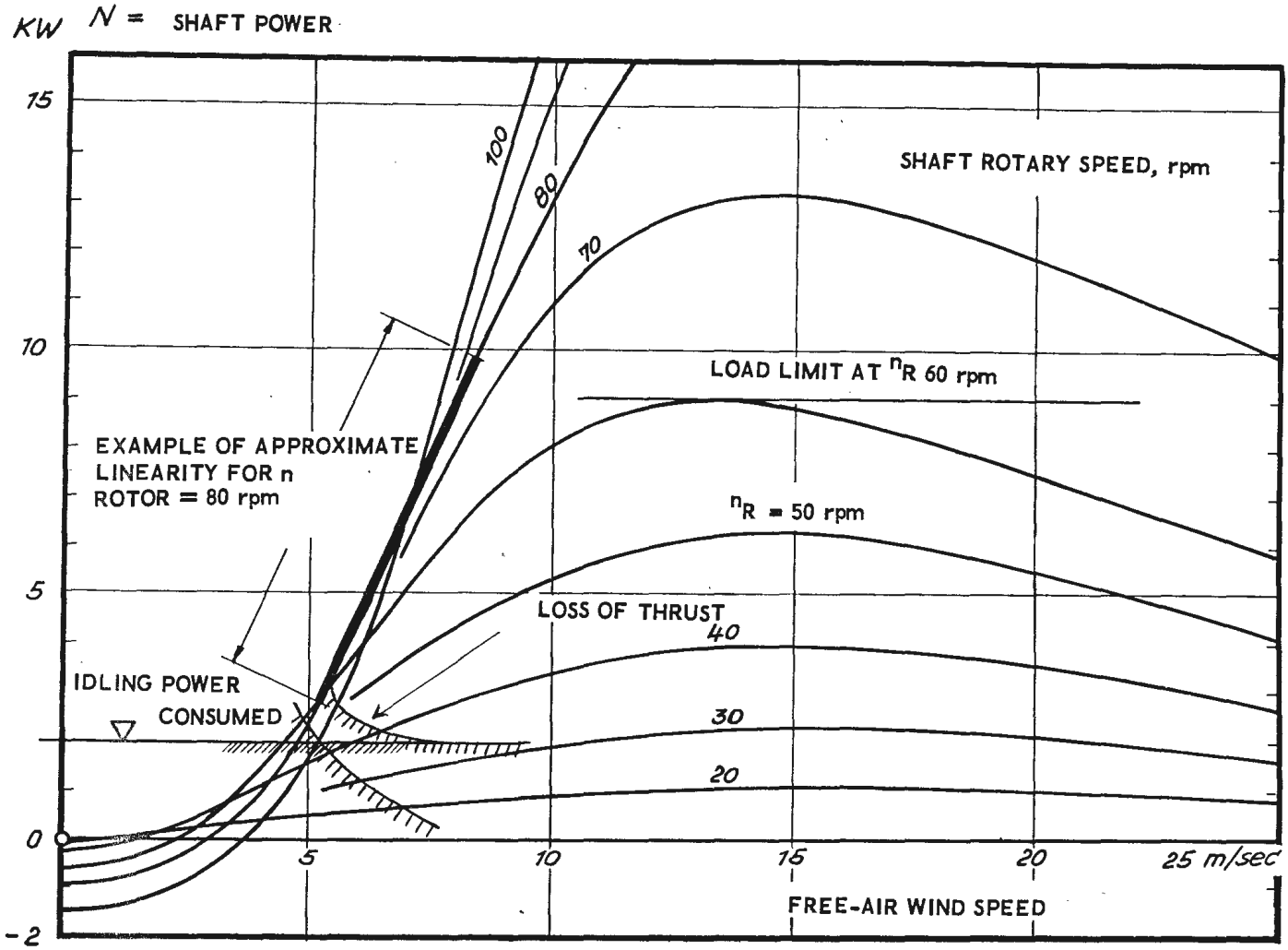


Figure 3

actually occurring conversion losses, the wind speed-power curves must start out at $v_o = 0$ with a negative value of power.

These curves for constant revolutions have a turning tangent in their touching points with the cubic parabola, which stands for the ideal state. Therefore the power-wind speed-relation in this region represents itself approximately as a straight line. This was confirmed by observations of three-phase stations, which fed into a net (see figure A2 - 115 in (3)). The fact that in the layout of a wind power station the choice of the fixed revolutions under consideration of the velocity frequency distribution at the site shows a distinct influence on the possible energy gain, has been pointed out by the author (2) as well as by J. Juul (4) some years ago.

It is possible to define the over-all efficiency η_a as proportion of the power coefficient c_L for a certain number of revolutions and wind speed to the optimally possible $c_{L\ \mathrm{opt}}$ (figure 2).

$$\eta_a = \frac{c_L\,(v_o)}{c_{L\,\mathrm{opt}}} \tag{5}$$

One then obtains curves for different revolutions, which represent the over-all efficiency against the converted power, and make plain the great significance of the right choice of revolutions (figure 4).

The fact may surprise that plottings of theoretical investigations as well as practical experience show the unexpected smallness of the energy gain — losses of a wind power station operated with a fixed number of revolutions against another one, whose wind wheel is run with optimal revolutions by an infinitely variable speed transmission (only 4 to 6 per cent) (2).

The curves in figure 3 further show why wind power stations with highly rated tip-speed ratio may be run without governing interference in all operating ranges under load when sufficient strength reserves in the gear unit and power reserves in the generator are provided (J. Juul). Therefore, a not inconsiderable gain of useful energy may even be achieved, because each wing blade is run for itself on power limitation at a free air speed which is unevenly distributed across the circular area. The supposition for a satisfying and safe functioning of this, conditional on the shape of the blade-governing procedure, is only that the rising part of the c_L, λ_o curve approximately reaches the form of a cubic parabola (figure 2). This is usually the case, however,

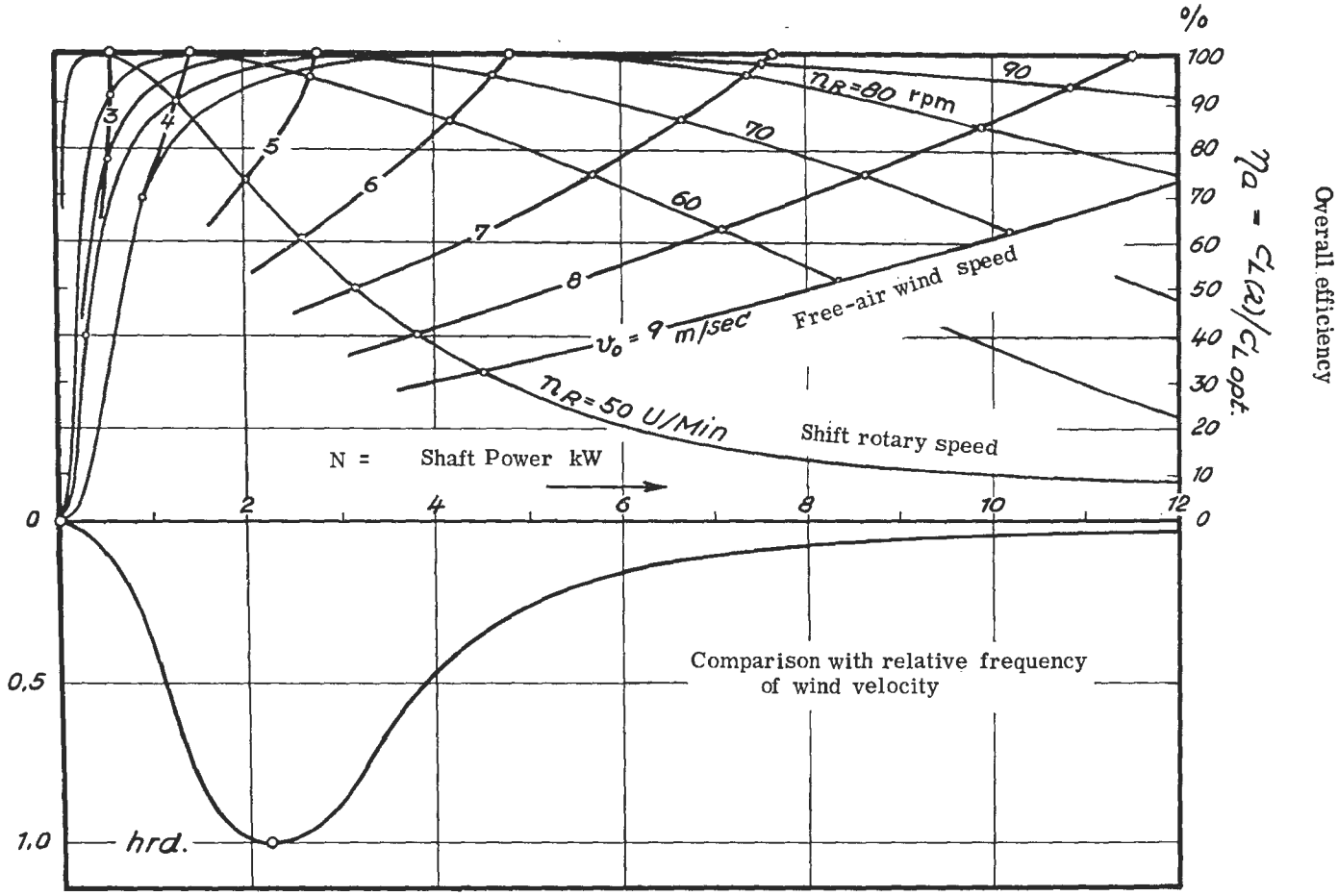


Figure 4

as nearly all wind tunnel tests show at models of high-speed wheels.

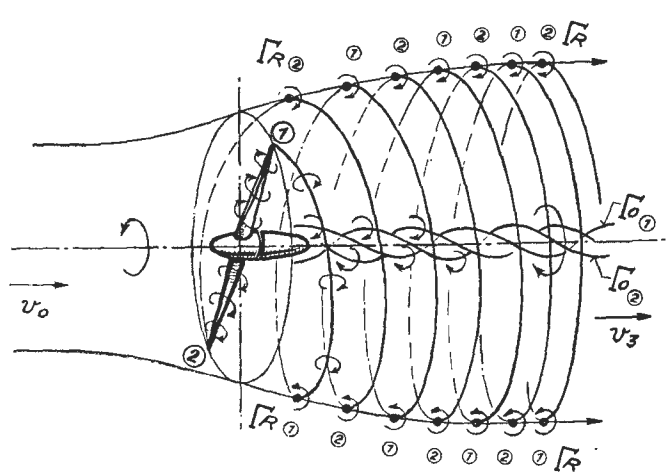
Radial circulatory distribution

The flow within the range of the free-wheeling windwheel is influenced by interference speeds, which are being induced by a system of bound and free vortices in the plane of the wheel and in the wheel's wake (figures 5/6.) The interference speeds influence the intensity distribution of the circulation Γ_r against the blade radius.

A comparison of the resulting optimum distribution of the intensity of the bound vortices Γ_r along the blade radius for the propeller on one hand and the wind turbine on the other hand indeed shows that with low load and equal propeller modulus the optimum vortex circulation distributions are quite similar to each other. Solutions of technical interest, however, produce a number of distinct differences, which do not allow off-hand an immediate comparison.

The propeller usually works with modest flow loading and propeller moduli, which correspond to tip-speed ratios around one. The slipstream therefore is only a little contracted, and the gradient of the planes of free vortices in the wake is large.

On the other hand, wind turbine wheels work with large flow loading as well as with high tip-speed ratios, and consequently have very small gradient of the discontinuity surface in the wake. The tip-speed ratios of modern wind wheels reach



Figures 5/6

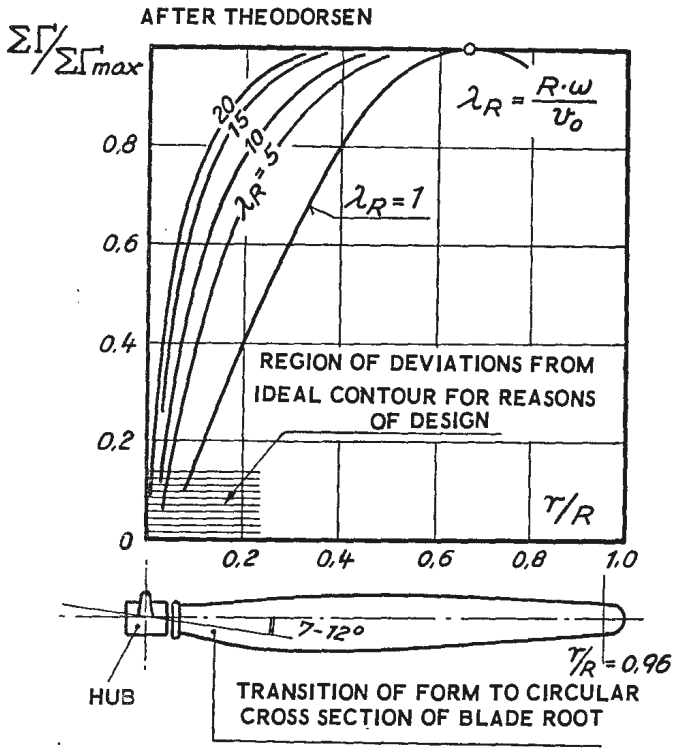


Figure 7

magnitudes from 8 to 16, resulting in a multiple of tip-speed ratios of propellers.

The consequences resulting from this for the optimum circulatory distribution become especially obvious if (at first for an infinite number of blades) the proportion of the optimal local circulation Γ_r to the circulation at the blade tip Γ_r is plotted against the square of the radius value r, which has been made dimensionless by the blade tip radius R (figures 7 and 8). With regard to the optimum layout, the necessary circulation drop of wind turbine wheels in the direction of the wheel hub is situated within a zone (as may easily be comprehended), in which considerable deviations of optimum shapes are hard to avoid because of manufacturing and static, i.e., constructive reasons.

The expansion of air flow in the wind wheel's wake is large (figure 9) in comparison with usual values of contractions of propellers. In the most favorable operating range the stream enlarges to about $\sqrt{2}$ times the wheel diameter D.

A careful arithmetic check of the interference speeds being induced by the free, helical, and conically enlarging vortices in the blade plane, and of the local circulation values Γ_r caused by these inter-

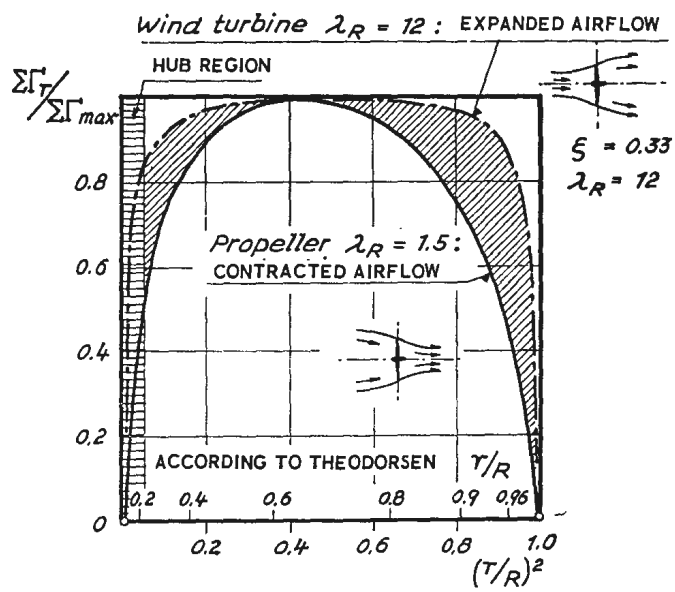


Figure 8

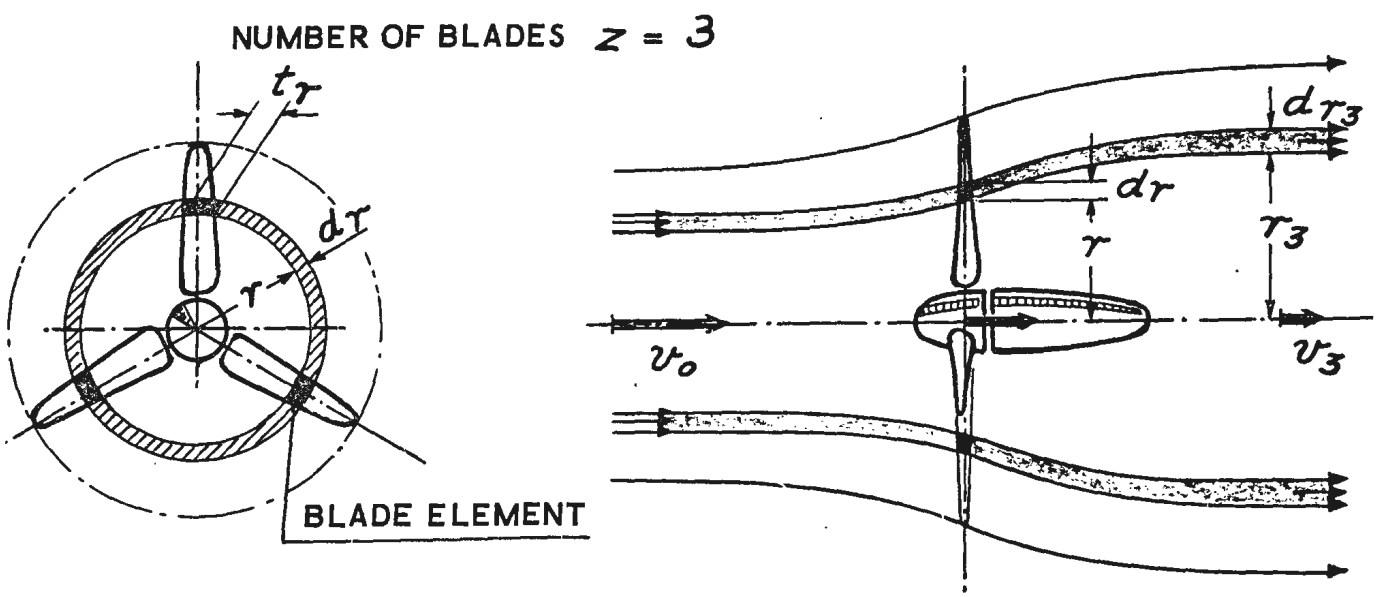


Figure 9

ference speeds, has revealed that the circulation drop, even with a finite number of blades in the direction of the blade tips, becomes extraordinarily rough. It does not start out — till near the blade tips where the application of the simple theory of the "bearing line of the radius jet" is no longer permissible.

The checking of an example corresponding to technical designs (wing blades of the WEG 100 kW — windpower station) has yielded that within the range from 30 per cent to 96 per cent of the blade tip radius the resulting circulation Γ_r deviates only inconsiderably from that which would occur with an infinite number of blades. In the case of the computed example the deviation reached an amount worth mentioning only at more than 98 per cent of the blade tip radius with about 6 per cent drop against the conditions with an infinite number of blades.

The accuracy of this at first unexpected result was verified to the author by Strscheletzky (5). On the occasion of a VDI meeting at Stuttgart in 1944, Spannhake had already pointed to the fact that with strongly expanding flow in the wake of free-wheeling turbine wheels circulation drop must be taken into account. It is considerably stronger than with contracted flow.

From this an extremely valuable simplification results for the layout of wind turbine wheels. It is permissible to design blade contour, angle of decalage distribution, running characteristics, etc., according to the blade element theory. The possible errors, which have to be taken into account with regard to working behaviour and especially to power prediction, remain within the limits of the exactness of given design values (manufacturing accuracy, profile polars, etc.).

Characteristic power values of the blade element

For the following statements it is assumed in a simplified manner that the radial components of speeds in the wheel region may be neglected. This is permissible for the computation of the axial and twist losses because for this only the regions far off and beyond the wind wheel must be considered, where the radial speed components disappear at stationary flow in the direction of the wind wheel shaft.

Furthermore we neglect the fact that the speed changes in the wake within the annular space between r_3 and $r_3 + dr_3$ (figure 9), influenced by the considered blade elements, are not constant over the circumference of the annular space. This neglect is permissible because of the high tip-speed ratios of wind turbine wheels, and with regard to the relations presented in the preceding chapter.

If we define the decreasing factors as

$$\zeta = \frac{V_3}{V_o} \tag{6}$$

then we receive the known relation for the axial power coefficient shown up by Betz

$$c_{La\,(r)} = \frac{1}{2}\,(1 - \zeta^2_{(r)})\,(1 + \zeta_{(r)})^* \tag{7}$$

which yields a possible optimum value for

$$c_{La\,(r)} = \frac{16}{27} = 0\ 5963;\ \text{for}\ \zeta_{(r)} = \frac{1}{3}$$

The twist, as well as the friction losses at the blade element, is neglected.

If one takes into account the twist losses (in friction-less flow) as well as the fact that the air in the wake passing the annular space is pushed outwards, i.e., to larger radii, because of continuity reasons, then one obtains for the power coefficient

$$c_{L\ \text{ideal}\ (r)} = \lambda^2_{a\,(r)}\,(\delta_{3\,(r)} - 1)\,(1 + \zeta_{(r)})^2/2\,\zeta_{(r)} \tag{8}$$

$$\delta_{3\,(r)} = \sqrt{1 + 2\,\zeta_{(r)}\,(1 - \zeta_{(r)})/\lambda^2_{o\,(r)}} \tag{9}$$

For the blade element computation a difficulty arises, because the magnitude of the outward displacement depends on the extent of the reduction of all radii, which are smaller than the radius of the blade element considered. There is a further difficulty, because the optimum value of the reduction coefficient depends on the tip-speed ratio and radius (figure 10), and for small values of $\lambda_{o\,(r)}$ it is larger than the value resulting from (7).

But this fact is not as disturbing as it may seem at first sight since the power coefficient optimum is flat and the twist influence which causes the displacement of the optimum value of the decreasing factor does not take effect until small tip-speed ratios, i.e., in the vicinity of the hub. There the displacement flow around the hub body and the deviations from the theoretical ideal shape of the blade, conditional on design, cover all other influences anyhow. Therefore the decreasing factor $\zeta_{(r)}$ may be assumed without hesitation to be constant for the region within the blade element, and equal to

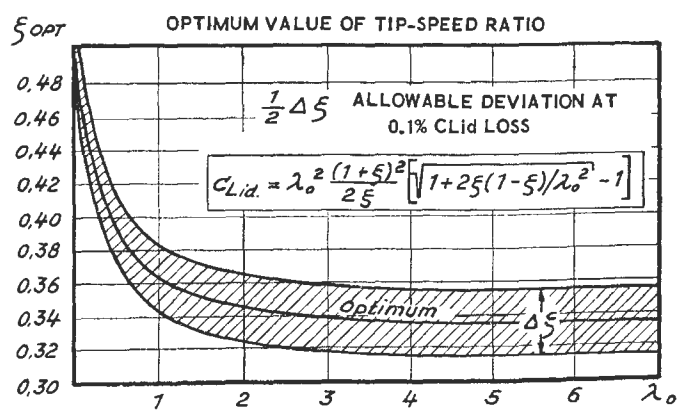


Figure 10

* All coefficients related to the blade element are marked by the index r, which is put in parentheses.

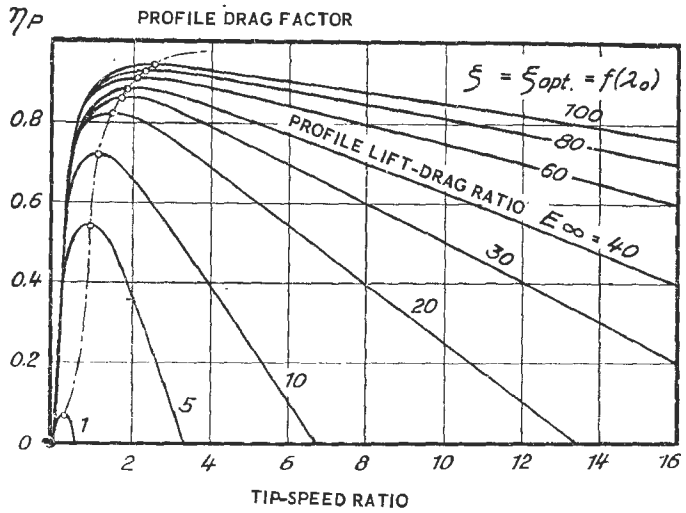


Figure 11

that which has been presupposed for the considered annular space.

The influence of the profile resistance is taken into consideration by (10) and (11) (figure 11),

$$\eta_{P(r)} = \frac{2\,\lambda_{o\,(r)}}{1+\zeta_{(r)}} \cdot \frac{\left(\frac{c_a}{c_{wp}}\right)_{(r)} - \lambda_{\mathrm{eff}\,(r)}}{1+\left(\frac{c_a}{c_{wp}}\right)_{(r)} \lambda_{\mathrm{eff}\,(r)}} \tag{10}$$

a relation which counts for propellers in a similar form (6). In (10) the conception of the effective tip-speed ratio λ_{eff} at the blade element is used

$$\lambda_{\mathrm{eff}\,(r)} = \lambda_{o\,(r)}\,(1+\delta_{3\,(r)})/(1+\zeta_{(r)}) \tag{11}$$

This is the cotangent of the angle φ_{eff}, which is enclosed by the vector of the relative speed between blade element and air, and the plane of rotation (figure 13).

The local power coefficient $c_{L\,(r)}$, which is affixed to the considered radius r, is obtained as a product from the power coefficient defined by (8) and (9) with the local profile friction coefficient $\eta_{p(r)}$ (10) and (11)

$$c_{L\,(r)} = c_{L\ \mathrm{ideal}\,(r)} \cdot \eta_{p(r)} \tag{12}$$

Because of the previously mentioned relations, a mean value formation by integration of the product $r \cdot c_{L\,(r)}$ against the radius is sufficient to receive the total power coefficient of the wheel spider under the considered working conditions (13).

$$c_{L\,\mathrm{ges}} = \frac{\eta_z}{R}\int_r^R r\, c_{L\,(r)}\, c/r \tag{13}$$

(η_z correction factor for the influence of finite number of blades).

We receive the value φ_{eff}, which is important for further computation, from (14) with $\lambda_{\mathrm{eff}\,(r)}$ from (11)

$$\varphi_{\mathrm{eff}\,(r)} = \mathrm{arc\ cot}\ \lambda_{\mathrm{eff}\,(r)} \tag{14}$$

Blade element and wake

In the equations (8) and (9) for the power coefficient of the frictionless working wheel element in (10) and (11) for the profile friction coefficient, and in (14) for the magnitude of the effective angle of attack φ_{eff} we had met the tacit presupposition that the arguments $\zeta_{(r)}$ and $c_{a\,(r)}$ determining the functions indeed may reach the supposed values. But this is neither self-evident nor the case off-hand.

The fact is obvious and easily understood that the decreasing factor $\zeta_{(r)}$, the tip-speed ratio $\lambda_{o\,(r)}$, consequently $\varphi_{\mathrm{eff}\,(r)}$ too, must be in a defined relation with the width sum of the blade elements $z^0\ t_{(r)}$ (z number of wing blades, $t_{(r)}$ width of the blade at radius r), the angle $\beta_{(r)}$ between zero-lift flow at the blade elements and the plane of rotation, and also with the possible lift coefficients $c_{a(r)}$ at the blade elements.

In order to show up this relation we recall that the speed reduction in the wake of the wheel involves a pulse change of the air masses which passed the previously described control space. The pulse change can only be explained as a consequence of a force acting in the control space. But this force can only act at the blade elements. It is the sum of the axial components of the aerodynamic forces coming about at the blade elements. The size of all these axial components ds is:

$$\Sigma\, dS^{(r)}_{(r)} = K_{G\,(r)} \frac{\lambda_{\mathrm{eff}\,(r)} + \left(\frac{c_{wp}}{c_a}\right)_{(r)}}{\sqrt{1+\lambda^2_{\mathrm{eff}\,(r)}}} \left(\frac{dca}{d\alpha}\right)_{(r)\,\lambda\to\infty} \alpha_{\mathrm{eff}\,(r)}\, w^2_{\mathrm{eff}\,(r)}\, \frac{\rho}{2}\, z t_{(r)}\, dr \tag{15}$$

with

$$\alpha_{\mathrm{eff}\,(r)} = \varphi_{\mathrm{eff}\,(r)} - \beta_{(r)} \qquad \text{(see figure 12)} \tag{16}$$

The value $K_{G\,(r)}$, the lattice constant (6), only has the meaning of a minor correction for the high-speed wheel mainly in the outer wing, which may be checked easily.

$$K_{G\,(r)} = \delta_{(r)} \frac{4\,r}{z t_{(r)}}\, \mathrm{tg}\, \frac{z t_{(r)}}{4\,r} \sim 1 \tag{17}$$

$\beta_{(r)}$	0°	5°	10°	30°	50°
$\delta_{(r)}$	1.00	0.85	0.76	0.34	0

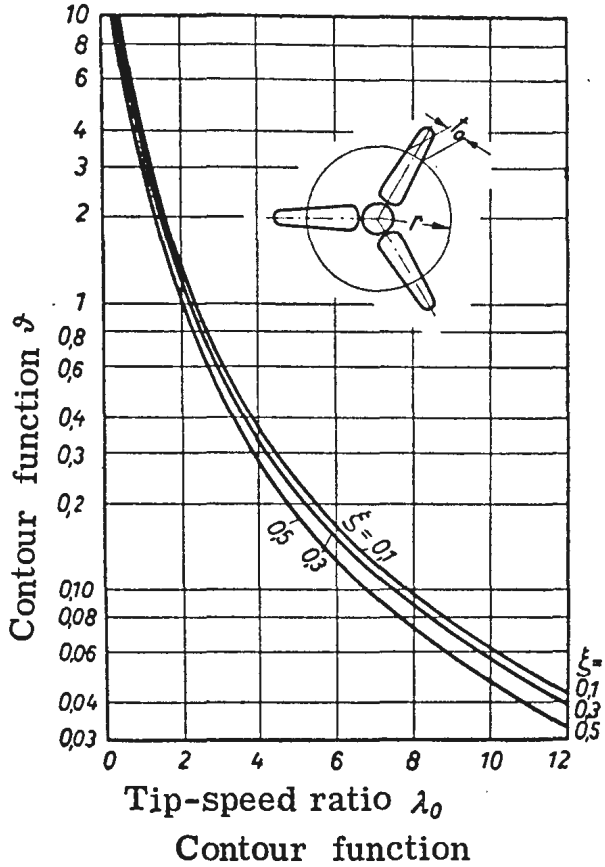


Figure 12

Since $\Sigma ds_{(r)}$ is equal to the pulse change of the air mass passing the control space

(18) $$\Sigma ds_{(r)}^{(r)} = V_o^2 \frac{\rho}{2} (1 - \zeta^2_{(r)})\ 2\ \pi r\ dr$$

and φ_{eff} as well as

(19) $$W_{\text{eff}\,(r)} = V_o \frac{1 + \zeta_{(r)}}{2} \sqrt{1 + \lambda^2_{\text{eff}\,(r)}}$$

may be represented as functions of $\zeta_{(r)}$ and $\lambda_{o\,(r)}$, by equating of (15) and (18) with (19) we receive

(20) $$K_{E\,(r)}\ \delta\ (\zeta\ \lambda_o)_{(r)} = K_{G\,(r)}\ \varphi_{(r)}$$

and

(21) $$\delta\ (\zeta \lambda_o)_{(r)} = \frac{4\ (1 - \zeta_{\text{eff}\,(r)})}{(1 + \xi_{(r)})\ \lambda_{\text{eff}\,(r)} \sqrt{1 + \lambda^2_{\text{eff}\,(r)}}}$$

with

(22) $$K_E = \frac{1}{1 + \dfrac{cw\ \rho}{ca\ \lambda_{\text{eff}}}} \cdot \sim 1$$

The contour function $\delta\ (\zeta, \lambda_o)$ defined by (21) is thus independent from the lift gradient $(dca/da)\lambda \to a$, the blade contour $t_r = f_t\ (r)$ and the setting of the blade $3(_r) = f_s(r)$, but its equivalent $\delta_{(r)}$ only contains such values

(23) $$\delta_{(r)} = ca_{(r)} \frac{t_{(r)}\ z}{2\ \pi r}$$

The expression $\dfrac{t_{(r)}\ z}{2\ \pi r}$ in (23) is the local geometric surface density $\delta_{(r)}$, i.e., the effective, aerodynamic surface density of the wheel element.

Blade contour and decalage

Since for a chosen (optimum) operating condition of a windwheel those lift coefficients at the blade profiles are to be achieved for which the lift-drag ratio $E\infty = ca/cwp$ reaches its maximum, the lift coefficients $c_{a\,(r)}$ at first are supposed to be given for the design of the blade width run. With that we obtain the blade width affixed to each radius from :

(24) $$t_{(r)} = \frac{2\ \pi r}{z\ ca_{(r)}} \frac{K_{E\,(r)}}{K_{o\,(r)}}\ \delta\ (\zeta\ \lambda_o)_{(r)}$$

The chosen designation of $\delta\ (\zeta,\ \lambda_o K_{(r)})$ as contour function has been explained herewith. The character of this function, which determines the blade contour, becomes especially clear, when it is plotted against $\lambda_{0\,(r)}$ with parameter $\zeta_{(r)}$ (figure 12).

Attention must be paid to the facts that $t_{(r)}$ represents the length of an arc in the distance r from the axis of rotation, and that (23) is a contour without rounding-off near the blade tip.

Such a rounding-off can be recommended for several reasons. It should, however, extend only over a relatively small radius range (for a rotor with the layout-tip-speed-ratio 10 it should extend over about 1.5 per cent of the radius, or about 30 per cent of the blade width with $r \to R$, for instance) (7).

Because of manufacturing reasons (geometrically simple contour shape, no excessive blade width in the vicinity of the hub, etc.) one is often forced to choose high design-c_a at the blade root, i.e., profiles with large maximum lift coefficients, even if we have to put up with disadvantageous profile glide ratio.

If we operate a wheel of given contour with a tip-speed ratio, which differs from the layout state, then lift coefficients turn up, which differ from $c_{a\ \text{opt}}$.

In the operation of wind turbines, those regions are often of special interest in which the lift rise at the blade elements is non-linear because of separation of air flow, and only known through wind-tunnel tests. Therefore it suggests itself to search for the solution of (20) by means of a graphic procedure for the general case. To that effect we plot the logarithm of the contour function $\delta\ (\zeta,\ \lambda_o)$ (21) against $\varphi_{\text{eff}}\ (\zeta,\ \lambda_o)$ (14). In the resulting diagram $\zeta_{(r)}$ and $\lambda_{o\,(r)}$ appear as parameters (figure 13). This diagram has universal validity for the layout of free-wheeling turbine wheels.

The relation between $K_G \cdot \delta_{(r)}$ against $\alpha_{\text{eff}\,(r)}$ is fixed for a blade element $t_{(r)}$ with given profile. If we plot log $K_G \cdot \delta_{(r)}$ against $\alpha_{\text{eff}\,(r)}$ in the same scale as log $\delta\ (\zeta,\ \lambda_o)_{(r)}$ against $\varphi_{\text{eff}}\ (\zeta,\ \lambda_o)_{(r)}$ (figure 15) and arrange to coincide the transparent sheet with the log $\delta\ (\zeta,\ \lambda_o)_{(r)}$, $\varphi_{\text{eff}}\ (\zeta,\ \lambda_o)_{(r)}$ diagram (figure 13),

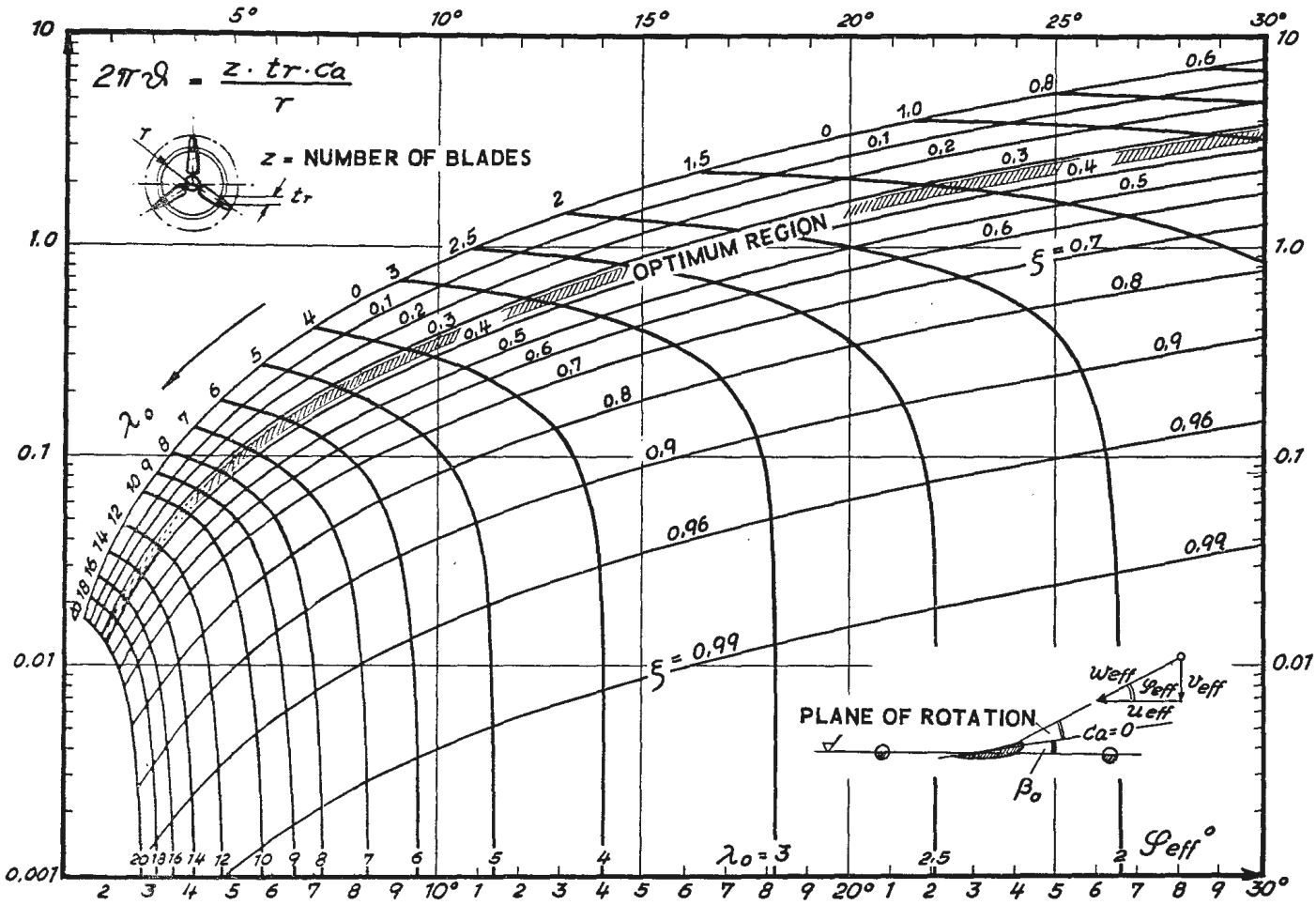


Figure 13

then all possible working points of the wheel appear as points of intersection of the $\zeta_{(r)}$ constant and $\lambda_{o\,(r)}$ constant group of curves with the log $\delta_{(r)}$, $q_{\text{eff}\,(r)}$ curve (figure 14) valid for section r.

In diagram (figure 14) it is recommended to connect with each other the points of equal lift-drag coefficients $E\infty(r)$, which are to be taken from the respective airfoil characteristics (for the expected Reynolds numbers), besides the log $\delta_{(r)}$, $q_{\text{eff}\,(r)}$ curves.

In order to locate optimum working points it is only required to shift diagram $\delta_{(r)} = f_{15}$, (q_{eff}) (figure 14) over $\delta\,(\zeta, \lambda_o) = f_{14}$ (f_{eff}) (figure 13) in the direction of the (linear) abscissa for so long until both (in 13 and 14 marked by hatching) optimum ranges coincide.

There is, however, yet another condition to be fulfilled. In the zone of coincidence, $\lambda_{o\,(r)}$ must have the value corresponding to the desired wheel revolutions n and the wind speed v_o which is possible only when $t_{(r)}$ has been laid out correctly for the supposed values (n, v_o). The size of the displacement in the direction of abscissa for each of the $t_{(r)/r}$ = constant curves corresponding to a certain radius yields the correct value of the setting angle $\beta_{(r)}$ affixed to each radius, i.e., the decalage.

Setting of the blade and wheel characteristic

Once contour and decalage have been laid down, the trace of the wheel characteristics for any values of λ_o and β can be determined. To that purpose the log $\delta_{(r)}$ curves (figure 14) for selected, according to equally strong influence on $c_{\text{L ges}}$ distributed radii are plotted respectively displaced against each other about $\Delta\beta/r_n^{n+1}$ in the direction of the abscissa. These are brought to coincide with figure 13 under consideration of the $\lambda_{o\,(r)}$ values, as previously described.

A perfect coincidence of log δ $(\zeta, \lambda_o)_{\text{opt}}$ (see (8) and (9)) with log $\delta_{(r)\,\text{ca from } E\,\text{opt}}$ for the supposed λ_o values is only given for the layout state, as the diagram shows. Every change of tip-speed ratio $\lambda_o\,(R)$ at the relative radius causes a proportional displacement of the values of the tip-speed ratios $\lambda_{o\,(r)}$ at all radii considered.

The new points of intersection of the log δ $(\zeta, \lambda_o)_{(r)}$ = constant curves (figure 13) with log $\delta_{(r)}$ determine the values of $\zeta_{(r)}$ and $c_{a\,(r)}$, which correspond to the changed tip-speed ratios.

With that, all required factors to be set into the equations (7) to (13) are fixed for the determination of the wheel power coefficient at changed tip-speed

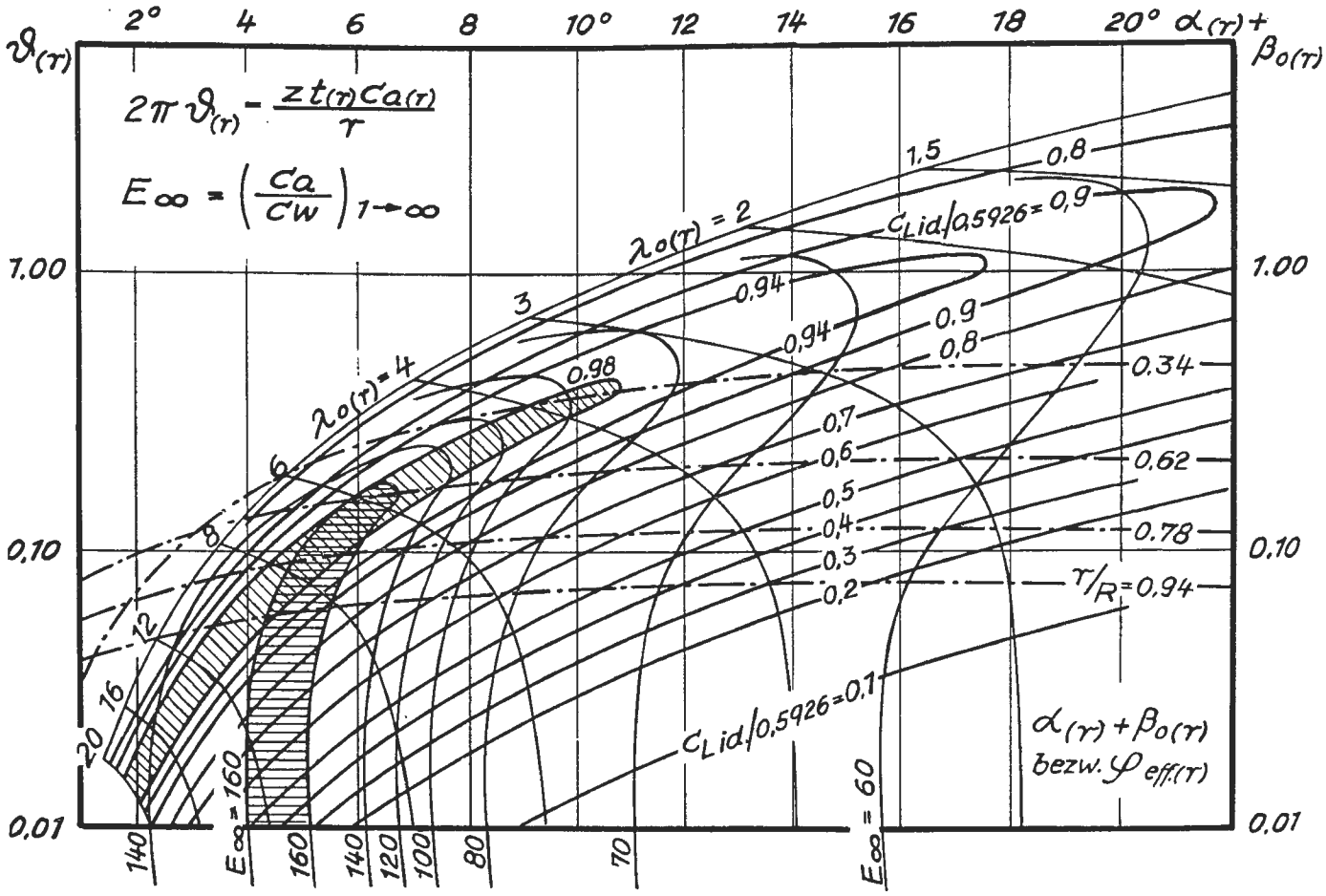


Figure 14

ratio. The repetition of this procedure for several values of $\lambda_o(R) \lessgtr \lambda_o(R)$ layout yields the sought-after wheel characteristic point for point for a certain setting angle $\beta_{(R)}$ of the blade. Of course each change of $\beta_{(R)}$ calls forth a change of the wheel characteristic, a self-evident fact (figure 15) (8), well known in the nature of axial-flow machines, the cause of which takes effect in the displacement of the transparent

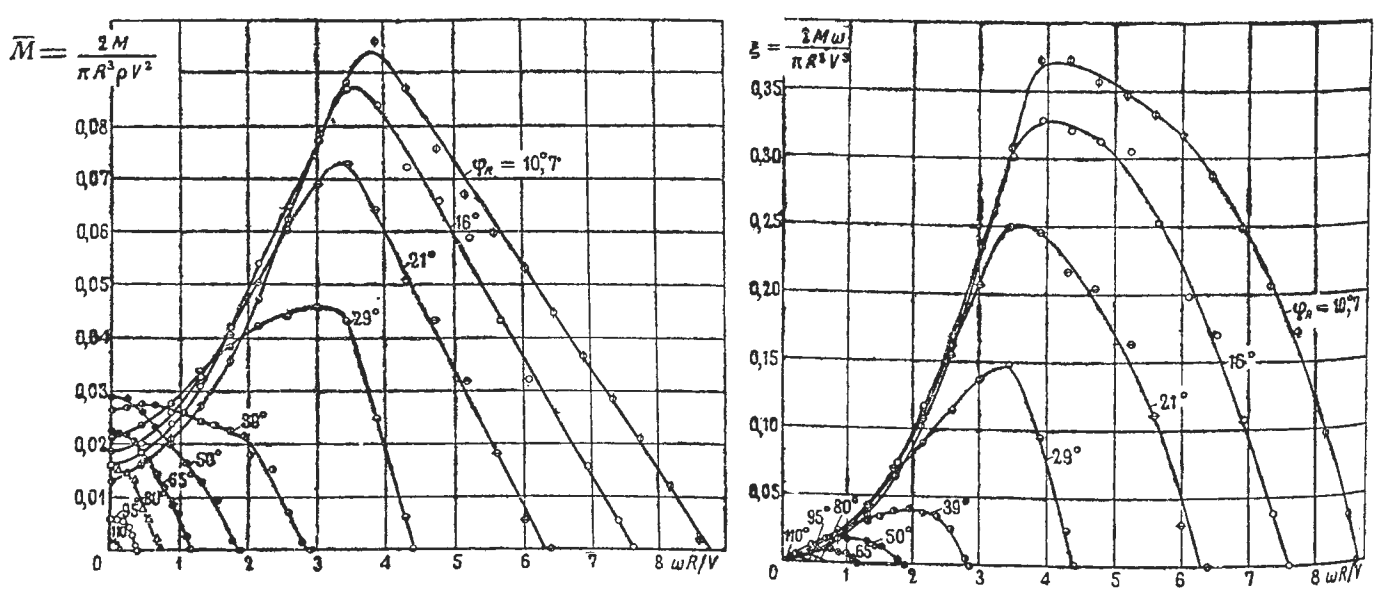


Figure 15

Left : Moment curves of two-bladed " Syur " rotor, $D = 0.36$ m with variable-pitch blades at length $lr = R/3$ and various pitch angles. *Right :* Power curves of two-bladed "Syur " rotor, $D = 0.36$ m at various pitch angles.

log $\delta_{(r)}$ curves over the diagram (figure 13) with urgent clearness.

Conclusions for the operation of wind power stations

The designing engineer takes a special interest in two phenomena of the practical operation: the behaviour of the wheel in storm gusts, and the limits of tip-speed at small values of $\beta_{(R)}$.

We gather from (2) that the tip-speed ratio λ_o at constant revolutions is inversely proportional to the wind speed v_o.

Investigations by Robitzsch (9) concerning the statistical abundance of gust maximae in dependency from its intensity have shown that 80 per cent of all gust maximae exceed the mean value of wind speed by 20 per cent to 50 per cent, whilst maximae with speeds larger than twice the mean value are quite scarce.

Therefore the static dimensioning of the wing blades applies for the case of the frequently-to-be-expected stress at $\lambda_{o\,(r)\,\mathrm{gust}} \sim \lambda_{(r)}/1{,}2\ldots 1{,}5$, and the quite-seldom-to-be-expected case of a sudden drop of the tip-speed ratio to half the amount of the original state.

The diagrams (figure 13) show that the more frequent case is also the more dangerous one because the air force coefficients at the blade always pass through its maximae whilst at the rare, heavy storm gusts the maximae of c_a and the optimae of ζ are surpassed in such a short time that the resulting shock is absorbed by the mass forces of the evading blade. The air forces turning up at the blade because of burbling then surpass just slightly the normal operating loads.

With small values of $\beta\,(R)$ and high $\lambda_o\,(R)$ the curves of log $\delta_{(r)}/q_{(r)}$ reach partly into the region of the log $\delta\ (\zeta, \lambda_o)_{(r)}, \varphi_{\mathrm{eff}\ (r)}$ — diagram, in which $\zeta < 0$. At that the blade element concerned is working as a fan. When this state extends over a large portion of the blade radius, it will there result in backflow against the direction of the wind, and thus in the formation of standing annular vortices. As a further consequence of this phenomenon, the power coefficient passes through zero and finally becomes negative.

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Summary

A procedure for the optimum layout of wing-blades of wind turbines is described. After an interpretation of the linear region between power and wind speed under net operation, i.e., at constant number of rotations of the wind wheel, and an explanation of Juul's procedure of load regulation without adjustment of the blade gradient, an explanation is given for the layout of wing blades for wind turbine wheels. At that, it seems allowable to restrict oneself on the blade element theory without having to put up with noticeable mistakes.

Functions are shown and explained, which restore the relation between power coefficient, profile friction loss and air flow direction of the blade element with the reduction of flow speed and tip-speed ratio affixed to undisturbed flow.

Hereupon the required size of the blade width at given operating conditions is determined from the pulse loss of the axial flow on one hand and the air forces, required to that at the blade element, on the other hand. The lift coefficient affixed to blade width, number of blades and element radius proves to be a function of the effective angle of attack φ_{eff}, whereby the reduction factor ζ and the tip-speed ratio, affixed to undisturbed flow, λ_o, show up as parameters.

The resulting diagram allows a simple, graphic

determination of all values defining the operating condition of the blade element. With that, the power coefficients tip-speedratio-characteristics for wing wheels with given blade shapes can be determined with passable expense for any blade setting. For the design of wind wheels we receive blade width and angle of decalage trace against the radius. The effect of storm gusts upon the turning wheel and the setting in of backflow over certain regions of the blade radius at flat blade setting and high tip-speed ratio can be easily followed up and determined besides many other phenomena.

DISPOSITION AÉRODYNAMIQUE DES PALES DES TURBINES ÉOLIENNES PRÉSENTANT UN GROS PARAMÈTRE DE FONCTIONNEMENT

Résumé

On décrit une technique visant à donner une forme idéale aux pales de turbine aérienne. Après une interprétation de la partie linéaire de la courbe qui représente le rapport entre la puissance et la vitesse du vent dans des conditions normales de fonctionnement, c'est-à-dire pour une vitesse de rotation constante de la roue, et une revue de la technique de Juul pour le réglage de la charge sans modification de pas, on donne une explication sur la disposition des pales destinées aux rotors de turbines éoliennes. Il semble indiqué, en ce faisant, de s'en tenir à la théorie des éléments sans que ceci entraîne d'erreurs trop appréciables.

On établit et on explique les fonctions qui rétablissent le rapport entre le coefficient d'utilisation, les pertes dues aux frottements le long du profil et la direction de l'écoulement de l'air sur l'élément avec une réduction de la vitesse d'écoulement et du paramètre de fonctionnement dans le cas d'un régime sans turbulence.

On fixe alors la largeur de la pale pour des conditions d'utilisation déterminées d'après les pertes dues aux pulsations de l'écoulement axial d'une part et les forces éoliennes nécessaires par rapport à la situation à la pale d'autre part. Le coefficient de portance que l'on donne à la largeur de la pale, au nombre de pales et au rayon de l'élément est une fonction de l'angle utile d'attaque φ_{eff}, de par lequel le facteur de réduction ζ et le paramètre de fonctionnement pour le cas d'un écoulement sans perturbations λ_o, deviennent les paramètres de calcul.

Le diagramme qui en résulte permet la détermination graphique simple de toutes les valeurs qui définissent les conditions de fonctionnement de l'élément de pale. Avec ces données, on peut déterminer les caractéristiques ayant trait aux coefficients de puissance relatifs aux divers paramètres de fonctionnement quand on connaît la forme des pales d'une manière raisonnablement exacte pour tous les pas. Pour la fabrication des roues aériennes, on part de la largeur de la pale et de la trace de l'angle de décalage par rapport au rayon. L'effet des rafales sur la roue éolienne, et celui de l'apparition de contrecourants sur certaines régions du rayon de la pale lorsqu'elle est en drapeau, avec un paramètre de fonctionnement élevé, peuvent être suivis et déterminés facilement, ainsi que nombre d'autres phénomènes.

DESIGN OF WIND POWER PLANTS IN DENMARK

J. Juul *

Sydøstsjællands Elektricitets Aktieselskab (SEAS) in 1947 inaugurated a series of investigations on the feasibility of utilizing wind power for the production of electricity to be fed into existing AC grids. These investigations were made in recognition of the fact that extensive networks, built for the distribution of electric energy from one or several main power stations, may also be used for the collection of energy from many smaller wind power plants. Since its foundation in 1914, SEAS had noticed also that fuel shortage may occur. Fuel is found in scant quantities in Denmark, and during the two world wars and other political difficulties it was very expensive and difficult to obtain.

In order to determine the amount of wind energy and the seasons of its occurrence, automatically recording anemometers were mounted in various places in Denmark. Figure 1 shows a map of Western Europe on which are marked — in the case of Denmark — the measurements taken by SEAS and the (Danish) Meteorological Institute. In Germany, the measurements are by Meteorologisches Amt für Nordwest-Deutschland, in Great Britain by the Electrical Research Association and in France by Électricité de France.

The figures quoted represent annual mean wind velocity in m/s and, as far as Denmark and France are concerned, also the annual wind energy expressed in kWh per m² in the vertical plane.

In a corner at the foot of the map is shown a large scale section of North Jutland on which is drawn to scale the expanse of swept area necessary for the production of the 4 000 million kWh corresponding to the annual consumption of electricity in Denmark. Subsequently, a provisional wind tunnel was built, in which wind mills with 2 m² swept areas could be tested at wind velocities of up to 6 m/s. About 30 different blade designs and blade profiles were tested. On the basis of these experiments a pilot mill with a swept area of 7.5 m diameter was built in 1950 near Vester Egesborg on the island of Zealand.

By means of this pilot mill, measurements of effect at various blade tip velocities and wind velocities were taken. The thrust, also, was measured and various devices for making the mill fully automatic were tested. These investigations were mainly finished during 1950, after which the mill was put into continual operation until the summer of 1960. It was then dismantled, its task as experimental mill being considered at an end and its small size making its continued operation unprofitable.

On the basis of the experiments with the Vester Egesborg mill, a DC wind power plant on the island of Bogø, built by the firm of F. L. Smidth & Co., was reconstructed for AC production. It was originally erected in 1942 because during the war it was difficult to obtain fuel oil for the Diesel engines which produced DC for the local power plant. This plant was taken over by SEAS later on and reconstructed for AC production.

The existing mill tower with its machine cabin and gear box was still serviceable and was provided with 3 blades having a swept area diameter of 13.5 m, corresponding to a swept area of 132 m², as well with a 45 kW AC generator. Electric automatics were also installed in accordance with asystem worked out by experiments and tested at the Vester Egesborg mill. The same applies to the blade construction.

The Bogø mill was put into operation in 1952 and has virtually been in continual operation ever since, without any apparent defects. During one period of 9 months, it was actually in continual operation without anything being done to its mechanical or electrical parts. When after that period it was at last stopped, it was only for the purpose of lubrication and routine inspection.

The results obtained with the two experimental mills were so promising that the Association of Danish Electricity Works (Danske Elværkers Forening = DEF), on a proposal from SEAS, appointed a wind power committee to carry on the work on wind power problems.

On application from the committee, the Danish Government granted the DEF an amount of 300 000 Danish crowns (about £15 000) for the erection of a larger sized experimental mill near Gedser with a swept area of 24 m diameter. Later on, a further amount of 225 000 crowns was granted for investigations and measurements of wind velocities at heights above ground of 25 and 45 m in various places in Denmark. Details of the costs of the Gedser Mill are as follows:

	Crowns
Tower (incl. examination of ground of the site)	76 000.00
Machine cabin (incl. mounting)	75 000.00
Blades and rotor hub	44 000.00
Chain drive, brake, hydraulic brake lever	20 000.00
Generator, transformer, distribution switch board etc.	57 000.00
	272 000.00
Projecting blades, transformer and tower	48 000.00
TOTAL COST	320 000.00
Special measuring instruments, measurements and scientific investigations	55 000.00
($ 56.000)	375 000.00

* Former Sectional Engineer, Haslev, Denmark.

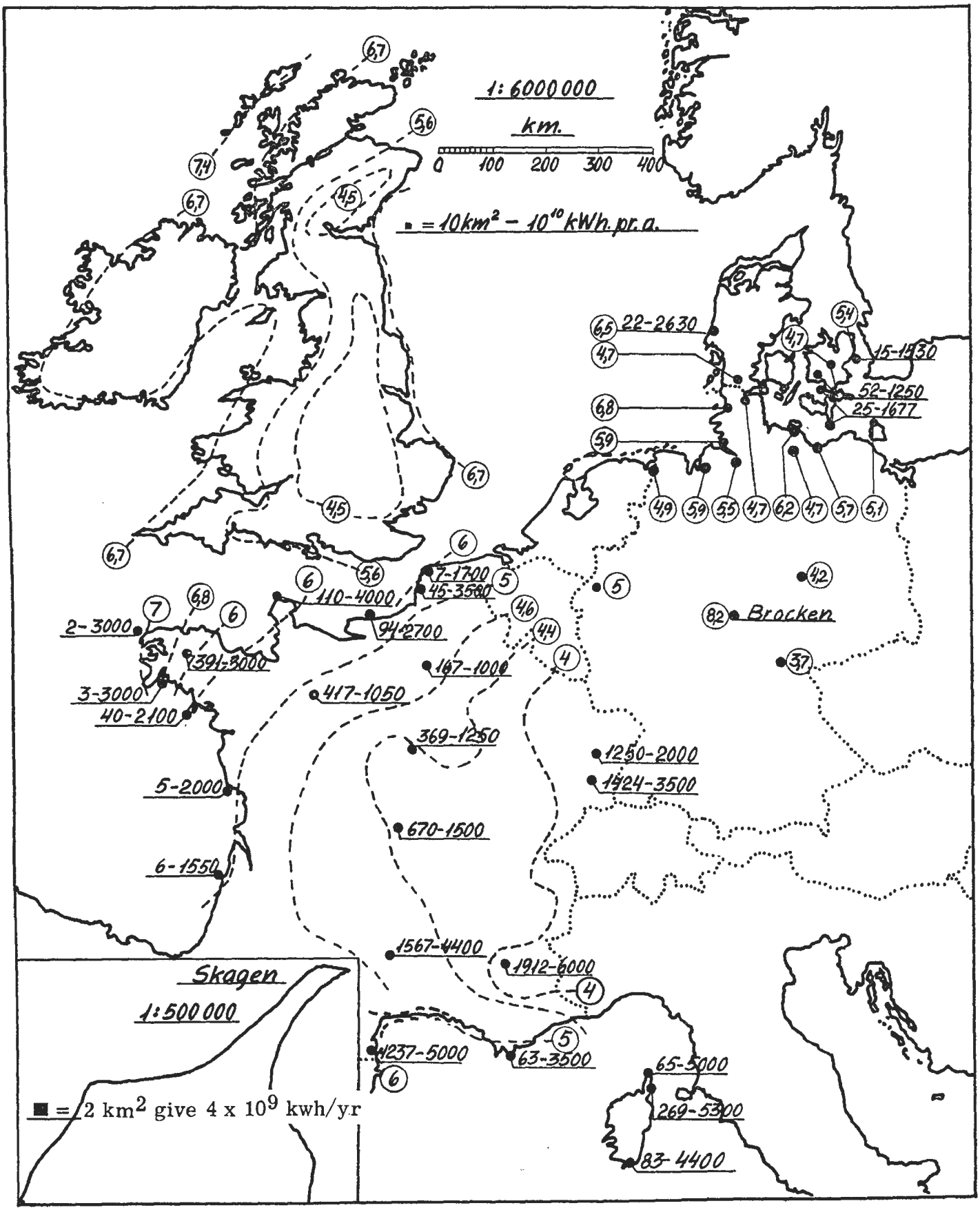

Figure 1. Map of western Europe with wind speeds and wind energies

The figures in the circles indicate the mean annual wind speeds. In the double figures, the first indicates the height of measurement, the second the energy in kWh/m², measured in the vertical plane. About 60 per cent of this energy can be fed to the electric network. The top of the map shows the scale together with the swept area required to produce 100 000 million kWh. At the bottom of the map, a part of Jutland is shown, with the swept area required to supply the present electricity consumption of Denmark drawn to scale on it

The blades, the electrical equipment and transformer station as well as the connection to the grid were all made by SEAS. The machine cabin was made and the mounting done by Aarhus Maskinfabrik and the prestressed concrete tower was built by the firm of Nielson & Co., contractors of Copenhagen.

All the work involved was performed with craftsmanlike methods and without special tools, excepting the tower for which special forms had to be made. Hence the building of the tower was fairly expensive, i.e., 75 000 crowns. When building similar plants and producing the component parts in series, the building costs can be reduced.

The specifications of the Gedser Mill are the following:

Swept area diameter: 24 m.
Swept area: 450 m².
Number of blades: 3.
Blade tip velocity: 38 m/s.
Rpm of blades: 30.
Height of tower: 25 m.
Generator: 200 kW, asynchronous, 8-polar, 750 rpm.
Generator slip: from 0 to full load 1 per cent.
Wind velocity for (automatic) start: 5 m/s.
Capacity: 200 kW at 15 m/s wind velocity and 5°C air temperature.
Transmission from rotor shaft to generator: double chain drive, ratio 1/25.

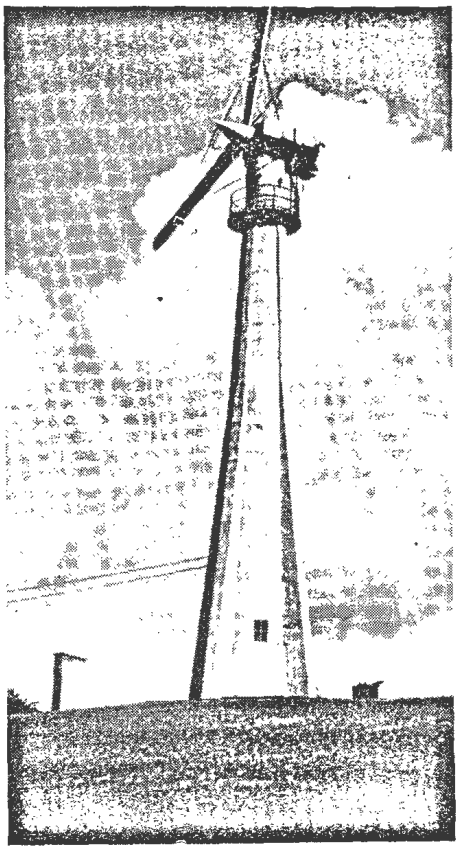

Figure 3. Bogø mill
Swept area 132 m². Diameter 13 m. 45 kW at 38 m/s wind speed

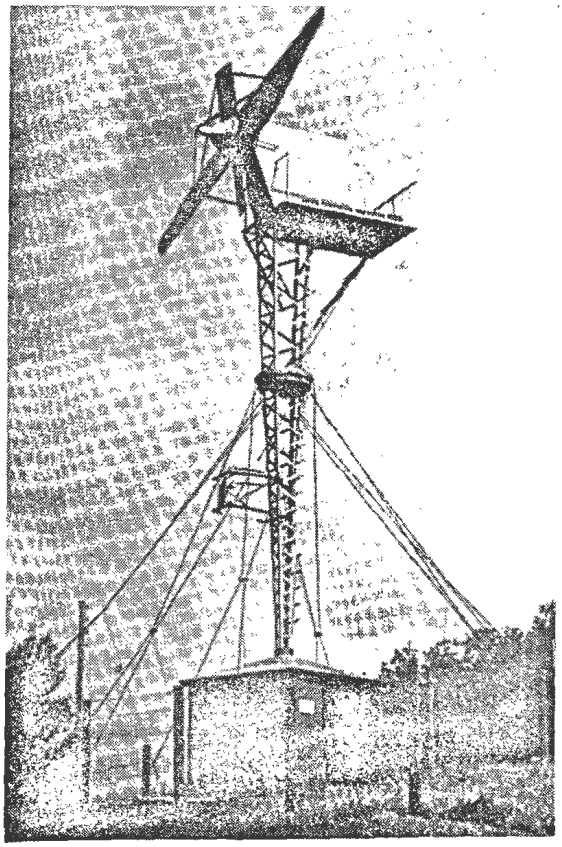

Figure 2. Pilot mill near Vester Egesborg
Swept area 45 m². Diameter 7.6 m. 13 kW at 38 m/s wind speed

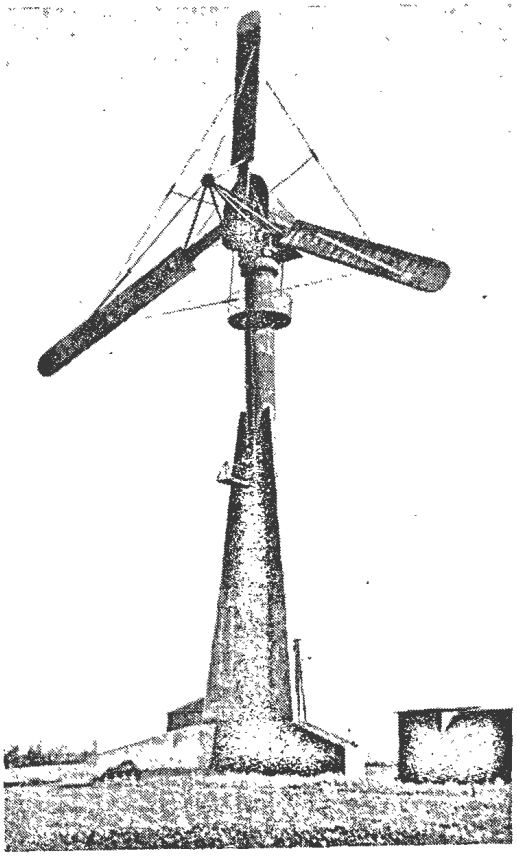

Figure 4a. Gedser Mill
Swept area 450 m². Diameter 24 m. 200 kW at 38 m/s wind speed

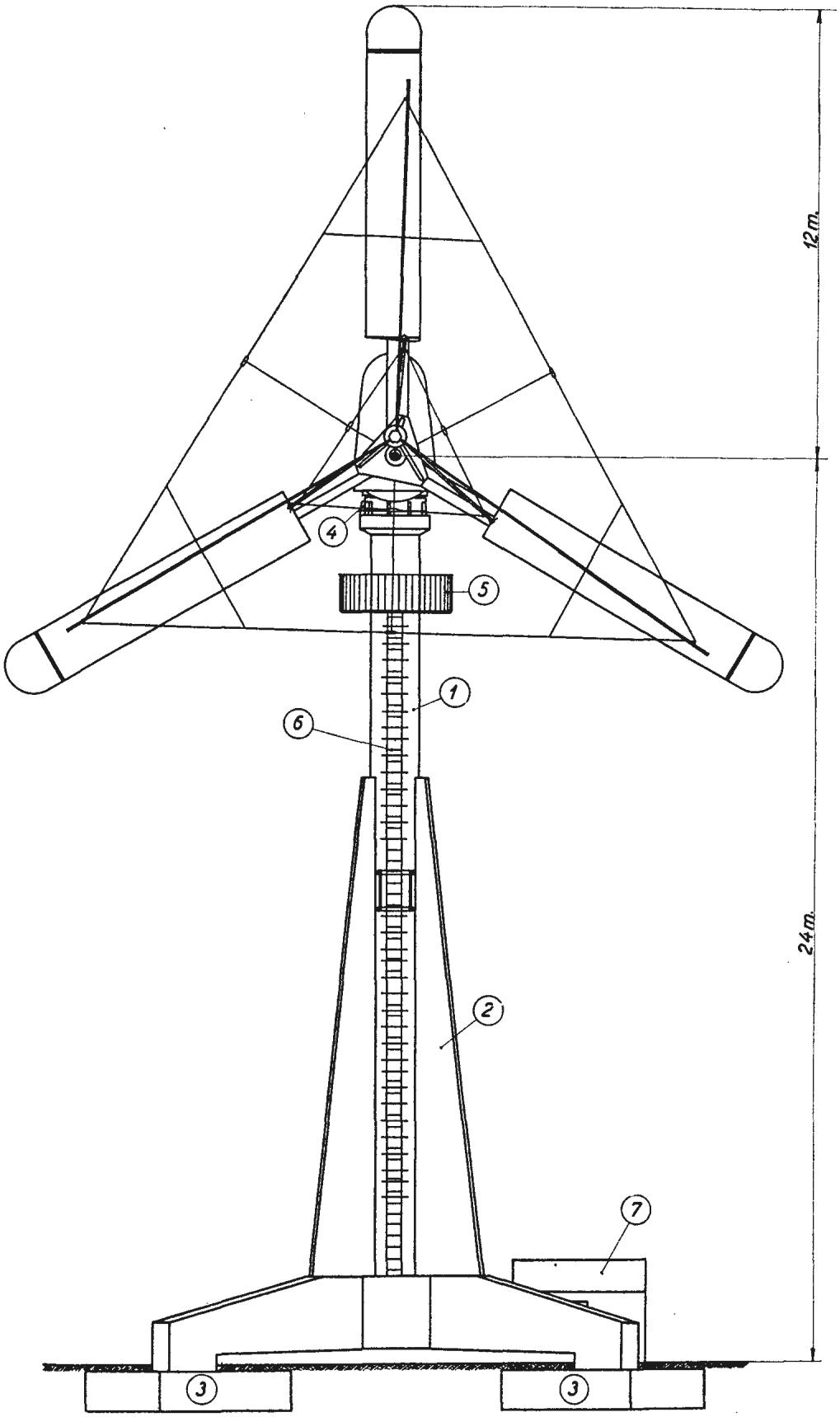

Figure 4b. Gedser Mill. Swept area 450 m². Diameter 24 m; 200 kW at 38 m/s wind speed

Design and construction of the Gedser Mill are based on the results attained by experiments and the experience gained during the research work and from the experimental plants at Vester Egesborg and on the island of Bogø.

The Gedser Mill was completed in the summer of 1957. After the mill had been tested and adjusted and some minor alterations had been made and when various measurements of efficiency and mechanical conditions had been worked up, the mill was put into continual operation in June 1958. Since that time it has been working, practically day and night, in connection with the SEAS grid, without mishaps of any significance.

A description of the more important details of the construction of the mill are given below.

The blades

Through experiments in the SEAS provisional wind tunnel, the blade profile shown in figure 5 was found to be the most advantageous. It was also found that a 3-blade mill with this blade profile had, at 6 m/s wind velocity, the power coefficient shown in the figure and that this coefficient has its maximum value when the blade tip velocity is 5 to 6 times as high as the wind velocity.

Curve 1 in figure 6 indicating the annual number of hours during which the various wind velocities occur, was found through wind energy measurements taken in the southern part of Zealand by SEAS. Curve 2 indicates the corresponding annual amount of energy, which has its maximum at 8 m/s. As wind mills which are coupled with normal asynchronous AC generators in connection with extensive AC grids are bound to operate at a number of revolutions which only varies in relation to the generator-slip — which is normally between 1 per cent and 4 per cent — a number of revolutions and a blade tip velocity must be chosen which best take advantage of the maximum annual wind energy occurring locally, which in this present case was 8 m/s. The mill has its maximal power coefficient at a blade tip velocity of about 5 times the wind velocity and as shown in figure 5 the blade tip velocity chosen was 38-40 m/s.

It may possibly be advantageous to arrange the transmission between blades and generator so as to make the blade tip velocity higher or lower than 38 m/s, where different wind conditions from those of South Zealand are prevailing. The question whether great effect of the mill during fewer hours per annum or less effect during many hours of the year is to be preferred should also be taken into consideration. In either case the actual amount of

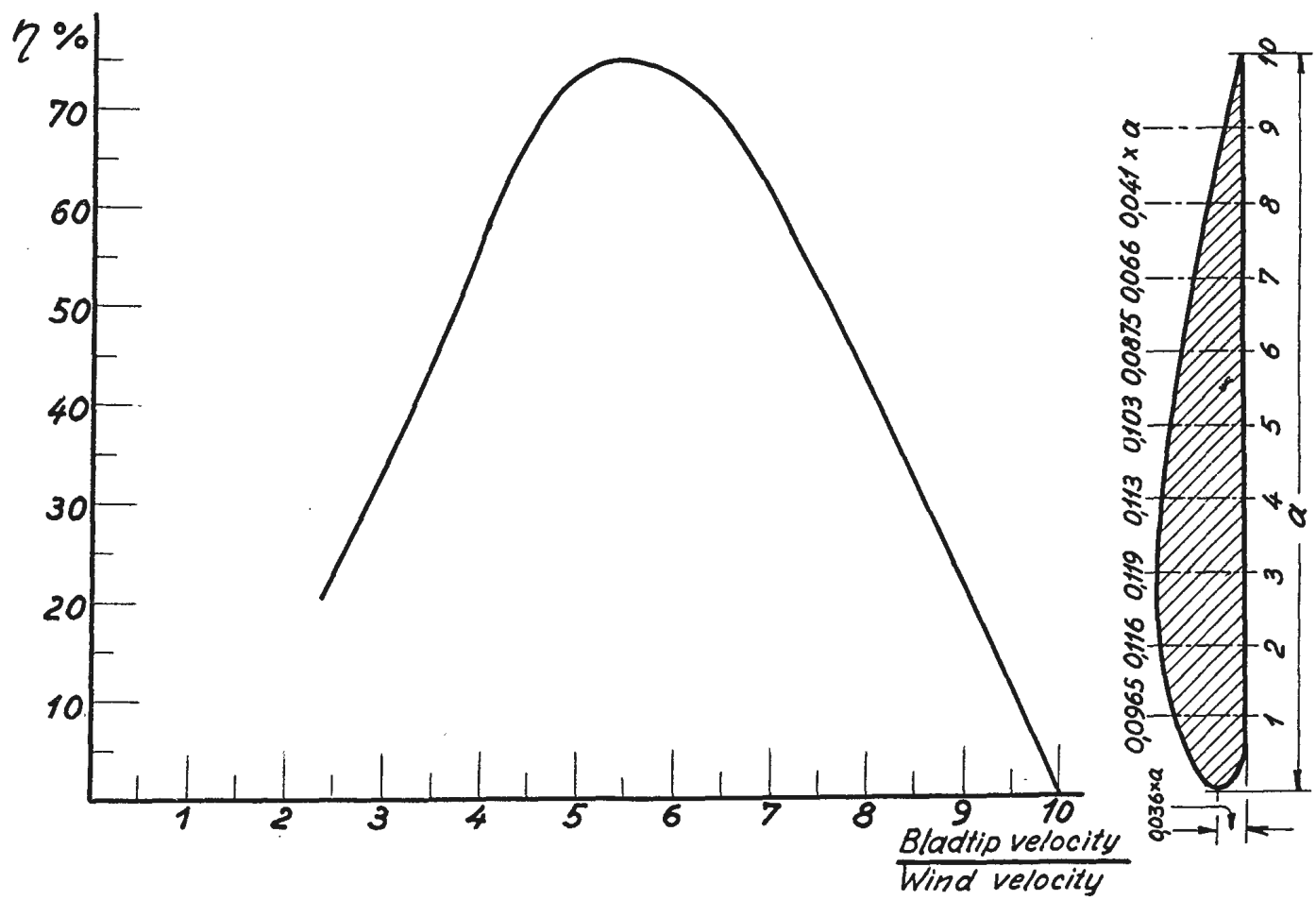

Figure 5. Blade profile and efficiency curve

λ = blade-tip velocity/wind speed

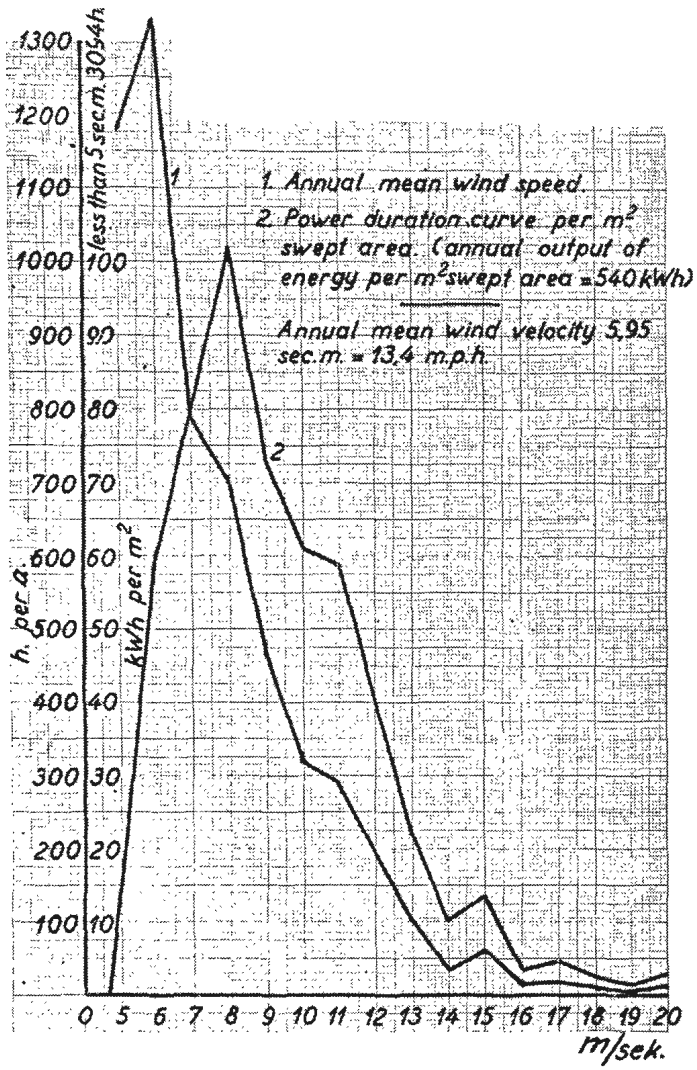

Figure 6

Curve 1. Annual mean wind speed 5.95 m/s, measured near Vester Egesborg mill; curve 2. Calculated annual output : 540 kWh/m² of swept area. Measured output in 1953 : 525 kWh/m² of swept area.

energy would appear to be nearly equal but this of course depends upon whether the wind energy is available in the shape of high wind in a few hours of the year or as lighter winds of daily occurrence.

By using the relation, as shown in figure 7, between the effect curve 3 of the wind and the power coefficient curve 1 of the mill, the effect curve 2 of the mill can be constructed or, if the latter is known, the power coefficient curve can likewise be constructed. In figure 7 the mill effect curve is seen to be nearly flat at 15 m/s wind velocity. This is due to the phenomenon called "stalling", in airmen's parlance, which may cause an aeroplane to crash when the air current, for some reason or other, hits the wings at too obtuse an angle of attack, thus causing an unfavorable flow-off of the streaming air from the wings and bringing about a reduced lift coefficient corresponding, in the case of the mills, to a relatively smaller pulling power at increasing wind velocity.

In the design of the pilot mills constructed by SEAS, the stalling phenomenon is used for controlling the effect. In this manner a simple method of preventing overloading in a gale has been found. Such fluctuations of the mill effect are caused by the natural changes of the wind velocity which are absorbed without difficulty by an extensive supply network.

The mill, however, must be so contrived that it can be stopped whenever necessary because of lubrication or a breaking-off of the connection to the grid. This purpose is served by special break flaps at the tips of the blades. They are shown in figure 8.

The brake flaps (1) constitute 12 per cent of the surface area of the blades and are, under normal operating conditions of the mill, an integral part of the blades. Each of the flaps is fixed to a tubular carrying rod (2) which will, when actuated by the automatics of the mill, travel about 300 mm along the longitudinal axis of the blade and move in a link-motion (3) in the fixed part of the blade. By this movement, the brake flap is twisted about 60° out of the plane of the blade, thus counteracting the remaining part of the blade and bringing the mill to a dead stop. The brake flaps are governed by a

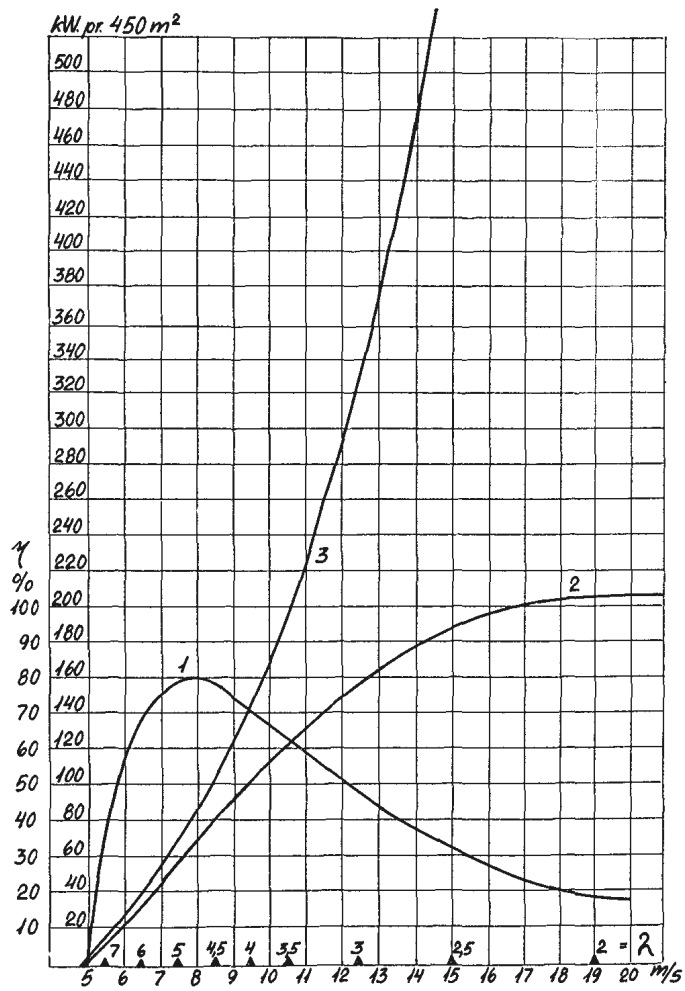

Figure 7

Curve 1. Power coefficient curve*; curve 2. Effect curve of Gedser mill; curve 3. Wind energy, calculated by the formula $D^2 \times V^3 \times 0.000285$, for $D = 24$ m

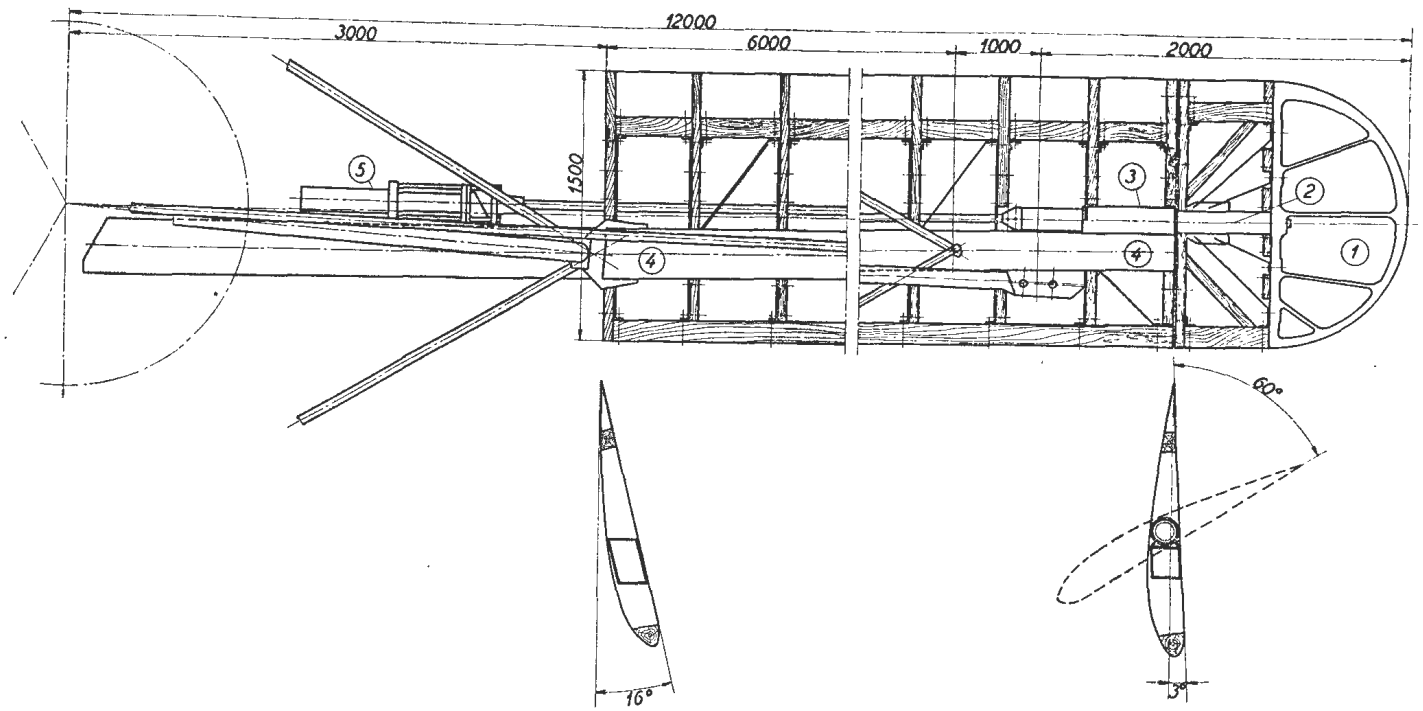

Figure 8. Design of blades used at Gedser Mill

hydraulic servo-motor (5) in connection with the mill system of automatics. When the mill starts, the servo-motor will pull the brake flaps into working position. When it stops, the centrifugal power will force the flaps out into braking position.

The blade beam (4) is quadrangular and made of 16 mm and 10 mm welded steel plates. The cross section of the beam alters linearly from the hub to the extreme beam end as shown in the figure. Flat bar fish plates are welded on the beam and streamlined wooden transverse ribs are fastened to the fish plates with screws. In the leading edge and near the trailing edge of the blade wooden mouldings are mounted.

Light alloy metal sheeting of 1 mm thickness is fastened to the transverse rib system by galvanized flat-headed wood screws, the sheeting thus forming the streamlined body of the blade. The blade has a twist at the blade root of 14° decreasing to 3° at the brake flap.

Through wind tunnel experiments, this was found to be the minimal twist necessary for making the mill start automatically at 5 m/s wind velocity, and at the same time it lends the blade the greatest possible pull.

When the blades were designed as described above, it should be remembered that the possibilities of production were restricted, as they could only be made by manual power craftsmanship. In a possible future industrial production in series, these blades can undoubtedly be more cheaply made of pressed steel sheets welded into hollow shell-like constructions to be bolted to the hub by flanges. It is possible as well to make the blades of other material than steel, e.g., plastic reinforced with glass fibre, if this proves economically advantageous.

The pressure of the wind and the mechanical strains on the blades depend on the speed of the blades in relation to that of the wind. At 38 m/s blade tip velocity the thrust per m² swept area of a 3-blade mill has been determined, through the research work done by SEAS at the Vester Egesborg mill, to be as shown by curve 1 in figure 9 while curve 2 indicates the thrust when the mill is at a standstill.

During investigations of such variations of the wind velocity as occur within the width of the swept area (24 m), calculations of such torsional stresses

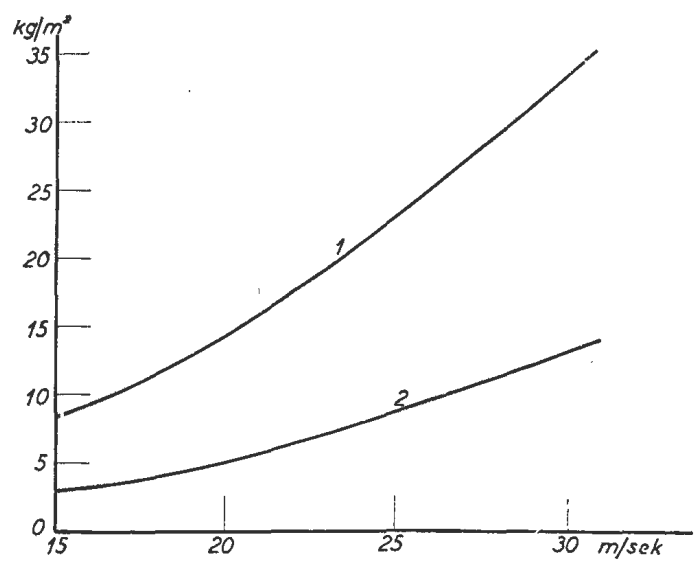

Figure 9. Axial pressure at Gedser Mill, kg/m² per m² of swept surface

Curve 1. Pressure per m² while operating at 38 m/s wind speed; curve 2. Pressure per m² after mill has stopped

as may arise around the vertical axis of the mill tower have been made. This moment of torsion was found to be 5 300 kgm which in addition to the above mentioned thrust has been used as a basis of calculation of the dimensions of blades, machine cabin and constructive parts of the tower.

During the calculations it appeared that, when an aerodynamically advantageous profile is to be used, it is practically impossible to build steel blades to be freely suspended from the hub without stays or guy wires. Hence the construction of the blades is based on the use of stays for carrying the thrust and guy wires for absorbing its varying plus and minus bending moments arising in the blade beams at the rotating of the blades.

When calculating the steel constructions, a stress of 600 kg per cm² was considered the maximum where fluctuating one-way forces are concerned, and 200 kg per cm² where strain and stress change between opposite directions on account of the rotation.

In the Gedser Mill, a measurement cylinder is placed between the tower and machine cabin. It is 450 mm high and it has strain gauges. Measurements by these have been taken at wind velocities up to 20 m/s and the results seem to agree quite well with the thrust calculated in advance, whereas the pre-calculated 30 m/s velocity torsional stresses attained the calculated value already at 20 m/s wind velocity. In view of the thrust and the weight of the several parts, however, the dimensions of blades, tower and cabin are on a rather liberal scale, so that the parts in question will easily resist the greater tortional strains.

Mr. Askegaard, a civil engineer who has been in charge of strain gauge measuring of the mill, gives an account of the measurements in Paper W/15. The Electrical Research Association has taken strain gauge measurements on the blades of the Gedser mill. Opportunities to take these measurements offered only wind velocities up to 15 m/s, but the results seem to agree with the values determined in advance by SEAS.

The machine cabin

The design of the machine cabin is shown in figure 10. The blade beams (1) are bolted on the blade hub (2) which has two built-in ball bearings (3) and (4). The latter (4) cannot be replaced without removing the blades and hub. Its dimensions are therefore very ample so that according to calculations it should have a very long life. Ball bearing (3) is the axial pressure bearing and can be replaced without removing the blades and the hub which are mounted on a spindle (5) fixed in the cabin and bored. The bore (6) serves as an oil pressure pipe for the service motors which are mounted on the blades for pulling the brake flaps into flush position.

Between the bore (6) in the fixed spindle and the rotating oil pipe system of the hub, a self-tightening stuffing box (7) is inserted. Connecting with the oil pressure pipe of the spindle is a safety valve (8), sealed by a stopper made of a metal which will melt at 110°C. In case of heating of the spindle, due to defects in the bearings, the stopper will melt and let out the oil, thus stopping the mill.

On the hub is mounted a twin sprocket (9) which, by means of double 2½″ roller chains (10), pulls the sprocket (11) on the secondary shaft (12). The secondary shaft has a triple sprocket (13) with appurtenant 1½″ roller chain (14) pulling the generator shaft (15). The shaft is connected to the generator (16) by an elastic coupling (17) fitted with snap pegs (18) that will snap in case of relay defects which may cause a faulty coupling of the generator to the grid and thus give rise to dangerous jolts in the mechanical parts and the blades.

The bearing pedestals (19) and (20) as well as the hydraulic pumping plant (21) and the generator are mounted on a bottom frame (22). The bull gear is made of welded sheet steel and is fixed to the bottom of that frame.

The stationary inner ring is a toothed rim, the teeth of which are in mesh with the yawing motor gear which has a built-in worm gear that locks the yawing mechanism, in the cabin, when the yawing motor is stopped. The yawing motor is automatically governed by a vane (24) mounted on top of the cabin. Access to the cabin is from the tower platform by means of the ladder (25). Above the ladder is a manhole in the frame bottom. The stationary inner part of the bull gear is fastened to the tower by means of a 450 mm high measuring cylinder (26), on which strain gauges are placed. By means of these and the appurtenant measuring instruments, the axial pressure and the torsional influences can be measured. The dimensions of the measuring cylinder have been kept fairly small for the greatest possible sensitivity.

For this reason another cylinder (27) of more ample dimensions has been placed outside and

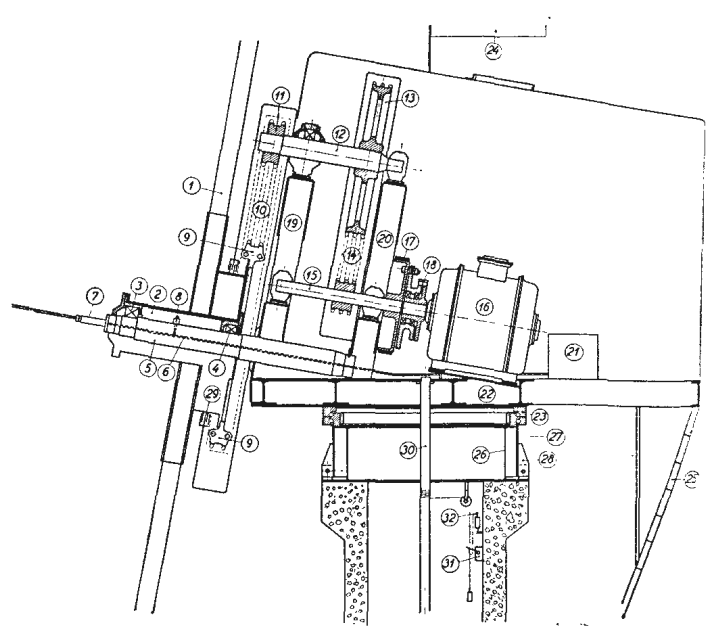

Figure 10. Design of machine room

around the measuring cylinder. It is of larger dimensions and is provided with fish plates (28) that grip around cams on the bottom plate to which the measuring cylinder is welded. Whenever no measuring is going on, the cams and some conical loose-fitting bolts in the fish plates take over the load.

The sprockets and the chains are contained in a chain casing. The primary chain drive is lubricated by means of an oil bath, while the secondary chain drive is lubricated by an oil pump with an oil pressure relay that will stop the mill if the oil pressure ceases. To prevent the oil from leaking and the rain from penetrating into the casing of the primary chain, a labyrinthine obtorator is inserted between the stationary and the rotating part.

The elastic coupling (17) is bowl-shaped, thus having an outer face that is used as a mechanical brake. The brake-shoes are released when the oil pressure of the hydraulic system is turned on at the starting of the mill. When the oil pressure ceases on stopping of the mill the brake-shoes will be pressed against the braking face by a lever. The brake will not be able to stop the mill, however. This is done by means of the brake flaps of the blades but the mechanical brake will secure the blades if work on the mill has to be done. The entire machinery of the mill is encased in a housing of galvanized sheet steel and on top of the housing the vane (24) is mounted. The vane is in mechanical connection with a relay that governs the yawing motor.

The cables to the generator as well as the control cables are carried to the machine cabin through a rubber tube fixed in the floor of the cabin and freely suspended in the tower so that it will stand being twisted ten turns either way without being damaged.

In that way the use of slip rings for cable connection to the cabin has been avoided. Experience shows that the yawing will cause, annually, only about 10 turns, clockwise.

In the tower is placed a relay (31) connected with a cord that passes a pulley and is wound round the rubber tube (30) so as to disconnect the control cables, thereby stopping the yawing mechanism and the mill, in case the cables get too many turns. At the monthly inspection the mill — if necessary — is turned back the opposite way, by manual operation of the yawing mechanism, until the cord round the rubber tube has been unwound.

Another cord is also fastened to the relay. It is connected with a loosely placed weight that will fall off its stand and influence the relay, thus stopping the mill, in case abnormal vibrations occurin the tower.

The tower

Figure 4 shows the complete construction of the tower. It also shows how the blades with their stays and guy wires as well as the machine cabin are mounted on the tower. This consists of a vertical tube (1) made of prestressed concrete, whereas the buttresses (2) and the foundation (3) consist of ordinary reinforced concrete. (4) is the above-mentioned measuring cylinder, placed between tower and cabin. There, (5) is a service platform by which access is gained by an inside as well as by an outside ladder (6). Near the tower there is a steel sheet house (7). The tower was conceived and and calculated by B. Hejlund Rasmussen, Copenhagen.

Diagram of the Gedser Mill

The diagram is shown in figure 11. The mechanical parts are shown schematically and cables of generator and auxiliary motors are drawn as single lines for the purpose of simplifying the diagram.

When starting the mill the high tension circuit breaker (31), the low tension breaker (28), as well as the control cable circuit breaker (41), are switched on. The cut-in magneto (15) will then close the valve (16) and the electromotor (19) and the oil pumps (20) will start and put pressure on the hydraulic system. The pressure causes the service motors (5) to pull the brake flaps (2) of the blades (1) into position for operating the mill, in which position they form an integrating part of the blades. Further, the service motor (7) will release the mechanical brake (6) on the generator shaft (8). If the wind velocity is 5-6 m/s the mill will start. As soon as the 8-pole generator has attained 750 rpm the centrifugal relay (9) will switch on the contactor (24) and connect the generator to the grid system, into which it will feed energy when the wind velocity is above 5 m/s. In case the wind velocity decreases to less than 5 m/s, the generator will take energy from the grid system and the return current relay (26) will then switch off the current for the cut-in magneto of the contactor (24) which then switches off the generator from the grid system until a wind of 5-6 m/s velocity starts blowing again and the centrifugal relay switches the generator on to the grid system once more. In the Vester Egesborg and Bogø mills the generator slip is 5 per cent and 4 per cent, and in the case of these two plants the required selectivity between the centrifugal relay and the return current relay can be obtained.

The Gedser Mill generator, however, has but 1 per cent slip and here the centrifugal relay could not with sufficient accuracy switch off the connection to the generator contactor after the return current had gone into action. Hence it became necessary to build a damping switch into the return current relay to retard its action and prevent it from switching on the connection to the centrifugal relay until the latter had, on account of the reduced number of rpm of the mill, had sufficient time to switch off the connection with the cut-in magneto of the contactor.

The mill is stopped by switching off the low tension circuit breaker (28) or the control cable circuit breaker (41). The tension on the contactor (24) will then be cut off as will also the generator connection with the grid system. The tension on the cut-in magneto (15), also, will be cut off. The valve (16) will turn on the oil for the service motors (5) and (7)

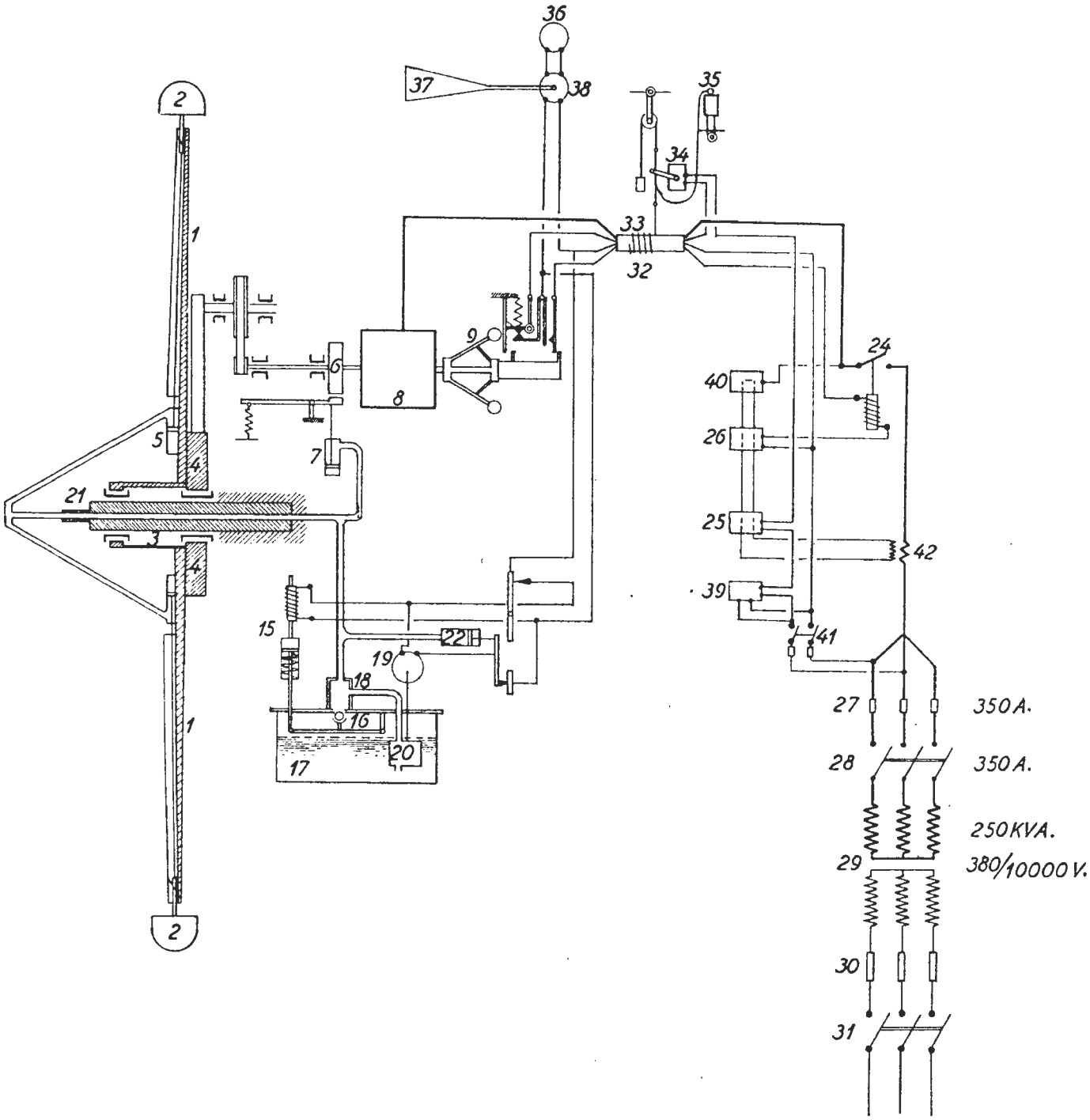

Figure 11. Schematic diagram of mechanical operation and electrical circuit

and put the brake flaps of the blades as well as the mechanical brake (6) into operation, thereby stopping the mill.

The vane (37) serves to keep the blades in the right position in relation to the direction of the wind; it is connected with the reversing device (38). The latter can cross two phase cables to the yawing motor (36) so as to reverse its direction of yawing, when the wind veers towards the right or the left respectively. When the wind attacks the swept area perpendicularly, the mill will be kept in this position by means of a worm gear in the yawing motor gear box. The movements of the vane are damped by means of a shock absorber filled with oil.

Various precautionary measures have been taken for stopping the mill when any damage occurs or in case the connection to the grid system is broken off.

If the grid system connection is broken off and the generator is not excited by the grid, its contactor

(24) will be switched off, as will the cut-in magneto (15); the oil pressure will then cease and the mill be stopped by the braking devices.

If there are capacitors of the requisite capacity in such part of the grid as may remain connected with the mill generator, the grid will be excited capacitively. If the load exceeds the output which the mill is capable of bearing, its rpm and its generator voltage will automatically drop until at length it stops. If the load, however, happens to be less than the output, the mill will increase its rpm and its generator voltage.

In that case the overvoltage relay (39) will switch off the control cable, if this has not already been done by action of the centrifugal relay safety switch which can likewise switch off the control cable. The switching off may also be done by an overpressure switch built into the hydraulic system and influenced by the pressure cylinder (21).

In the draw bar of the cut-in magneto (15) is a built-in spring that makes the closing-valve (16) function also as a safety valve that will open for the oil in case of overpressure. Thereby the brake flaps of the blades will prevent the occurrence of dangerous situations caused by an excessive number of revolutions. Thus safeguards against racing of the mill have been established in several ways.

The various safeguarding appliances lock themselves when they have been in operation, so that the mill cannot be started before they have been released by hand. The several appliances are made selective so that only one of them need function to bring the mill to a standstill.

Normally the generator cannot be overloaded even in the most violent hurricane, the mill effect being automatically limited by the stalling of the blades in high wind.

If a break of phase occurs in the grid system, the generator windings in phases *r* and *s* may be overloaded, hence an overcurrent relay (25) is inserted which, in that case, will switch off the control cable, thus stopping the mill. The relays (25) and (26) and the kWh-meter (40) operate together with current transformers (42) in the main cable.

The control system diagrams of the former Vester Egesborg mill and the Bogø mill are on the whole identical. In the Bogø mill, instead of a hydraulic regulating system, a powerful spiral spring is used. The spring is loaded by means of a winch and an electromotor and keeps the brake flaps of the blades pulled into their flush position when the mill is operating. In the Vester Egesborg mill, instead of oil pressure, compressed air is used. Condensation water can, however, form in the system. This is unfortunate, especially in frosty weather, but all three systems have been able to function in such manner that no mishaps of any importance have occurred.

Summary

In 1947, Sydøstsjællands Elektricitets Aktieselskab, SEAS (The South-East Zealand Electricity Co. Ltd.) inaugurated a series of investigations on the possibilities of utilizing wind power for the production of electricity in connection with the existing AC grid.

On various sites in Denmark, anemographs for the measuring and recording of wind velocity were mounted and a temporary wind tunnel was made in which wind motors of up to 2 m² swept area could be tested. About 30 different blade designs and blade profiles were tested. On the basis of these experiments, a pilot plant of 7.5 m swept area diameter (44 m² swept area) was built, in 1950, near Vester Egesborg on Zealand. By means of this plant, measurements of the effect were taken at various blade tip velocities and wind velocities. As well as this, the thrust was measured and various devices for making the plant fully automatic were tested.

On the basis of the experiments made with the Vester Egesborg plant, a DC wind power plant on the island of Bogø, designed and constructed by the firm of F. L. Smidth & Co., was converted into an AC plant. Since 1942 this plant had been producing DC in connection with a local diesel-electric power works which had been dismantled and reconstructed for AC supply from the SEAS grid. The existing tower and machinery were used and the wind motor was provided with 3 blades. An asynchronous AC generator as well as the automatics necessary for the production of AC and the feeding of it into the grid were installed as well. The plant started operating in the autumn of 1952 and is still working.

The operating results of the two experimental plants were so promising that, at the suggestion of SEAS, the Association of Danish Electricity Works appointed a Wind Power Committee to carry on the wind power work.

The Wind Power Committee received grants from the Danish Government totalling 525 000 Danish crowns (about $80.000) for the erection of a 200 kW pilot plant — the "Gedser Mill" — and of 3 wind measuring stations.

The Gedser Mill, the construction cost of which (apart from 55 000 crowns for measuring equipment and 48 000 crowns for projecting) amounted to 272 000 crowns (about $41.000), was finished during the summer of 1957. After some adjustments of the plant had been made, measurements of the produced energy taken and investigation of such phenomena as gradually appeared in connection with its operation made, it was finally put into service in June 1958 and has been in operation since then.

The "Gedser Mill" is the most recently built and largest Danish experimental wind power plant and is to a material extent designed on the basis of experience gained from the aforesaid pilot plants.

The "Gedser Mill" has a 25 m high tower made of prestressed concrete. On top of the tower is mounted a measuring cylinder carrying the machinery.

The three blades of the rotor have a length of 12 m, thus forming a swept area of 450 m². Through a chain drive with a ratio of 1:25 the blades drive an eightpole, 200 kW asynchronous generator (3 × 380 V, 50 periods). The blade tip velocity is about 38 m/sec. corresponding to $\frac{1}{2}$ r/sec. The wind motor starts automatically at a wind velocity of 4-5 m/sec. and the plant renders 200 kW at 15 m/sec.

RÉALISATION DES CENTRALES ÉOLIENNES

Résumé

En 1947, la compagnie d'électricité du Sud-Est de la Zélande (Sydøstsjællands Elektricitets Aktieselskab, SEAS) a commencé une série de recherches sur la possibilité d'utiliser l'énergie éolienne en vue d'une production d'électricité susceptible de s'intégrer dans le réseau de distribution en courant alternatif déjà en service.

On a, en divers lieux du Danemark, des anémographes destinés à la mesure et à l'enregistrement de la vitesse du vent et on a construit un tunnel aérodynamique provisoire se prêtant à l'essai d'aéromoteurs ayant une surface balayée pouvant aller jusqu'à 2 m². On a soumis à ces essais environ 30 modèles de pales et de profils de pales. Sur la base de ces expériences, (1950) on a réalisé une centrale-pilote ayant un diamètre balayé de 7,5 m (surface balayée 44 m²) près de Vester Egesborg dans l'île de Zélande. On a mesuré les débits réalisés au moyen de cette installation pour diverses vitesses en bout de pale, ainsi qu'en fonction de la vitesse du vent. On a mesuré en outre la poussée et on a essayé plusieurs dispositifs visant à rendre l'installation complètement automatique.

Sur la base des expériences faites à la centrale de Vester Egesborg, on a converti une centrale productrice de courant continu, installée sur l'île de Bogø, mise au point et construite par la firme F.L. Smidth & Compagnie, en installation fournissant du courant alternatif. Depuis 1942, la compagnie débitait du courant continu en association avec une centrale à moteur diesel qui avait été démontée et reconstruite pour fournir du C.A. au réseau de la SEAS. La tour et les machines restaient utilisables et l'aéromoteur a été doté de trois pales. Un alternateur asynchrone et les dispositifs automatiques nécessaires pour la production de courant alternatif et sa fourniture au réseau ont également été installés. Le fonctionnement de l'installation a commencé au cours de l'automne de 1952 et elle marche encore.

Les résultats donnés par l'exploitation des 2 centrales expérimentales étaient si prometteurs que, sur la recommandation de la SEAS, l'Association des centrales électriques danoises a nommé un comité spécial de l'énergie éolienne qui a été chargé de poursuivre les travaux sur cette question. Le comité a reçu des octrois de fonds du gouvernement danois atteignant un total de 525 000 couronnes danoises (environ 80 000 dollars) en vue de l'installation d'une usine-pilote de 200 kW — la centrale de Gedser — et de trois stations anémométriques.

La centrale de Gedser, dont les frais de construction (à part 55 000 couronnes danoises pour le matériel de mesure et 48 000 couronnes danoises pour les projets) s'élevaient à 272 000 couronnes danoises (environ 41 000 dollars) a été terminée pendant l'été de 1957. Après avoir procédé à quelques réglages, on a fait des mesures sur l'énergie produite et étudié les phénomènes qui apparaissaient en liaison avec son exploitation, puis on l'a mise en service définitivement en juin de l'année 1958 : elle fonctionne depuis lors.

La centrale de Gedser est la plus grande centrale à énergie éolienne danoise de construction récente et elle a été réalisée, dans une large mesure, sur la base de l'expérience acquise au moyen des installations-pilote mentionnées ci-dessus.

La centrale de Gedser a une tour de 25 m, en béton précontraint. A la partie supérieure de cette tour, on trouve un cylindre de mesure sur lequel repose la machine.

Les trois pales du rotor ont une longueur de 12 m, si bien que la surface balayée est de 450 m². Ces pales entraînent un groupe moteur-alternateur asynchrone de 200 kW à huit pôles par l'entremise d'une commande à chaîne (réduction, 25 ăl) (3 × 380 V, 50 périodes). La vitesse linéaire en bout de pale est de l'ordre de 38 m/s, ce qui correspond à $\frac{1}{2}$ tour par seconde. Le moteur démarre automatiquement quand la vitesse du vent atteint 4 ou 5 m/s et l'installation débite 200 kW pour une brise de 15 m/s.

WIND POWER PLANTS SUITABLE FOR USE IN THE NATIONAL POWER SUPPLY NETWORK

Aladár Ledács Kiss *

The supply of mineral energy sources in Hungary is severely limited, and the natural sources of energy are also insignificant, with the exception of wind energy. It has therefore been necessary to take serious measures for the utilization of wind energy.

The first step was the collection of data on the magnitude of the wind energy. Since only measurements already available could be considered, such measurements had to be selected from those of the National Meteorological Institute. An additional consideration was that the location of the measurements must be easily reached from Budapest. The wind energy of the measuring location selected on this basis was 745 kWh/m² per year measured at an elevation of 15.6 m above ground level, which corresponds to 1 120 kWh/m² per year measured at an elevation of 35 m.

The second step was the design of an experimental wind power plant for wind conditions which would drive a generator with a capacity of 200 kW.

My task initially was to determine what type of construction could be used for building such a wind power plant with the lowest investment cost. In my design study prepared for this purpose I outlined four versions, all of which had bladed wind wheels having horizontal shafts, since those with vertical shafts cannot be considered as a result of the extremely high investment costs. Of the four versions, Types A, B, and C operate with one wind wheel, and Type D operates with two wind wheels, taking equal capacity as a basis.

Type A

The wind wheel drives a primary drive mechanism, followed by a secondary drive mechanism, which drives a 200-kW asynchronous generator, with $n = 1\,000$ rpm.

Type B

The wind wheel, which in this case turns at 20 rpm, directly drives a special 300-pole 200-kW asynchronous generator. This generator was specially designed for this case by my colleague Mihály Gohér, who also supplied its measurements, weight, and costs. In this case, therefore, there is no need for a drive mechanism.

Type C

The wind wheel first drives a transmission by a chain drive. This transmission is then connected to a secondary drive mechanism, which drives the 1 000-rpm asynchronous generator.

Type D

There are two wind wheels, which together have a capacity equal to one wind wheel in the previous cases. These two wind wheels separately drive one 100-kW asynchronous generator each by means of the Type C drive mechanism.

The cheapest in construction cost among these proved to be Type C. Taking the costs of this as a basis, Type A proved 34 per cent more expensive, Type B 71 per cent, and Type D 66 per cent. The increased cost of Type A is caused by the huge primary drive mechanism, which weighs 19 tons. In Type B the cost of the 300-pole generator alone constitutes 73 per cent of the total cost of the wind power plant, so that for a small wind power plant, a multipole generator is not economical. In Type D, the nacelle holding the two wind wheels is very expensive, regardless of whether we place the wind wheels one beside the other or one above the other. In addition, two dynamos of 100 kW capacity each cost more than one of 200 kW capacity.

The results therefore showed that the Type C single-wind-wheel wind power plant was the most advantageous. This was therefore designed. A sketch of the designed 200-kW experimental wind power plant is shown in figure 1.

The shaft of the wind power plant is located at 35 m above ground level. For the structure of the tower, designs were made both for an all-steel framework construction and for a tower which could be built up like a chimney out of prefabricated reinforced concrete elements. The latter proved to be 20 per cent cheaper and its maintenance is also simpler and cheaper. We decided therefore in favor of the reinforced concrete tower.

The wind wheel has a diameter of 36.6 m. It has four blades, whose pitch is not variable. Their weight is 2 800 kg each. Wind power plants of this size have been built in the past with three-blade wind wheels. The difference in cost between the two is merely the cost of one additional blade, whereas the four blades are better balanced and can be braced better than the three blades, and are also better able

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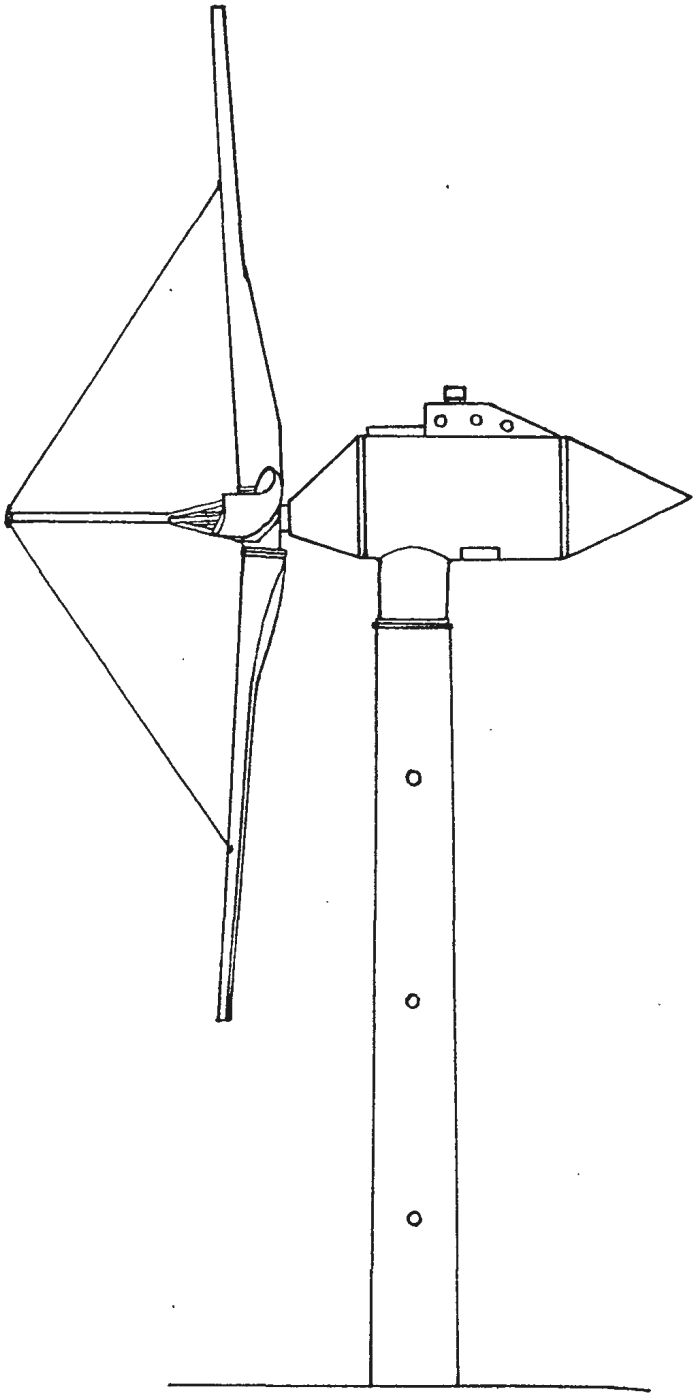

Figure 1

to utilize weak winds, which are substantially more frequent. Streamlined Göttingen-type blades are used. The structure is of welded steeel plates, with an external aluminum covering. The blades may be mounted and removed separately on the finished wind power plant, since the hub of the wind wheel has a box-type welded plate construction, into which the fastening screws of the blades can be inserted, tightened and secured on the inside. The blades are bent forward and kept fixed in this position by tubular rods attached to an extension of the shaft.

In other constructions up to the present time the shaft is generally tilted, and the plane of the wind wheel is tilted backward at the same angle, since the wind apparently blows at the same angle to the surface of the ground. This concept, however, is incorrect, since the movement of the wind is turbulent in the lower air layers as a result of friction against the ground, while the flow above it, which may be considered laminar, has a lower velocity at the bottom and gradually increasing velocity towards the top, so that only the advancing front of the air layers is tilted forward, while the streamline of the wind itself remains completely *horizontal.* A horizontal-shaft wind wheel with blades tilted forward therefore corresponds better to the wind flow conditions than a tilted-shaft wind wheel which is bent backward. The horizontal shaft constitutes a simpler and cheaper solution. The tip-speed ratio of the wind wheel is $\lambda = 5$.

The shaft rotates in roller bearings. At the rear end of the shaft is the sprocket wheel, which has a chain drive ratio of 4:1. The shaft rotation rate is 17.85 rpm, that is, slow enough to make the use of a chain drive still very advantageous, since the velocity of chain motion is less than 2 m/sec.

The rotation, having been multiplied by four by the chain drive is carried by a transmission shaft to the speed-up gear mechanism located at the rear part of the nacelle, which has a ratio of 14:1, so that its output shaft rotates at 1 000 rpm. This shaft directly drives the 200-kW asynchronous generator, which has the same rotation rate.

The entire mechanism is placed in a horizontal cylindrical gondola, whose rear end has a streamlined conical shape. The four-ton rammed concrete counterweight is located in this.

The nacelle lies on a circular roller bearing rim in a rotatable fashion on the top of the reinforced concrete tower. The rotation is performed by two opposite gears connecting to the gear rim fastened to the steel-cylinder top of the tower, together with the drive mechanisms connected to them. The wind wheel is turned to face into the wind by a rudder-controlled automatic device.

At a wind velocity of 3 m/sec the wind wheel is already in synchronous rotation and begins to generate power. The power output is 100 kW at a wind velocity of 8m/sec and reaches the capacity of 200 kW at a wind velocity of 10.4 m/sec. The allowable overload is 280 kW, which the wind power plant reaches at a wind velocity of 12 m/sec. At wind velocities higher than this the output does not exceed this value. This limiting of output at the higher wind velocities is performed by an automatic device which turns the wind wheel a little away from the wind. This change in direction is so designed that the generator output will not exceed 280 kW. If the wind velocity decreases thereafter, this same automatic device again turns the wind wheel to face into the wind.

In wind power plants up to the present time, the limiting of the load was accomplished by changing the pitch of the wind wheel blades. The load-dependent

automatic pitch adjustment of the blades is based on an incorrect concept. This was done only to imitate the load regulation systems of heat and water power plants. In the case of heat and water power plants, however, the energy source is storable and is always at the disposal of the engineer as required by the load. Load regulation of heat and water power plants therefore cannot be performed in any way except on the basis of the load as it appears. If we do the same in the case of wind power plants, then when there is wind and there is no load, the wind goes past without being utilized, and conversely, when there is no wind and there is a load, the load remains unfulfilled. Wind energy must therefore be used immediately and fully when it appears, so that the load must be adjusted to the wind energy. In other words, care must be taken to provide automatically a suitable load for the utilization of wind energy as it may show up at any time. For this purpose there is no need for variable-pitch blades. Variable-pitch blades make the system more expensive, decrease its reliability, and severely limit its construction dimensions.

For this reason we must also avoid using the variable pitch of the blade for overload regulation. In the 200-kW wind power plant in Denmark, the tips of the blades were made with variable pitch, but even this is complicated and expensive. In the solution we used there is no need for even partial adjustability of the blades, because in a very strong wind the wind wheel turns aways from the wind to a suitable extent, and in fact, if need should arise for complete shutdown, the plane of the wind wheel can be set completely parallel to the wind direction and can be braked by a small brake force.

In case of a weak wind or calm, the automatic device disconnects the generator entirely, so that the wind wheel will not be driven by the power network current.

The nacelle is turned away from the wind only if the wind direction has already changed by at least 15°. The return rotation of the nacelle has the same amount of dead space, so that the wind wheel and nacelle will not turn back and forth at every slight change in wind direction. The same occurs in overload limiting.

The wind wheel is kept at a synchronous rotation rate by the period of the power network current.

The wind power plant operates completely automatically, so that there is no need for any permanent operating personnel, and only periodic checking is required.

If the wind power plant is erected at the abovementioned location, where the wind conditions are already known, it will produce an average of 320 000 kWh per year. This energy will for the time being be somewhat more expensive than the energy produced by modern heat power plants, because this wind power plant, being a unique construction, has considerably greater initial costs. This wind power plant, however, is intended only to provide experience concerning the suitability and reliability of the individual construction solutions.

Together with the calculations and design for this 200-kW wind power plant, it also had to be decided what size of wind power plant of this type could be constructed and whether the construction of wind power plants larger than this will be advantageous.

For every wind power plant in which the low rotation rate of the wind wheel has to be speeded up to the rotation rate of the generator, the most critical point is the first stage of the speed-up mechanism. As we have seen for the Type A wind power plant, where the first speed-up stage consists of a gear drive mechanism, this single mechanism would be a huge gear box weighing 19 tons. For this reason we had to use a chain drive instead in the Type C wind power plant, but the capacity of this is also difficult to increase. The industrial drive chains manufactured at present can take a maximum load of 14 000 kg, taking into account the greater reliability required for wind power plants. As a result of the limitation in the dimensions of the nacelle, the pitch circle diameter of the largest sprocket wheel should not exceed 2 400 mm, if possible. As a result of the low rotation rate of the wind wheel shaft, the chain velocity will thus always be less than 2 m/sec, so that the chain drive is well suited for primary speed-up use. The above data, however, also show that a single chain can transmit only an amount of power approximately equal to the maximum output of this experimental wind power plant. This cannot yet be called a large wind power plant. If we are to be able to build larger wind power plants, we must first of all transmit the power from the wind wheel shaft by more than one chain. Whether this is then used to drive a single large generator or instead several smaller ones is only a question of design. In the case of several generators only two, four, or at most six generators can be considered, that is, always an even number, because we must avoid putting the transmission shaft on the center line of the nacelle, since there it would inevitably be in the way.

The other fundamental condition is the output capacity of the wind at the chosen location. Let the wind capacity be:

$$Q \text{ kWh/m}^2 \text{ per year}$$

measured at the elevation of the shaft of the wind power plant to be constructed. From the recording strip of the anemometer, we can read off the number of hours per year that the wind velocity has been 1, 2, 3, etc., m/sec. From this we can calculate the annual energy capacity of the individual wind velocities in a wind cross section of one square meter, and the sum of these will give the total annual wind energy for one square meter for the measurement location under consideration. The wind power plant will utilize a fraction of this equal to its annual average efficiency. The annual average efficiency also depends on the tip-speed ratio $\lambda = u/V_a$.

The annual average efficiency of the wind power plant at the most likely tip-speed ratio values is the following :

For $\lambda = 5 : \eta = 0.266$ and utilization factor $q = 0.172$

For $\lambda = 6 : \eta = 0.244$ and utilization factor $q = 0.158$

For $\lambda = 7 : \eta = 0.214$ and utilization factor $q = 0.139$.

The utilization factor q means that the wind power plant generator would deliver the energy it has produced in the entire year in 8 760 q hours if it were operating at full load. The capacity e of the generator per m² of wind wheel area is therefore

$$e = \frac{\eta Q}{8\,760 q} \tag{1}$$

The capacity of the generator on this basis is

$$E = \frac{D^2 \pi}{4} \cdot e = \frac{D^2 \pi}{4} \cdot \frac{\eta Q}{8\,760 q} \tag{2}$$

We have said that an industrial chain can be used for a maximum tension of 14 000 kg in the primary speed-up transmission with a wind wheel rotation rate of n rpm. Since the dimensions of the sprocket wheel are also limited, we can assume a maximum force arm of 120 cm, so that the torque which can be transmitted by an industrial chain drive is :

$$M = 120 \cdot 14\,000 = 1\,680\,000 \text{ cm-kg} \tag{3}$$

The torque which can be transmitted by z chains is equal to zM.

Asynchronous generators will take severe overloads. For safety's sake, however, we assume a maximum overload of 50 per cent, and thus the maximum torque which can be transmitted on the basis of chain capacity is :

$$zM = 71\,620 \cdot 1.36 \cdot 1.5\, E/n = 1\,680\,000 \text{ cm-kg} \tag{4}$$

whence

$$E = 11.5\, zn \text{ kW} \tag{5}$$

and

$$n = 0.087\, E/z \tag{6}$$

On the other hand, the circumference speed of the wind wheel is $u = \lambda V_a$, where V_a is the wind velocity for which the wind wheel tip-speed ratio is equal to λ, which we can call the fundamental wind velocity.

Furthermore,

$$u = n D \pi / 60 = \lambda V_a$$

whence

$$n = 60 \lambda V_a / D \pi = 19.1 \lambda V_a / D \tag{7}$$

Equating (6) and (7), we find that

$$0.087\, E/z = 60 \lambda V_a / D \pi$$

Substituting for E from equation (2), this becomes :

$$\frac{0.087 \cdot \eta Q}{8\,760\, q \cdot z} \cdot \frac{D^2 \pi}{4} = \frac{60 \lambda V_a}{D \pi}$$

whence

$$D^3 = \frac{60 \cdot 8\,760 \cdot 4 \lambda V_a qz}{0.087 \cdot \pi^2 \eta Q} = 2\,450\,000 \frac{\lambda V_a qz}{\eta Q}$$

and thus

$$D = \sqrt[3]{\frac{2\,450\,000 \lambda V_a qz}{\eta Q}} = 135 \sqrt[3]{\frac{\lambda V_a qz}{\eta Q}} \tag{8}$$

By means of this equation we can calculate the diameter D of the wind wheel. We can then calculate the rotation rate n of the wind wheel from equation (7) and finally the generator capacity E from equation (5).

The values of λ and z appearing in the equations must be selected in advance. Reference values are given for q and η; however, V_a cannot be chosen arbitrarily but must be computed. This calculation begins with e, the capacity of the generator per m² of wind wheel area, which can be computed from equation (1). The calculations required for the design of the wind power plant indicated that for the most advantageous value of the fundamental wind velocity V_a the wind power plant operates at exactly half load, that is, with a capacity of $e/2$. The corresponding wind efficiency w is obtained by dividing by the total efficiency c of the wind power plant. Thus

$$w = \frac{e}{2c} \tag{9}$$

where

for $\lambda = 5$ we have $c = 0.36$
for $\lambda = 6$ we have $c = 0.33$
for $\lambda = 7$ we have $c = 0.29$

For a wind having velocity V_a the energy per m² of cross section, expressed in kW, is :

$$W = 0.000615\, V_a^3$$

so that

$$V_a^3 = \frac{w}{0.000615} = \frac{e}{0.00123\, c}$$

whence

$$V_a = \sqrt[3]{\frac{e}{0.00123\, c}} \tag{10}$$

I have calculated these fundamental wind velocities for tip-speed ratios of $\lambda = 5$, 6, and 7, and have summarized the results in the following table :

Wind efficiency, kWh/m² per year	*1 000*	*1 500*	*2 000*	*3 000*	*4 000*	*6 000*	*8 000*	*10 000*
				V_a in m/sec				
For $\lambda = 5$	7.34	8.40	9.24	10.57	11.65	13.3	14.7	15.8
For $\lambda = 6$	7.57	8.67	9.53	10.93	12.00	13.8	15.1	16.3
For $\lambda = 7$	7.89	9.05	9.95	11.4	12.54	14.36	15.8	17.1

The torque M which can be transmitted from the wind wheel shaft by a single drive mechanism (chain drive) appears in these equations with a value which must be considered maximal in the present state of the art, for low rotation rate of wind power plant shafts. However, there will be progress in this, as in everything else, so that we must also give these equations in a form in which the torque M appears with no fixed value. In this case the equations are the following:

$$E = z\,Mn/146105 \tag{11}$$

$$n = 146105\,E/zM = 19.1\,\lambda\,V_a/D \tag{12}$$

$$D = \sqrt[3]{1.436\,\lambda\,V_a\,qz\,M/\eta\,Q} \tag{13}$$

On the basis of equations (5), (7), and (8), I have computed the principal technical data for those wind power plants which can be optimally designed for locations with wind capacity Q = 1 000-10 000 kWh/m² per year. Three wind power plants are shown for each wind capacity, calculated for tip-speed ratios of $\lambda = 5$, 6, and 7.

The first fact that is apparent is that the design of a wind power plant for such a system is not worth while for a tip-speed ratio of $\lambda = 7$, since it would be more expensive than the wind power plant designed for $\lambda = 6$ and only generate an equal output.

The second fact is that as between the wind power plant with tip-speed ratios of $\lambda = 5$ and $\lambda = 6$, the latter does not produce a sufficiently greater output to justify its greater cost. The latter therefore would be worth designing only because its output still is greater for the same wind conditions. The specific output would be cheapest for the wind power plant with $\lambda = 5$,. so that the Hungarian 200 kW wind power plant would be built with this tip-speed ratio.

For $z = 1$ and Q in the range 1 000-10 000 kWh/m² per year the generator size remains in the range 208-860 kW. Larger wind power plants can be designed only with an increase in z. In the present state of the art $z = 6$ appears to be the maximum value. For $z = 6$ and Q in the range 1 000-10 000 kWh/m² per year, wind power plants can be constructed with generators having E = 690-2 470 kW, and their annual output will be 1 050 000 to 3 750 000 kWh.

Is it possible to build still larger wind power plants? As we have seen, the greatest obstacle to the construction of larger wind power plants is the primary section of the speed-up transmission. As the progress of technology makes possible larger values of zM, it will become possible to build larger wind power plants of this type. Building a larger wind power plant means the same as placing the shaft of the wind wheel at a greater elevation. The first wind power plant shown in the table, with a capacity of 208-272 kW, has a shaft located about 35 m above ground level, where there is almost no turbulence, and the wind energy is also 50 per cent greater than that measured at 15 m. This is one reason for building as large wind power plants as possible. The other reason is that for the construction of larger wind power plants the specific investment cost is decreased, so that a cheaper output is obtained.

The entire speed-up transmission can be eliminated by driving a multi-pole generator directly from the wind wheel shaft. Here there are no problems of torque transmission. There are, however, limitations here as well, resulting from the limitation in the number of generator poles and therefore in rotation rate. The maximum number of poles which can be used with acceptable dimensions is 300, which corresponds to $n = 20$ rpm. Mihály Gohér has designed such a 300-pole generator and the resulting dimensions are feasible. Nevertheless, we shall consider for the present only generators with a maximum of 240 poles, since many of these have already been constructed in various parts of the world. The rotation rate of the wind wheel for such a wind power plant will therefore be $n = 25$ rpm. The calculations for such a wind power plant are carried out as follows: knowing Q we select λ, which at the same time determines the values of V_a and q. We calculate e from equation (1) and obtain

$$u = \lambda\,V_a$$

and

$$D = \frac{60 \cdot u}{n\,\pi} \tag{14}$$

from which we can now obtain the magnitude F of the wind wheel area. The generator capacity is therefore $E = Fe$ and the annual output is found from this to be 8 760 qE.

We must therefore start with the possible rotation rate n. This is a function of the feasible number of poles. It is seen from equation (14) that the diameter D of the wind wheel increases as n decreases and as u increases. Since u depends most strongly on λ, this must be as large as possible. A sample calculation will make this clear:

At a location with a wind capacity of Q = 1 000 kWh/m² per year:

if $\lambda = 5$ and $n = 25$ rpm, then:
D = 28 m, E = 108 kW, and annual output is 164 000 kWh

if $\lambda = 6$ and $n = 25$ rpm, then:
D = 34.7 m, E = 166 kW, and annual output is 230 000 kWh

if $\lambda = 7$ and $n = 25$ rpm, then:
D = 42.3 m, E = 248 kW, and annual output is 302 000 kWh.

It is probable that this result would be further increased by choosing $\lambda = 8$ and 9, which can be considered for location with lower values of wind capacity Q. For such values of λ, however, I did not have at my disposal the suitable η, V_a, and q values, and I have therefore left them out of my calculations for the time being. Since the above sample calculation gave the best values for $\lambda = 7$, I have computed and shown in table 2 the principal dimensions of the

Table 1

Wind efficiency in kWh/m² per year	λ	z = 1				z = 6			
		Wind wheel diameter D in meters	Wind wheel rotation rate n in rpm	Generator size E in kW	Wind power plant capacity in kWh per year	Wind wheel diameter D in meters	Wind wheel rotation rate n in rpm	Generator size E in kW	Wind power plant capacity in kWh per year
1 000	5	38.7	18.3	208	314 000	70.3	10.0	690	1 050 000
	6	41.64	20.9	240	331 000				
	7	44.65	23.6	272	332 000				
1 500	5	35.4	22.6	260	396 000	64.3	12.5	862	1 320 000
	6	38.04	26.1	300	415 000				
	7	40.88	29.6	340	415 000				
2 000	5	33.2	26.55	306	465 000	60.2	15.0	1 035	1 570 000
	6	35.7	30.6	352	486 000				
	7	38.3	34.8	400	488 000				
3 000	5	30.2	33.46	384	582 000	55.1	18.4	1 270	1 930 000
	6	32.62	38.4	442	610 000				
	7	35.0	43.5	500	610 000				
4 000	5	28.45	39.1	450	683 000	51.7	21.5	1 480	2 250 000
	6	30.54	45.0	516	714 000				
	7	32.87	51.0	585	715 000				
6 000	5	25.9	49.0	564	855 000	47.1	27.0	1 860	2 820 000
	6	28.0	56.5	650	900 000				
	7	30.0	64.0	737	905 000				
8 000	5	24.4	57.6	662	1 000 000	44.4	31.6	2 180	3 320 000
	6	26.2	66.2	760	1 050 000				
	7	28.2	74.8	860	1 050 000				
10 000	5	23.2	65.0	746	1 140 000	42.2	35.8	2 470	3 750 000
	6	25.0	75.0	860	1 190 000				
	7	26.84	85.0	980	1 195 000				

maximum constructible wind power plants for wind capacity values of $Q = 1\,000$-$10\,000$, from which it is apparent that multi-pole generators are more advantageous even for a location with a wind capacity of $Q = 2\,000$ kWh/m² per year and become still more advantageous for higher values. For this system with $\lambda = 7$, generator capacity values of as much as $E = 8\,000$ kW can be achieved, which is more than three times the value obtainable with a speed-up transmission. The only drawback lies in the large dimensions and weight of the multi-pole generator, which can be seen from the table. (Data on the generators was also provided by Mihály Gohér.) Here also we find valid the rule of experience that the greater the size of the unit the smaller the specific investment costs, so that here also it is most advantageous to build the largest designable unit for the location with the specified wind capacity. This will produce

Table 2. Wind power plants with multi-pole generators

Wind capacity (kWh/m² per year)	Tip-speed ratio (λ)	Fundamental wind velocity V_a (m/sec.)	Wind wheel area F (m²)	Wind wheel diam. D (meters)	Wind wheel circumference velocity u (m/sec)	Annual average capacity of wind power plant (kWh/year)	Generator							
							Capacity E (kW)	n (rpm)	Number of poles	Diam. D_b of external structure (mm)	Stator caliber D_b (mm)	Axial length L of rotor (mm)	Pole pitch (mm)	Weight G (tons)
1 000 .	7	7.91	1 405	42.3	55.37	302 000	248	25	240	6 000	5 000	120	65.4	20
1 500 .	7	9.05	1 848	48.5	63.35	592 000	485	25	240	6 000	5 000	240	65.4	40
2 000 .	7	9.95	2 240	53.4	69.65	960 000	788	25	240	6 000	5 000	400	65.4	60
3 000 .	7	11.4	2 923	61.0	79.8	1 880 000	1 540	25	240	6 000	5 000	800	65.4	80
4 000 .	7	12.54	3 547	67.2	87.78	3 040 000	2 500	25	240	6 000	5 000	1 300	65.4	110
6 000 .	7	14.36	3 237	64.2	100.52	4 160 000	3 400	30	200	8 000	6 960	650	109.0	120
8 000 .	7	15.8	3 904	70.5	110.6	6 460 000	5 300	30	200	7 100	6 000	1 500	94.0	165
										8 000	6 960	1 040	109.0	155
10 000 .	7	17.1	4 572	76.3	119.7	9 900 000	8 000	30	200	8 000	6 960	1 500	109.0	200
			3 740	69.0		8 000 000	6 550	33.3	180	7 100	6 000	1 500	105.0	165

the cheapest energy, with which no energy production system working on heat energy will be able to compete.

The wind power plant systems in which the wind wheel first produces an intermediate power to drive a current-producing generator, and the energy to be transmitted to the power supply system is produced only by this generator, all suffer from the defect of being expensive and having high power output costs. The intermediate power is usually direct current or hydraulic pressure. By contrast, the wind power plant which produces network current directly always remains the only system which can be cheap and competitive in the production of electrical energy to be fed into a power supply network. Between the two types of systems examined in detail it is mainly the latter, the multi-pole generator wind power plant, which can be considered the modern wind power plant of future progress.

Summary

In Hungary, an experimental wind power plant is being constructed. This plant is located at a site having a wind power of 1 120 kWh/m² per year. The elevation of the wind wheel center line is 35 m above ground level. The wind wheel is fitted with four fixed-pitch blades having an external diameter of 36.6 m. Its primary speed-up gear uses a chain drive, while the secondary one contains a spur gear. The coupled asynchronous alternator is rated at 1 000 rpm. In order to protect the wheel against overload, it will be turned out of wind automatically. The said wind power plant operates fully automatically, without attendance, and will yield 320 000 kWh per year.

The paper outlines the possibilities of further development considering various wind powers. The proposed calculation method of establishing the optimal dimensions shows that at sites where wind powers from 1 000 to 10 000 kWh/m² per year occur, power plants having outputs from 208 to 860 kW containing a single-chain primary drive may be designed, yielding from 331 000 to 1 190 000 kWh per year respectively. For the same wind energy sources, by adopting a six-chain primary drive (which is held to be the upper limit) wind power plants having an output from 690 to 2 470 kW and yielding from 1 050 000 to 3 750 000 kWh per year could be designed. The capacity of wind power plants of this type is, therefore, strictly limited.

The major obstacle to development lies in the speed-up gear. This may be overcome by direct-driven multi-pole synchronous alternators. The paper presents a calculation method applicable for these machines, too. Wind power plants provided with a multi-pole alternator and operating at a tip-speed ratio of $\lambda = 7$ may be built for wind powers ranging from 1 000 to 10 000 kWh/m² per year, with outputs of from 240 to 8 000 kW and yielding from 302 000 to 9 900 000 kWh per year, respectively. The runner rotates at 25 to 33.3 rpm, the number of poles being from 240 to 180, respectively. The only drawback is the great weight of the alternator, varying from 20 to 200 metric tons. This is, however, rather a minor hindrance as, in turn, the speed-up gear can be eliminated so that it does not impede further development. By increasing the tip-speed ratio (λ), further success may be achieved and a best value for λ obtained, rendering optimal dimensions and output of the wind power plant. In the future, wind power plants equipped with multi-pole alternators will be favored.

CENTRALES ÉOLIENNES APPROPRIÉES POUR ALIMENTER UN RÉSEAU DE DISTRIBUTION D'ÉNERGIE

Résumé

En Hongrie, on est actuellement en train de construire une centrale éolienne expérimentale. Cette centrale se trouve en un site où l'énergie éolienne annuelle est de 1 120 kWh/m². La hauteur de l'arbre de la roue est de 35 m au-dessus du sol. Celle-ci est dotée de 4 pales à pas fixe et leur diamètre extérieur est de 36,6 m. Le train d'accélération primaire est constitué par une commande à chaîne tandis que le train secondaire contient un pignon à denture droite. Le nombre de tours de l'alternateur à synchrone couplé sur cette roue est de 1 000 à la minute. Pour empêcher la roue de s'emballer, elle est dotée de la mise en drapeau automatique. Cette centrale fonctionne d'une manière tout à fait automatique, sans inspection, et donnera 320 000 kWh par an.

Le mémoire souligne les possibilités de développement extérieur applicables aux diverses formes d'énergie éolienne. La méthode de calcul que l'on propose pour établir les dimensions idéales, démontre qu'en des lieux où une énergie éolienne de 1 000 à 10 000 kWh/m² par an se produit, des centrales ayant des puissances de 208 à 860 kW et contenant une commande primaire à chaîne unique peuvent être mises au point, donnant de 331 000 à 1 190 000 kWh par an respectivement. Pour les mêmes sources d'énergie éolienne, en adoptant une commande primi-

tive à 6 chaînes que l'on considère comme la limite supérieure, des centrales éoliennes ayant une puissance installée de 690 à 2 470 kW et donnant de 1 050 000 à 3 750 000 kWh par an, pourraient être mises au point. La capacité des centrales de ce type est donc strictement limitée.

Le gros obstacle au développement est constitué par le train accélérateur. Ceci peut être éliminé en se servant d'alternateurs synchrones multipolaires. On indique, dans le mémoire, une méthode de calcul applicable à ces machines. Les centrales éoliennes dotées d'un alternateur multipolaire et ayant un paramètre de fonctionnement de $\lambda = 7$ peuvent être construites pour des énergies éoliennes allant de 1 000 à 10 000 kWh/m² par an avec des débits de 240 à 8 000 kW et donnant de 302 000 à 9 900 000 kWh par an respectivement. La roue tourne à 25-33,3 tour/minute, le nombre des pôles étant de 240 à 180 respectivement. Le seul inconvénient est constitué par le poids considérable de l'alternateur, compris entre 20 et 200 tonnes métriques. C'est cependant un défaut assez peu important car, d'autre part, le train d'accélération peut être éliminé et ne s'oppose donc plus au progrès. En augmentant le rapport de puissance λ on pourra réaliser et obtenir une valeur idéale, ce qui permettra d'obtenir des dimensions parfaites et on aura un bon débit de la centrale éolienne. A l'avenir les centrales éoliennes dotées d'alternateurs multipôles devront être choisies de préférence.

WIND TURBINES OF NEW DESIGN IN JAPAN

Tomijiro Moriya * *and Yoshio Tomosawa* **

In Japan there have been, since early times, wind turbines of a very simple type. Even nowadays, in certain districts of Japan, many wind turbines for irrigation, made principally of wood, or bamboo, and straw mat, are still to be seen.

The acceptance of modern engineering concepts in wind turbine design can be said to date from shortly after the end of the Second World War, when Japan was extremely short of sources of energy. Since that time, however, fire and hydroelectric power plants have been added year by year and the problem of the shortage of energy has begun to be solved, while wind power plants have not been carried into effect on a large scale. But we require wind power plants for other purposes, such as supplying electric power to isolated islands, isolated villages or unattended wireless relay stations where wind power can be used to advantage.

The wind turbines which we are now going to describe are of a new type, first designed and manufactured for use by the Antarctic Observation Party of Japan in 1956. A wind turbine which is to be used in such an extremely cold region, and which must stand up to heavy storms, must be specially designed so as to be free from the need for maintenance work for long periods and so as to operate reliably even in stormy weather. For this purpose, the mechanism for varying the pitch angles of the blades should be as simple as possible and the parts needing some lubricant should be as few as possible. This wind turbine, unfortunately, drifted away while still packed awaiting transport to the base. The design, however, had certain advantages, and the Maritime Safety Board of the Japanese Government, after considering the design, decided to adopt this type of wind turbine to supply electric power to a lighthouse on Futaoi Island, an isolated island off Shimonoseki.

As the Antarctic wind turbine, mentioned above, could give us no data on its resistance to cold, we erected a small wind turbine in August 1960 for the purpose of a winter endurance test, near the top of Mt. Norikura, about 3 000 m above sea level, where the temperature in winter falls as low as —50°C or lower.

In the present paper, we are going to describe the mechanism for keeping the rotational speed constant, the practical utilization and the winter endurance test of these wind turbines.

The mechanism

These wind turbines are capable of maintaining constant rotational speeds regardless of wind speeds above design speed and of loads applied to the shaft, by varying the pitch angle of the blades automatically by means of a very simple mechanism utilizing the blades as a governor.

A diagramatical sketch of the mechanism is shown in figure 1.

The blade can be rotated, that is, the pitch angle of the blade can be changed about an axis, which is set with a backward tilt at a small angle δ, called the first tilting angle in figure 1. The blade is set so as to have the second tilting angle in relation to the axis mentioned above, in order to produce a moment about this axis due to the centrifugal force exerted on the blade when the turbine is revolving.

Let dm be the mass element of a blade situated at a point (X, Y, Z) in relation to the co-ordinate axes, where Y-axis coincides with the shaft of the wind turbine, and YZ-plane contains the axis, about which the pitch angle of the blade can be changed. The co-ordinates (X, Y, Z) can be expressed as

$$X = r \cos \varphi$$
$$Y = r \sin \varphi + \zeta \sin \delta$$
$$Z = r \sin \varphi \sin \delta + \zeta \cos \delta$$

the notations of which may be understood with the aid of figure 2. Then the moment about the varying-pitch-axis due to the centrifugal force exerted on the mass dm when the wind turbine revolves at an angular velocity ω is

$$dM_F = -\frac{1}{2} w^2 [r^2 \sin (2\varphi) \cos^2 \delta + r \zeta \cos \varphi \sin (2\delta)] \, dm$$

Therefore the whole moment for one blade is:

$$M_F = -\frac{1}{2} w^2 [\cos^2 \delta \int r^2 \sin (2\varphi) \, dm + \sin (2\delta) \int r \zeta \cos \varphi \, dm]$$

the integration being extended for the whole blade.

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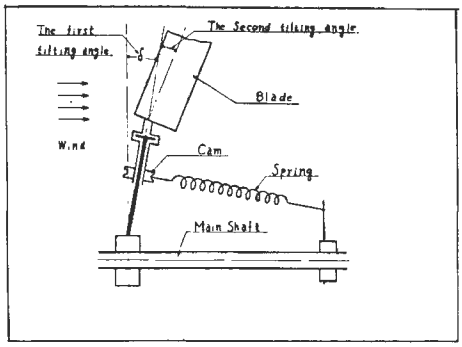

Figure 1

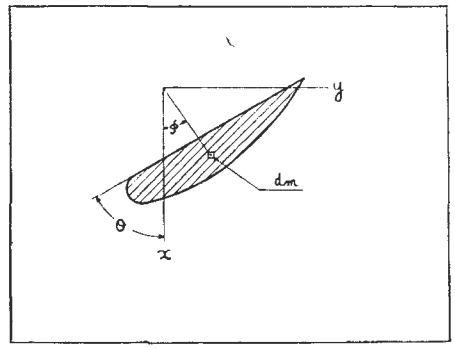

Figure 3

This moment is exerted in such a way as to decrease φ. If we set the blade so that the moment acts to increase the pitch angle, that is, the moment acts so as to rotate the blade towards full feathering, and if we designate the angle defining the position of the blade by θ, so that when the blade is in full feathering $\theta = 90°$, then the moment due to centrifugal force at a given angular velocity is shown, for example, as curve I in figure 4. The air force exerted on the blade, moreover, produces a moment about the same axis. Therefore, the resultant moment due to both centrifugal force and air force becomes that represented by curve II in figure 4.

We counterbalance the moment by a spring through a cam for the whole range of θ, so that the wind turbine can operate at any value of θ by balancing the moments one against another. The value of θ can be determined automatically, so that the torque of air forces about the shaft of the wind turbine at the predetermined angular velocity is balanced by the load applied to the shaft.

If, by chance, the angular velocity changes, for instance, if it is increased, then the moment due to centrifugal force exceeds the moment due to spring force and, as the pitch angle increases, that is, as the angle of attack of relative air flow and consequently the air force decrease, the torque of the air force decreases and the angular velocity also decreases until it reaches the predetermined one. At this instant, the moments about the varying-pitch-axis due to both centrifugal plus air force and spring force balance each other, and no more changes in blade angle can occur and the rotational speeds can be kept constant. If wind speeds or shaft loads change, the final blade angle is different from the initial one, because the wind turbine always revolves at constant speed, balancing the air force torque with the shaft load by automatically adjusting the blade angle.

Thus the wind turbine maintains a constant number of revolutions irrespective of the wind speeds and shaft loads.

Tests and the utilization features of the wind turbines

Wind tunnel tests of a small wind turbine

In order to test the operational features of the mechanism for changing the pitch angle of the blades automatically, we tested, in a wind tunnel, a small wind turbine, which is designed to supply electric power to unattended wireless relay stations. The specifications for this test were:

Diameter	1.2 m
Number of blades	3
Profile of the blade	Thin cambered plate
Design wind speed	7 m/sec
Design rotational speed	350 rpm
Design output power of the wind turbine	50 watts
Electric generator output	15 watts, D.C. 7 volts
Electric load in this test	10 watts

We tested this wind turbine in a wind tunnel, changing the wind speeds from 0 to 36 m/sec, and we collected data indicating the relations between

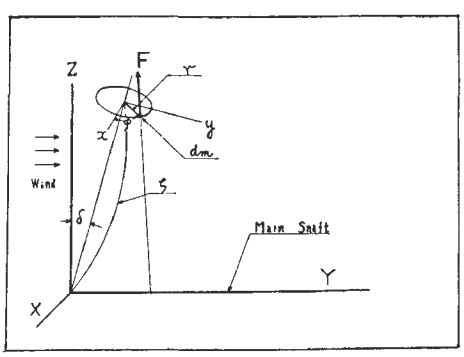

Figure 2

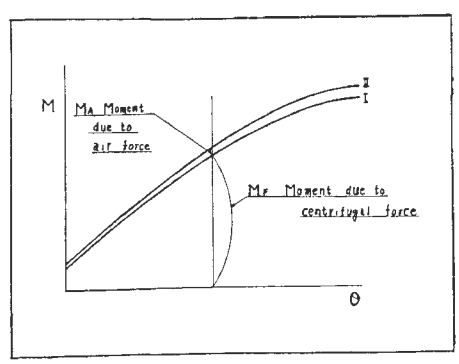

Figure 4

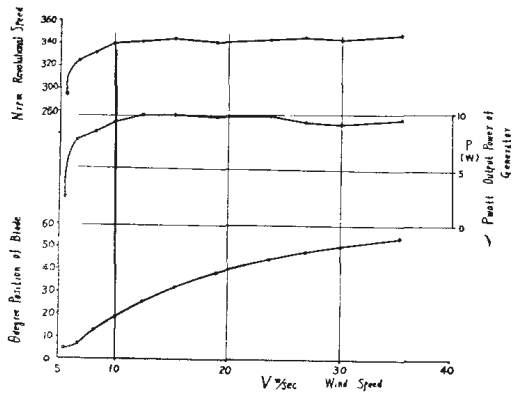

Figure 5

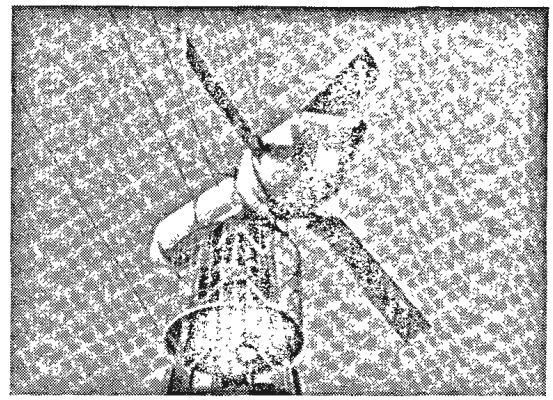

Figure 7

the various wind speeds, rotational speeds, pitch angle of the blades, and power output.

The mechanism which is used in this wind turbine for changing the pitch angle of the blades automatically is the same in principle as the one illustrated in the previous paragraph, but is slightly different in minor points. This mechanism proved so satisfactory that the rotational speed was kept nearly constant at from 340 to 350 rpm as shown in figure 5.

Utilization conditions of the wind turbine to supply electric power to a lighthouse on Futaoi Island

The specifications of the wind turbine are:

Diameter	7 m
Number of blades	3
Profile of the blade	Clark Y
Design wind speed	7.5 m/sec
Design rotational speed	65 rpm
Design output power of the wind turbine	2.5 kW
Electric generator output	2.1 kW D.C. 125 volts
Battery	420 ampere-hours
Load on this installation	maximum, 800 watts

In 1958, we established this wind turbine at the top of a hill, about 1 200 m north of and about 30 m above the lighthouse, which is situated on the southwest end of Futaoi Island. This site is windy all year round, especially in winter, because the west wind is predominant in this district. Figure 6 shows the relative positions of the lighthouse and the wind turbine, seen from the east side, with the lighthouse in the left-hand portion of the figure.

Figure 7 is a close-up view of the wind turbine. This wind turbine is still in operation without serious troubles, in spite of having been struck by typhoons on several occasions, and we have obtained many data regarding the relations between wind speeds, rotational speeds, and power output. Some of these records are shown in figure 8, and from these records, we see that the rotational speeds are kept at between 55 and 65 rpm, while the wind speeds vary between 6.5 m/sec and 10 m/sec. This fluctuation in rotational speeds is unsatisfactory. The cause of this fluctuation is to be found in the fact that the wind turbine is situated to some extent in the path of an upwind along the cliff of the west side of the island, producing a constant yawing motion, which causes the rotational speeds to be unsteady. When the yawing motion does not occur, according to the direction of the wind, the wind turbine operates steadily, while the mechanism itself has proved to be satisfactory, operating at constant speed irrespective of wind speeds and shaft loads.

Figure 6

Cold proof endurance test by a small wind turbine

We erected a small wind turbine, 1.2 m in diameter, near the top of Mt. Norikura in order to observe its reactions to extreme cold. The wind turbine was

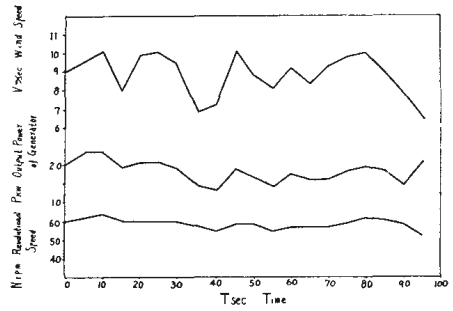

Figure 8

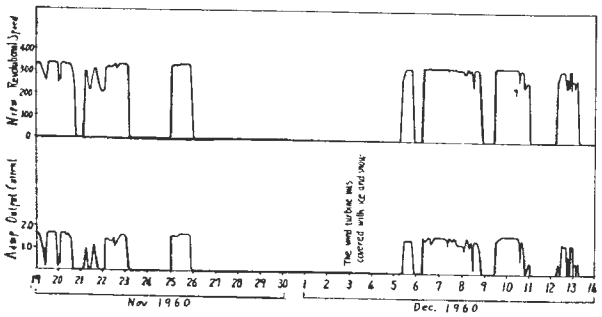

Figure 9

set up in August 1960 and is now in operation recording the output of electric current. Some of these records are shown in figure 9, in which the lower curve represents the output of electric current and the upper curve rotational speeds, as calculated from the current output.

Figure 10

As a manometer of the usual type could not be depended on in such cold and icy weather, we did not equip this turbine with a manometer, and we must be satisfied with the current output figures alone. Unfortunately we were not able to record the relation between wind speeds and rotational speeds.

In the curve of current output, when the current shows 0, the wind speed is supposed to be less than 5.5 m/sec, and when the current shows about 1.7 amperes, the wind speed is above the design speed. Figure 10 shows the conditions when the wind turbine was covered with ice and snow on 3 December 1960. The wind turbine stopped operation temporarily, and operated again steadily after two days.

We note that the wind turbine can operate safely in cold weather, and even though it may stop operation temporarily, there is no danger of its overrunning.

Conclusion

The mechanism for keeping the rotational speeds of the wind turbine constant irrespective of variations in wind speed and shaft loads has been proved satisfactory both by wind tunnel tests and by practical utilizations, although the mechanism itself is very simple.

The winter endurance test has also shown that icing does not produce dangerous conditions, though when icing is very thick the operation may be stopped temporarily.

In this paper, we have presented the formula for calculating the moment about a varying-pitch-axis due to centrifugal force, which must be balanced by the moment due to spring force together with that due to air force. We have also introduced some data of wind tunnel tests and practical applications.

As wind conditions depend heavily on local geographical features, such factors must be taken into consideration when setting up wind turbines.

Summary

Newly devised wind turbines, capable of maintaining a constant rotational speed, regardless of wind speeds and variations in the load applied to the shaft, have been adopted by the Maritime Safety Board of Japan to supply electric power to lighthouses on isolated islands. The mechanism is very simple. The pitch angle of a blade can be changed about an axis, which is set with a backward tilt at a small fixed angle. The blade is set so as to have another angle of tilt in relation to this axis, in such a way as to produce a moment about this axis due to the centrifugal force exerted on the blade when the turbine revolves. This moment is balanced by the moment produced by a spring force through a cam. We can design in such a way that these two moments balance each other at any position of the pitch angle at a predetermined rotational speed. When wind speeds or loads vary, the pitch angle of the blade must be changed in order to keep the rotational speeds constant. This can be done automatically by shifting the point of balance. Wind turbines with this simple mechanism prove very satisfactory, and even in typhoon conditions, the rotational speeds can be maintained at the same rate as for the wind speeds for which they were designed.

We made, first of all, wind tunnel experiments in order to test the operational features of the mechanism which changes the pitch angle of the blades automatically. The results were satisfactory.

In 1958, making use of the same mechanical principle, we established a wind power station for

the purpose of supplying electric power to a lighthouse on Futaoi Island, which has also given satisfactory results and is now in operation.

In 1960, we built a small wind turbine, 1.2 m in diameter, near the top of Mt. Norikura, about 3 000 m above sea level, in order to test endurance under very cold winter conditions. The results showed that, though the turbine stopped temporarily owing to freezing, it operated safely on the whole without running into dangerous over-revolutions.

TURBINES ÉOLIENNES D'UN NOUVEAU TYPE AU JAPON

Résumé

La commission de la sécurité maritime du Japon vient d'adopter des turbines éoliennes d'une conception nouvelle, destinées à fournir de l'énergie électrique aux phares situés sur des îles isolées. Elles se caractérisent par le fait que leur vitesse de rotation peut être tenue constante par un mécanisme très simple, quelles que soient la vitesse du vent et la charge imposée à leur arbre. On peut faire varier le pas de chaque aube autour d'un axe qui est incliné vers l'arrière d'un petit angle fixe. L'aube est montée de telle sorte que son inclinaison propre soit différente par rapport à ce même axe, de manière à la faire apparaître un moment sous l'action de la force centrifuge qui est mise en jeu lorsque la turbine tourne. Ce moment est compensé par celui que fournit un ressort agissant par l'entremise d'une came. La turbine peut être réalisée de telle sorte que ces deux moments s'équilibrent mutuellement quel que soit le pas, à une vitesse angulaire donnée.

Quand la vitesse du vent ou les charges varient, le pas de l'aube doit être changé de manière à maintenir constante la vitesse angulaire du système. Ceci peut se réaliser automatiquement en modifiant la position d'équilibre. Avec ce mécanisme extrêmement simple, les turbines éoliennes se sont avérées fort satisfaisantes et, même en plein typhon, on a réussi à maintenir le régime de rotation constant et conforme à celui qui était fixé par le projet.

On a commencé par exécuter des essais en tunnel aérodynamique pour vérifier les caractéristiques de fonctionnement du mécanisme qui sert à changer automatiquement le pas. Les résultats ainsi obtenus ont été satisfaisants.

On a réalisé, conformément aux mêmes principes, une centrale de production d'énergie éolienne dès 1958, laquelle était destinée à fournir le courant au phare de l'Ile Futaoi et qui a donné, elle aussi, des résultats satisfaisants et se trouve actuellement en fonctionnement.

En 1960, nous avons construit une petite turbine éolienne de 1,2 m de diamètre, installée près du sommet du Mont Norikura, à 3 000 m environ au-dessus du niveau de la mer, de manière à pouvoir la soumettre à des essais d'endurance par temps très froid. Les résultats ont démontré que, bien qu'elle se soit coincée une fois en raison de la gelée, elle a fonctionné de manière régulière dans l'ensemble, sans jamais s'emballer d'une manière dangereuse.

CONSIDÉRATIONS SUR UN ASPECT NATUREL DE L'AMÉNAGEMENT DE L'ÉNERGIE DU VENT

P. Santorini *

Considérons deux fluides, de densités d_a et d_e, en mouvement et interposons, dans leur flux d'écoulement, des dispositifs mécaniques, d'aires respectives F_a et F_e, servant à capter l'énergie cinétique de ces fluides. Il est alors facile de démontrer que :

$$F_e : F_a = d_a : d_e \qquad [1]$$

En considérant, comme fluides, l'air (indice a) et l'eau (indice e), il s'ensuit, avec les valeurs connues des densités respectives, qu'on a approximativement

$$F_a = 800\, F_e \qquad [2]$$

Donc, la captation de la même puissance éolienne exige des installations énormément plus volumineuses que dans le cas des forces hydrauliques.

Compte tenu de la relation [2] et des grandeurs des rayons de rotation des pièces motrices en mouvement, on peut être ensuite enclin à penser que l'énergie du vent est trop « diluée » pour pouvoir permettre, pour des raisons purement mécaniques, la construction de machines de puissance comparable à celle des moteurs hydrauliques.

On peut penser également que la nature même du souffle du vent, se manifestant non sous forme d'un écoulement continu mais, très souvent, sous forme d'une suite de rafales et de tourbillons se propageant en diverses directions, est telle que son utilisation pratique, dans une seule machine à l'échelle industrielle, imposerait des dimensions onéreuses hors de proportion avec la puissance développée.

En principe, il y a tout lieu de procéder à l'aménagement de la puissance du vent dans des conditions techniques et économiques qui lui sont intimement particulières.

En particulier, il y a intérêt à répartir la puissance totale à aménager sur le nombre correspondant de moteurs à vent du type produisant le kWh au prix le meilleur marché : à l'inverse de ce qui se passe ailleurs (turbines hydrauliques, diesels, etc.), ce sera un type de puissance unitaire plutôt faible, de l'ordre, peut-être, de 5 kW seulement [1] pour un moteur à axe horizontal, et de beaucoup moins encore, pour un moteur à axe vertical, dérivé du remarquable rotor de Savonius (1).

Dans ce même esprit d'économie, il devient intéressant d'installer ces moteurs à vent à très faible hauteur au-dessus du sol : tout le monde sait que plus on monte haut, plus grande est la vitesse du vent, mais la statique des constructions enseigne que chaque dizaine de mètres de plus en hauteur se paye d'une façon nullement en rapport avec le surplus de l'énergie ainsi captée.

En ce qui concerne l'emplacement nécessaire, on peut remarquer qu'il existe, dans chaque pays, un certain pourcentage du territoire ne pouvant servir à aucune utilisation ou exploitation productive : terrains rocheux, arides, versants de montagnes à plus ou moins forte déclivité, petits îlots inhabitables, etc. Sur toutes ces étendues, inutilisables à d'autres fins, le souffle du vent se fait sentir, même au ras du sol, en pure perte. Rien donc ne s'oppose à couvrir systématiquement l'étendue entière de ces régions, autrement inutilisables, par une espèce de « forêt » de petits « éléments éoliens », pourvus, chacun, de sa génératrice particulière, débitant leur contribution en courant électrique sur un collecteur général.

Il semble qu'il ne viendrait jamais à personne l'idée d'hésiter de planter des arbres ou de semer du blé sur des terrains de qualité convenable, quelque grande que soit leur étendue. Pourquoi ne ferait-on alors pas pareillement avec des batteries d'éléments éoliens, pour extraire d'un territoire aride et improductif l'immense quantité d'énergie électrique que génèrent, sur sa surface, les moindres brises du vent?

Il est clair qu'il s'agit, en l'occurrence, d'un principe fondamentalement différent de celui des puissantes machines isolées, dont l'installation, très coûteuse, n'est justifiée que pour de rares régions exceptionnellement favorisées par de fortes vitesses moyennes annuelles du vent. L'originalité de la présente suggestion consiste donc dans l'utilisation d'un très grand nombre de petits « éléments éoliens », installés, en guise d'une « forêt », l'un près de l'autre, presque au ras du sol, à peine à quelques mètres de hauteur, sur d'immenses étendues de terrain. Dans ces conditions particulières, ces petites machines, ayant l'aspect extérieur d'un petit cylindre à axe de rotation vertical, tournant, ce qui est d'une importance capitale, toujours dans le même sens, donc indépendamment des sautes dans la direction du vent, seront, par définition, plus solides que les énormes hélices des grandes machines à axe de rotation

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[1] Ce chiffre se base sur des offres réelles (janvier 1960) de constructeurs en mesure de livrer ces machines. Ainsi, pour l'aménagement de 10 kW, plusieurs constructeurs recommandaient l'installation, côte à côte, de deux moteurs de 5 kW chacun, au lieu d'un seul de 10 kW.

horizontal. Ces « éléments éoliens » pourront, sans aucun inconvénient, fonctionner à partir de la brise la plus légère jusqu'aux plus fortes rafales, là où les hélices doivent être mises « en drapeau », permettant ainsi la transformation intégrale en énergie électrique de tous mouvements de la masse de l'air dans une couche basse suivant les dénivellations du terrain, conduisant ainsi à l'expression aussi imagée que pittoresque d'un « écrémage éolien d'un territoire ». Il deviendrait alors, peut-être, possible de gagner, par les grandes surfaces de terrain, se trouvant disponibles partout, ce que les partisans des puissantes machines cherchent à obtenir, par unités isolées, dans de très rares régions exceptionnellement favorisées par de grandes vitesses moyennes annuelles du vent.

Il s'agit sans doute d'une nouvelle conception du problème qui nous occupe. En hydraulique, on a les hautes et les très basses chutes, et il ne viendrait aujourd'hui à personne l'idée d'écarter les chutes de quelques mètres de hauteur pour la raison qu'une roue Pelton ne pourrait y être installée. La conception du problème de la présente proposition attend donc aujourd'hui, par analogie, son Kaplan des très basses chutes.

Chaque « élément éolien », en raison de ses dimensions géométriques très restreintes, travaille dans des conditions naturelles optima de rotation continue dans le même sens, sans avoir à subir l'orientation forcée des hélices à axe horizontal. La question du rendement, qui est inférieur à celui des hélices, ne joue pas dans le cas du vent gratuit comme source motrice, puisque le critère principal est le prix de revient du kWh produit (2).

La méthode présente est basée sur une suite de raisonnements découlant de l'interprétation de la relation [2], connue évidemment depuis longtemps. En Grèce, il n'a pas fallu ces raisonnements théoriques pour arriver pratiquement à la même conclusion de la multitude des petits moteurs à vent : en effet, sur le seul plateau restreint de Lassithion, en Crète, 10 000 (dix mille) petits moulins à vent à axe horizontal sont installés, presque au ras du sol, pour le pompage de 35 à 50 m³ d'eau d'une profondeur de plus de 15 mètres, en 9 à 10 heures par jour, soit à raison de 1 litre d'eau par seconde (3).

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Résumé

Étant admis que la captation de la même puissance éolienne exige des installations énormément plus volumineuses que dans le cas des forces hydrauliques; que l'énergie du vent est trop « diluée » pour pouvoir permettre la construction de machines de puissance comparable à celle des moteurs hydrauliques; que la nature même du souffle du vent, se manifestant non sous forme d'un écoulement continu mais, souvent, sous forme d'une suite de rafales et de tourbillons se propageant en diverses directions, est telle que son utilisation pratique, dans une seule machine à l'échelle industrielle, imposerait des dimensions onéreuses hors de proportion avec la puissance développée; qu'il y a intérêt à répartir la puissance totale à aménager sur le nombre correspondant de moteurs à vent du type produisant le kWh au prix le meilleur marché, ce type étant d'une puissance unitaire plutôt faible; que, dans ce même esprit d'économie, il devient intéressant d'installer ces moteurs à vent à très faible hauteur au-dessus du sol; qu'il existe, enfin, dans chaque pays, un certain pourcentage du territoire ne pouvant servir à aucune installation ou exploitation productive (terrains rocheux, arides, versants de montagnes à plus ou moins forte déclivité, petits îlots inhabitables, etc.) et que le souffle du vent s'y fait sentir, même au ras du sol, en pure perte, l'auteur propose de couvrir systématiquement l'étendue entière de ces régions, autrement inutilisables, par une espèce de « forêt » de petits « éléments éoliens », pouvus, chacun, de sa génératrice particulière, débitant leur contribution en courant électrique sur un collecteur général.

Dans ces conditions particulières, ces petites machines, dérivées du rotor de Savonius, ayant l'aspect extérieur d'un petit cylindre à axe de rotation vertical, tournant toujours dans le même sens, donc indépendamment des sautes dans la direction du vent, seront, par définition, plus solides que les énormes hélices des grandes machines à axe de rotation horizontal. Ces « éléments éoliens » pourront donc

fonctionner à partir de la brise la plus légère jusqu'aux plus fortes rafales, permettant ainsi la transformation intégrale en énergie électrique de tout mouvement de la masse d'air dans une couche basse suivant les dénivellations du terrain. Il deviendrait alors, peut-être, possible de gagner, par les grandes surfaces de terrain se trouvant disponibles partout, ce que les partisans des puissantes machines cherchent à obtenir, par unités isolées, dans de très rares régions exceptionnellement favorisées par de grandes vitesses moyennes annuelles du vent.

En Grèce, il n'a pas fallu ces raisonnements théoriques pour arriver pratiquement à la même conception d' « écrémage éolien d'un terrain » par une multitude de petits moteurs à vent : en effet, sur le seul plateau restreint de Lassithion, en Crète, 10 000 (dix mille) petits moulins à vent primitifs, à axe horizontal, sont installés, presque au ras du sol, pour le pompage de 35 à 50 m³ d'eau d'une profondeur de plus de 15 mètres, en 9 à 10 heures par jour, soit à raison de 1 litre d'eau par seconde.

CONSIDERATIONS ON A NATURAL ASPECT OF THE HARNESSING OF WIND POWER

Summary

This paper is based on the following assumptions. The harnessing of wind power requires installations of enormously greater bulk than those required for water power. Wind power is too diluted to permit the construction of machines comparable in power to hydraulic equipment. The very nature of the wind, which manifests itself, not in the form of a continuous flow, but often in the form of a series of gusts and vortices moving in various directions, is such that its practical utilization, in a single industrial-scale machine, would impose burdensome dimensions, out of proportion to the power developed. It would be of advantage to distribute the total power to be derived among the corresponding number of wind-driven generators of the type with the lowest energy cost per kWh. This type is of a rather low unit power. In the same spirit of economy, it would be advisable to install these wind-driven generators at very low altitudes above ground. Finally, a certain percentage of the area of every country—including rocky or arid terrain, mountain slopes that are more or less steep, little uninhabitable isles, and the like—cannot be used for any installation or other productive purpose; even at ground level, the potential wind power is completely lost. The author therefore proposes that the entire area of these regions be otherwise utilized and systematically covered by a kind of "forest" of small "wind power elements", each with its own generator, feeding its contribution in electric current into a common collecting grid.

Under these peculiar conditions, these little machines, derived from the rotor of Savonius, in the form of a small cylinder with a vertical axis of rotation, always turning in the same direction, and thus independently of the abrupt changes in wind direction, would be, by definition, more rational than the enormous propellers of great machines rotating about a horizontal axis. These "wind power elements" could thus operate over the entire range of wind speeds from the lightest breeze to the strongest blast, thus permitting the integral transformation, into electric energy, of all the movements of the air mass in the ground layer that follows the changing contours of the terrain. It would thus, perhaps, be possible to gain, by means of large areas of land, which are available everywhere, the same results as are sought by the partisans of powerful machines, by means of large units sited in very infrequent regions exceptionally favoured by high mean annual wind speeds.

In Greece, this theoretical reasoning has not been necessary to arrive practically at the same concept of "skimming off the wind power of an area" by means of a multitude of small wind machines. Indeed, on the single small plateau of Lassithion in Crete, there are 10 000 (ten thousand) primitive little windmills with horizontal axis, sited almost at ground level, to pump 35 to 50 m³ of water a day, from a depth of over 15 m, in nine or ten hours of daily operation, that is, at the rate of 1 litre of water a second.

A WIND-DRIVEN ELECTRICAL GENERATOR DIRECTLY COUPLED INTO AN A.C. NETWORK — THE MATCHING PROBLEM

L. H. G. Sterne * *and G. Fragoianis* **

The wind-driven generator system considered in this paper comprises a fixed-pitch windmill mechanically coupled (through a step-up gear) to an A.C. generator directly feeding into an A.C. network. The matching problem may be expressed as follows: given (*a*) the windmill diameter [1] and (*b*) the mean wind speed at the site, what is the optimum choice of (*a*) the gear ratio between windmill and generator and (*b*) the rated power of the generator?

If the wind speed were always some constant value, the choice of both these parameters would be simple; the gear ratio should be such that the windmill would operate at maximum efficiency (i.e., at a rotational speed at which it produces maximum power) and the rated power of the generator would be this maximum power precisely.

In practice, however, the wind speed at any known site varies widely over any substantial interval of time. As the rotational speed is more or less constant when the generator is coupled to an existing A.C. network, the range of operation of the windmill (in terms of the non-dimensional speed parameter) also varies widely and it is impossible to achieve maximum efficiency at all times.

Furthermore, if the rated power of the generator is sufficient to absorb the power available at the highest wind speeds, it will be unduly costly (and also heavy and this will add to the cost of the windmill tower) considering that, for nearly all the time, it will operate at lower power. Furthermore, the heating losses in the generator can be expected to increase with its size, and in consequence, the overall energy output will be less at lower wind speeds than for a smaller rated power. On the other hand, if a generator of very small rated power is chosen, a low total energy output will obviously result and the windmill itself will be costly in relation to the energy produced.

The optimum lies somewhere between these extremes; the question is "how substantial a fraction of the total time should the generator operate at its rated power?"

Many factors enter into this problem; some can readily be expressed in mathematical terms, others cannot. The purpose of this paper is to consider a few of the more obvious ones which can be so expressed.

The problem is really one of matching three sets of physical characteristics, namely, the power output of the windmill as a function of wind speed, the electrical power output of the generator as a function of the input mechanical power and the speed-duration function of the wind at the chosen site.

Power output from a windmill

In presenting results of wind-tunnel tests on windmill rotors, the mechanical power P extracted from the wind is, preferably, plotted against the cube of the wind speed V, instead of against the speed itself, as appears to be common practice. The reasons for this departure from convention are twofold: first, the latter method gives too great a prominence to the values at low wind speeds (which are usually of no practical importance anyway in that they are normally below the "cut-in" speed of the generator), and secondly, it is found, not surprisingly, that over a substantial range of speed the power output is close to being a linear function of V^3, and hence curve drawing is easier and interpolation more reliable. Figure 1 shows an idealized plot of the variation of power P against V^3.

The author also considers it to be more satisfactory in presenting results on windmill performance to reduce power and speed to non-dimensional terms so that tests at various rotational speeds and wind-

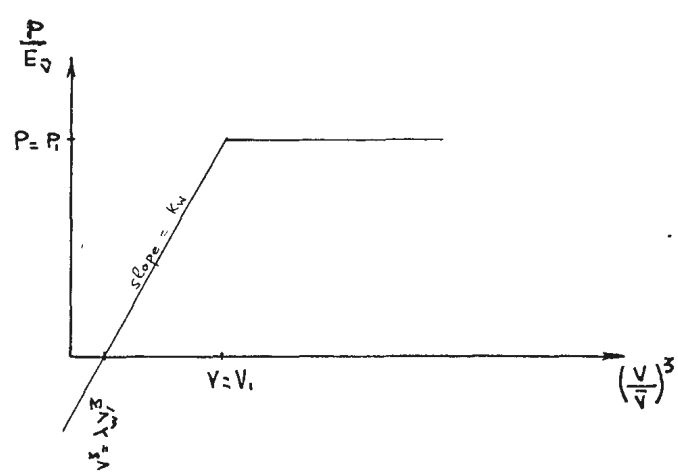


Figure 1

* Training Center for Experimental Aerodynamics, Rhode-Saint-Genèse, Belgium.

** Appendices by G. Fragoianis.

[1] Equally, the rated power could be taken as one of the given conditions and an optimum choice sought for the windmill diameter.

mill diameters tend to collapse on to a common curve.

In detail, it is recommended that the power coefficient

$$C_p = \frac{P}{\frac{\pi c}{8} \rho n^3 D^5}$$

is plotted against the cube of the non-dimensional wind speed parameter, i.e. against

$$\left(\frac{V}{n D}\right)^3$$

where P = output power of windmill measured in electrical units
c = the factor required to convert mechanical units into electrical units
ρ = air density
n = the rotational speed of the windmill rotor
D = the windmill diameter
V = the speed of the wind

If the power P is measured in mechanical units, c_p is then simply given by

$$c_p = \frac{P}{\frac{\pi}{8} \rho n^3 D^5} \qquad [1]$$

provided a self-consistent set of units is employed.

Results, presented in this form and obtained from tests made by G. Fragoianis in the low-speed subsonic wind tunnel at the Training Center for Experimental Aerodynamics are given in appendix A.

Up to a certain value V_1 of V, depending on the windmill design and Reynolds number, it appears that C_p varies linearly with $\left(\frac{V}{nD}\right)^3$.

For larger values of V, the form of curve of C_p against V varies considerably from test to test, depending apparently on both the design and Reynolds number. It would seem that the ideal arrangement is to choose a combination of design and Reynolds number so that C_p is a constant (C_{p1}) for $V > V_1$.

In the analysis given in this paper, it is assumed that matters have been arranged in this way so that

$$C_p = k_w = \frac{V^3 - \lambda_w V_1^3}{n^3 D^3} \quad \text{for } O \leqslant V \leqslant V_1 \qquad [2]$$

$$C_p = C_{p_1} = \frac{K_w (1 - \lambda_w) V_1^3}{n^3 D^3} \quad \text{for} \quad V \geqslant V_1 \qquad [3]$$

In using results of windmill tests to calculate the output of a windmill-generator set, it is, however, more useful to rewrite the above equations ([2] and [3]) thus :

$$\frac{P}{E_{\bar{V}}} = k_W \left(\frac{V^3}{\bar{V}^3} - \lambda_W \frac{V_1^3}{\bar{V}^3}\right) \quad \text{for } 0 \leqslant V \leqslant V_1 \qquad [4]$$

$$\frac{P}{E_{\bar{V}}} = \frac{P_1}{E_{\bar{V}}} = k_W (1 - \lambda_W) \frac{V_1^3}{\bar{V}^3} \quad \text{for} \quad V \geqslant V_1 \qquad [5]$$

where

$$E_{\bar{V}} = \frac{\pi c}{8} \rho \bar{V}^3 D^2$$

and $\bar{V}$ is the mean (annual) wind speed.

Thus the output power from the windmill increases linearly with V^3 until $V = V_1$, when it reaches its maximum value P_1. Precisely zero power is produced when $V^3 = \lambda_w V_1^3$ (see figure 1).

Coupling an A.C. generator to the windmill

The function of a generator is to convert the mechanical power P delivered by the windmill into electrical power E, the efficiency of the process being less than unity; or if P and E are measured in the same units, $E < P$.

It is often assumed, in making a simple calculation of the output from a wind-generator set, that this efficiency is some constant equal to its mean value over the range of operation, that is, E varying from zero to E_R. It appears easy to improve upon this simplification. A certain mechanical power is required to run the generator at exactly zero electrical output, and the electrical output increases roughly linearly for higher input powers. Thus, we may write.

$$E = k_G \rho - \lambda_G E_R \qquad [6]$$

where $\lambda_G E_R$ is the mechanical input corresponding to zero electrical output. Very roughly, λ_G is a constant for a given order of magnitude of E_R. It decreases from, say, 0.20 for 1 kW to, say 0.05 for 100 kW.

Matching the windmill to the generator simply requires that $P = P_1$ when $E = E_R$. Substituting this relationship into the previous equation, we obtain :

$$(1 + \lambda_G) E_R = k_G P_1 \qquad [7]$$

Combining equations 4-7 :

$$\frac{E}{E_{\bar{V}}} = k \left(\frac{V^3}{\bar{V}^3} - \lambda \frac{V_1^3}{\bar{V}^3}\right) \quad \text{for } 0 \leqslant V \leqslant V_1 \qquad [8]$$

$$\frac{E}{E_{\bar{V}}} = \frac{E_R}{E_{\bar{V}}} = k (1 - \lambda) \frac{V_1^3}{\bar{V}^3} \quad \text{for} \quad V \geqslant V_1 \qquad [9]$$

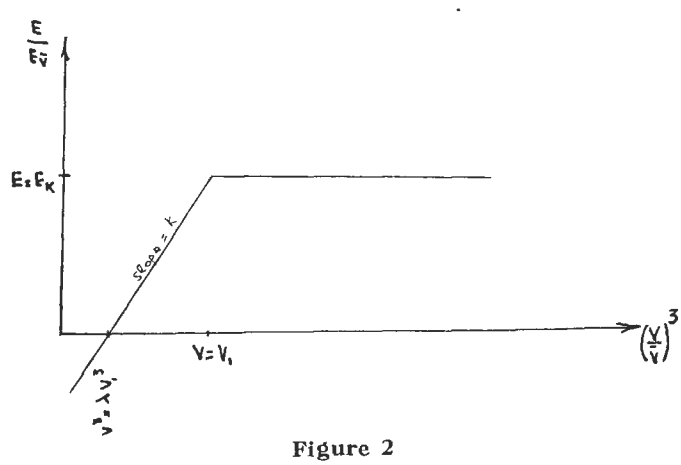


Figure 2

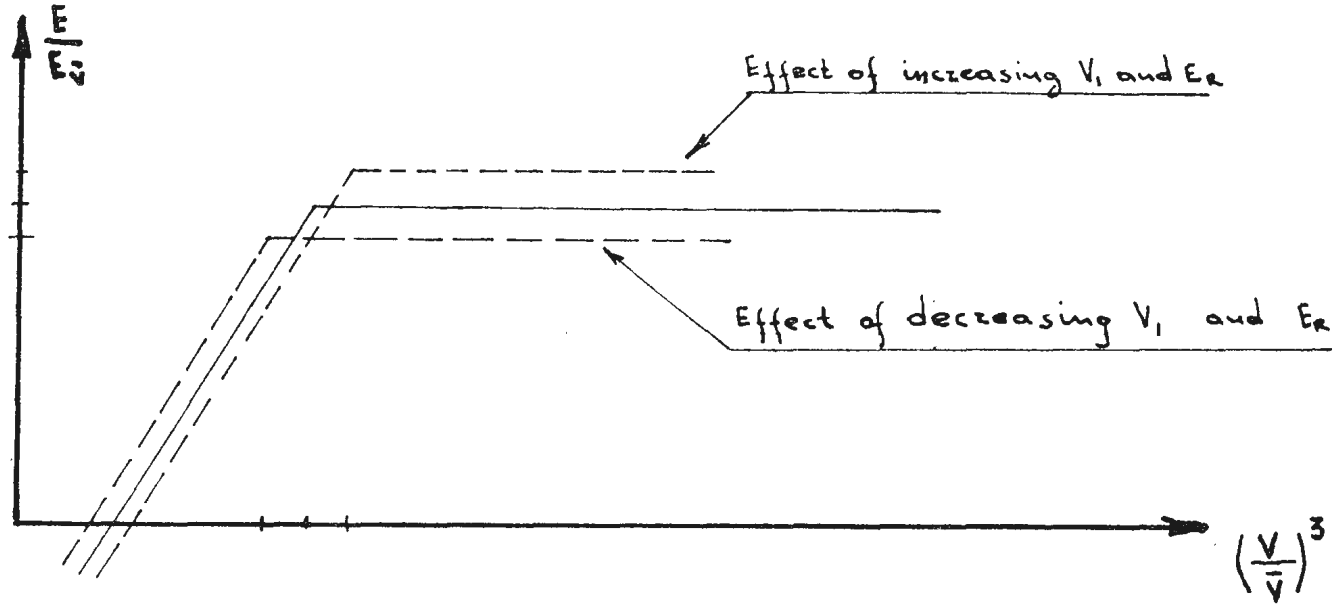


Figure 3

where

$$k = k_W\, k_G$$

$$\lambda = \frac{\lambda_W + \lambda_G}{1 + \lambda_G}$$

Thus the electrical power output from the windmill-generator set is zero at a wind speed equal to $\sqrt[3]{\lambda}\, V_1$; below this speed the output is negative, and above this speed the electrical power varies linearly with V^3 up to $V = V_1$, at which it reaches the rated power (E_R) of the generator. At higher wind speeds than V_1, the power remains equal to E_R (see figure 2).

The generator has been matched to the windmill; it now remains to match both to the wind-speed conditions at the site; this means that we must select the optimum value of V_1. To see the problem physically, let us suppose that a value for V_1 (and with it E_R) has been selected and then consider the effect both of increasing its value and of decreasing it, keeping k and λ constant in each case. These effects are shown in figure 3.

The wind-speed-duration function

As shown in figure 3, the effect of increasing V_1 is to reduce the output at low speed and to increase it at high speed. The relative importance of these loss and gain increments depends upon the relative frequency of low and high wind speeds, that is, upon the shape of the speed-duration function. This function $Z(V)$ is defined as the proportion of time (over a whole year) in which the wind speed exceeds V. Thus, for a small value of δV, the proportion of time during which the wind speed lies between V and $V + \delta V$ is

$$-\frac{dz}{dv}\,\delta V$$

Assuming that the windmill generator is cut out at wind speeds for which the generator output would be negative, the mean (annual) output is

$$\overline{E} = \int_{\sqrt[3]{\lambda}\,\frac{V_1}{\overline{V}}}^{\infty} E\left(-\frac{dz}{dv}\right) dv \qquad [10]$$

substituting the value of E given above ([8] and [9])

$$\frac{\overline{E}}{E_{\overline{V}}} = k\left\{\Phi\left(\lambda\,\frac{V_1^3}{\overline{V}^3}\right) - \Phi\left(\frac{V_1^3}{\overline{V}^3}\right)\right\} \qquad [11]$$

where

$$\Phi\left(\frac{V^3}{\overline{V}^3}\right) = \int_v^{\infty}\left(\frac{V'^3}{\overline{V}^3} - \frac{V^3}{\overline{V}^3}\right)\left(-\frac{dz}{dv'}\right) dV'$$

It appears from the available statistics of wind-speed duration at various sites that Z, as a function of $V/\overline{V}$, taken over a year, varies very little from site to site. In appendix B, a representative form for $Z(V/\overline{V})$ is given and also the corresponding values of Φ.

The mean value $\overline{E}$ can be expressed as two figures of merit, one as a fraction of E_R and the other as a fraction of $E_{\overline{V}}$ namely, the specific output :

$$S = \frac{\overline{E}}{E_R} = \frac{1}{(1-\lambda)} \cdot \frac{\left\{\Phi\left(\lambda\,\frac{V_1^3}{\overline{V}^3}\right) - \Phi\left(\frac{V_1^3}{\overline{V}^3}\right)\right\}}{\frac{V_1^3}{\overline{V}^3}} \qquad [12]$$

and the "mean efficiency" :

$$\bar{y} = \frac{\overline{E}}{E_{\overline{V}}} = K\left\{\Phi\left(\lambda\,\frac{V_1^3}{\overline{V}^3}\right) - \Phi\left(\frac{V_1^3}{\overline{V}^3}\right)\right\} \qquad [13]$$

where

$$E_{\overline{V}} = \frac{\pi c}{8}\,\rho \cdot \overline{V}^3 D^2$$

$$E_R = \frac{\pi c}{8}\,k\,(1-\lambda)\rho\, V_1^3 D^2$$

and k, λ are parameters depending upon the design of the windmill and generator.

Economics

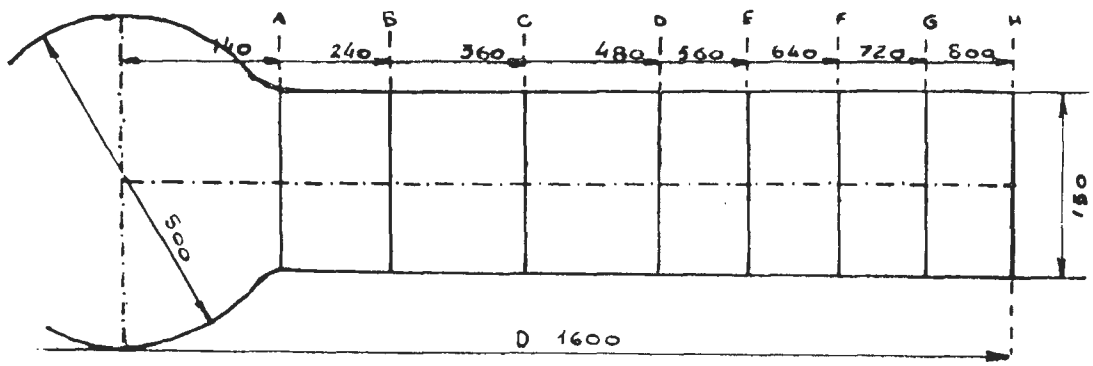
The optimum choice of site, windmill height and diameter and the rated power of generator is that which gives the best return for a given cost. In practice, generators are available only in particular sizes and there are various practical restrictions on the choice of site. Accordingly, the problem breaks down to choosing one of a finite number of alternatives. To compare the relative merits of such alternatives, it is often sufficient to compare the ratio of the mean output $\overline{E}$ to the capital cost, and the results summarized in the preceding paragraph provide a means of calculating this ratio.

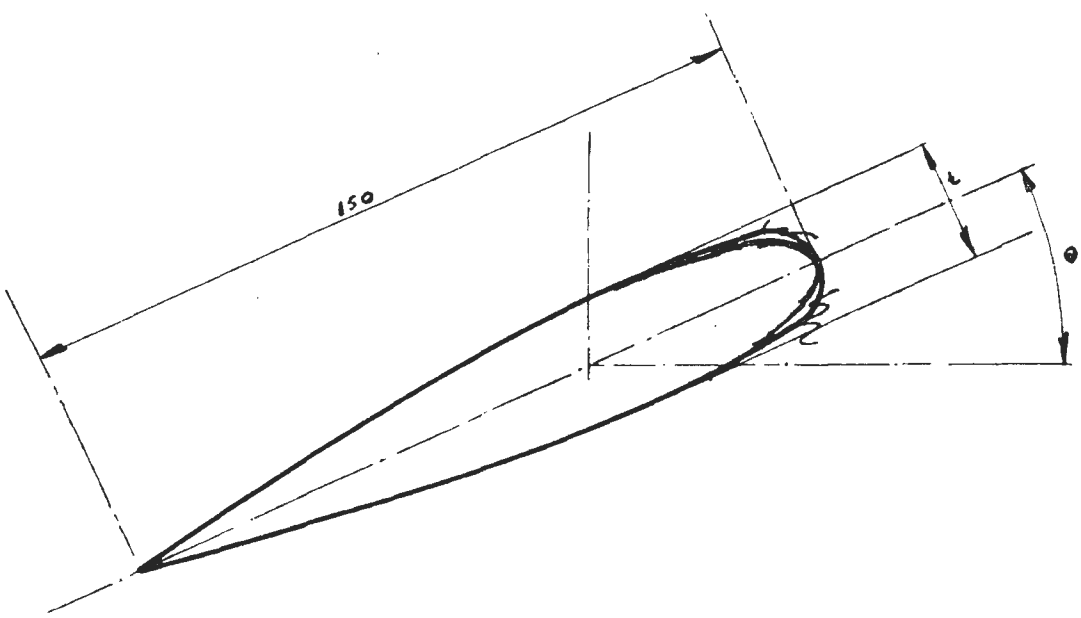
In appendix C, values of s and $\bar{y}$ based on the assumed Z function are deduced for typical values of k and λ.

APPENDIX A

Tests on model windmills

Both models tested were two-blade wooden fixed-pitch windmills of 1.60 metres diameter. The details of the designs are shown in figure 4 and the results in figure 5.





MODEL	SECTION	A	B	C	D	E	F	G	H
I + II	MAX. THICKNESS (mm) t	39	36	31.5	27	24	21	18	15
I	BLADE ANGLE θ	20°	20°	12°	4°	0°	0°	0°	0°
II	BLADE ANGLE θ	0°	0°	0°	0°	0°	0°	0°	0°

Figure 4
(All dimensions in mm)

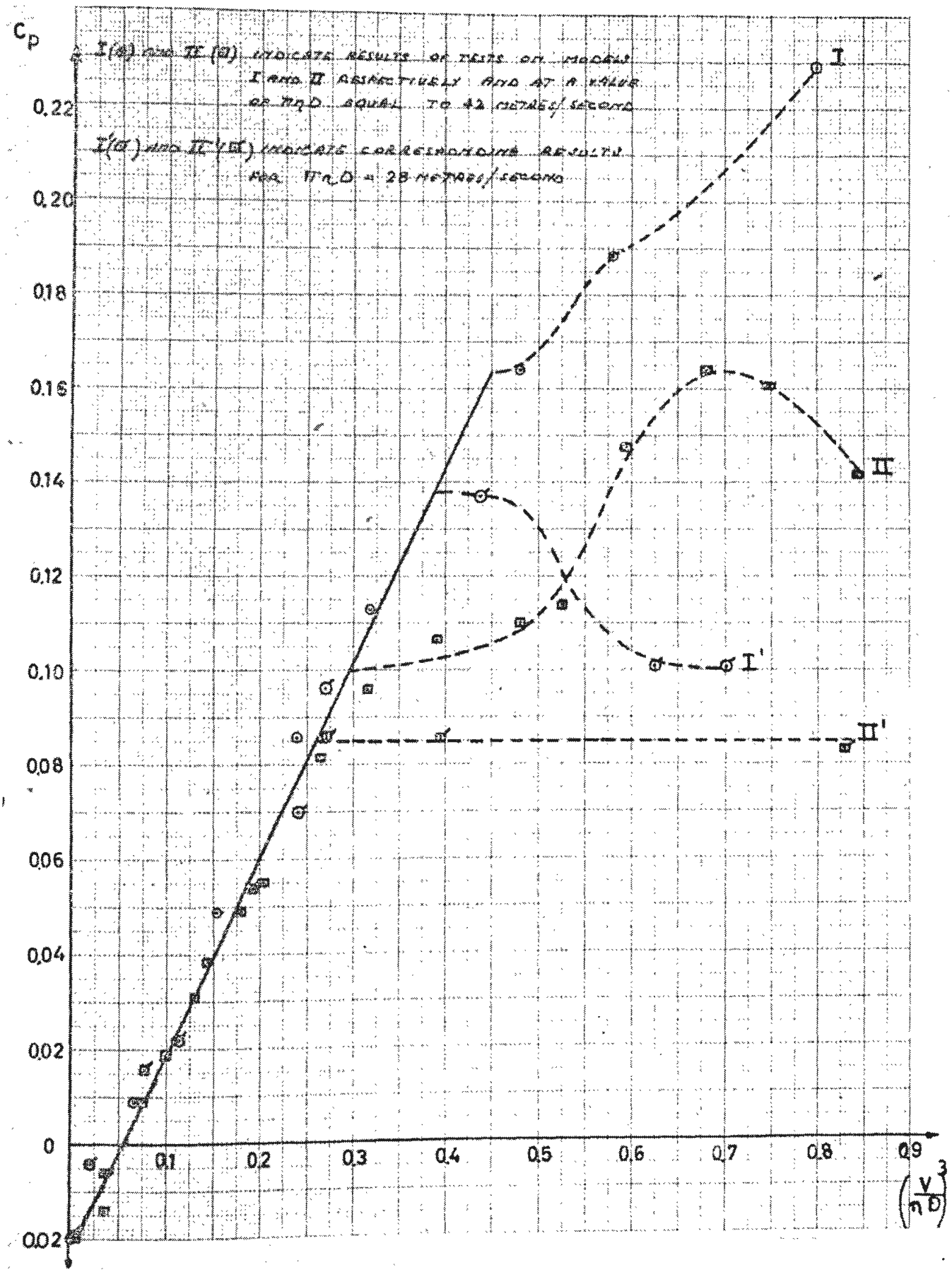

C_p
I (●) AND II (□) INDICATE RESULTS OF TESTS ON MODELS I AND II RESPECTIVELY AND AT A VALUE OF πnD EQUAL TO 42 METRES/SECOND
I' (○) AND II' (□) INDICATE CORRESPONDING RESULTS FOR πnD = 28 METRES/SECOND
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.02
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
I
II
I'
II'
$\left(\frac{V}{nD}\right)^3$

Figure 5

Tests were made in the open-jet tunnel at the Training Center for Experimental Aerodynamics at Rhode-Saint-Genèse, Belgium, and the torque was measured by means of a strain-gauge balance.

APPENDIX B

The time-duration function Z and its related function Φ

The wind-speed-time-duration function Z of V has been defined as the proportion of time in which the wind velocity exceeds some value V. Thus $Z(0) = 1$ and $Z(\infty) = 0$. In order to perform, with reasonable simplicity, the algebraic analysis required in solving the matching problem, an attempt has been made to represent typical plots of the time-duration function against V/V_{mean}, by means of well-known and well-tabulated mathematical functions.

Consideration was limited to the family of functions defined by the equations:

$$Z(\chi) = \frac{2}{\sqrt{\pi}} \int_{\chi}^{\infty} e^{-t^2}\, dt \qquad [14]$$

with

$$\frac{V}{\overline{V}} = \lambda_n \chi^h \qquad [15]$$

λ_n being a constant such that $\overline{V}$ is the mean value of V

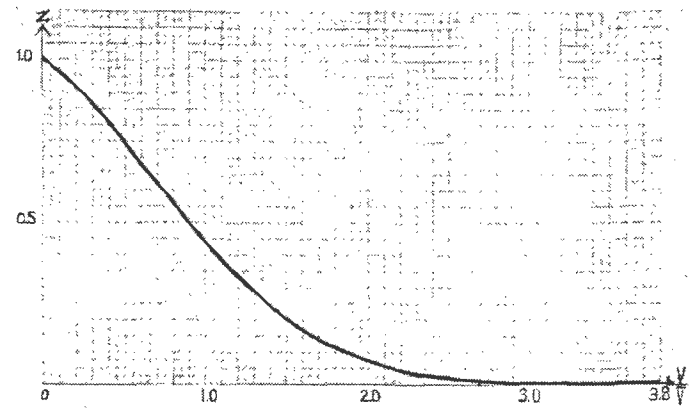


Figure 6

i.e.

$$\frac{2}{\sqrt{\pi}} \lambda_n \int_0^{\infty} \chi^n e^{-\chi^2}\, d\chi = 1 \qquad [16]$$

$$\therefore \lambda_n = \frac{\sqrt{\pi}}{\Gamma\left(\frac{n+1}{2}\right)} \qquad [17]$$

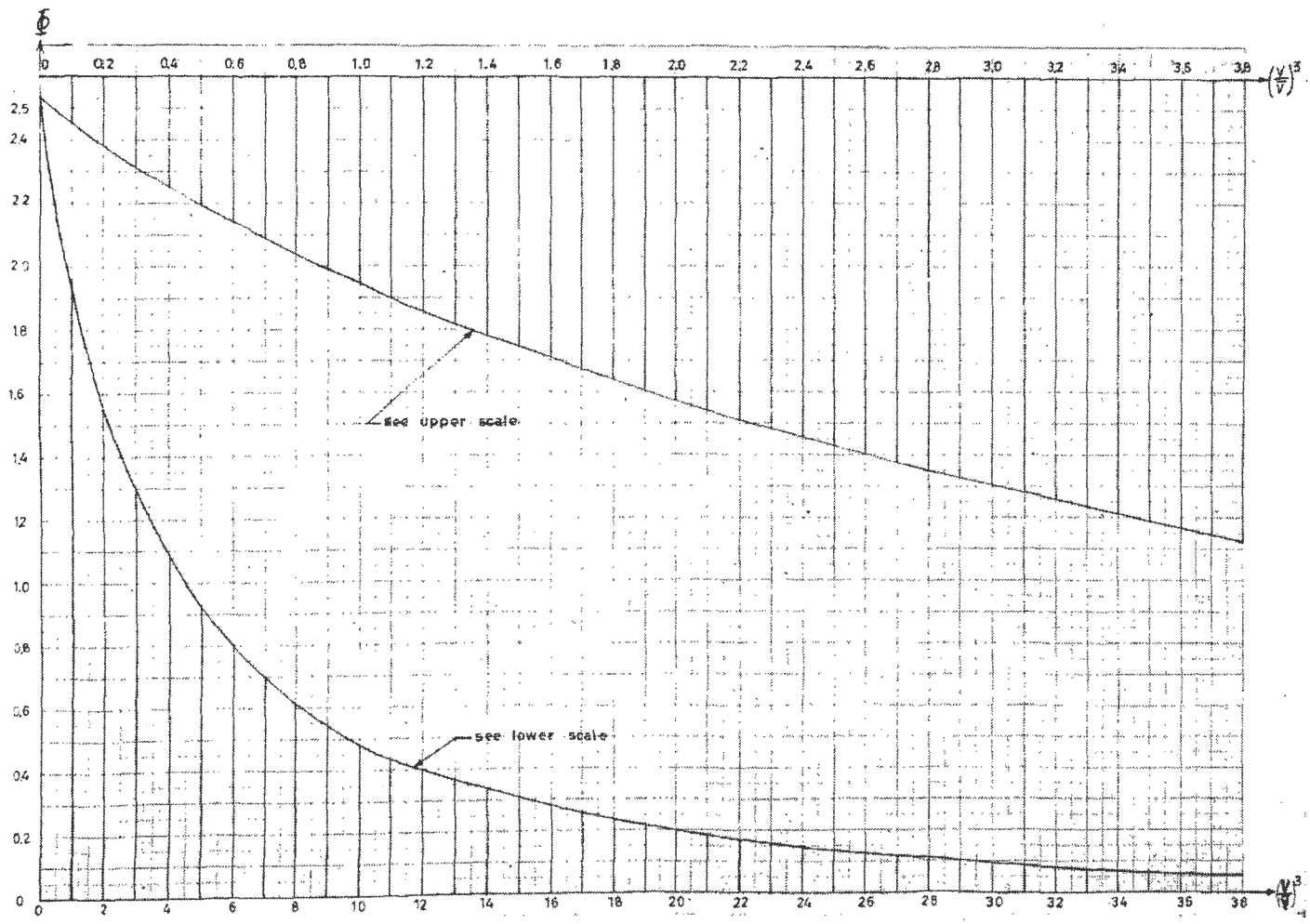


Figure 7

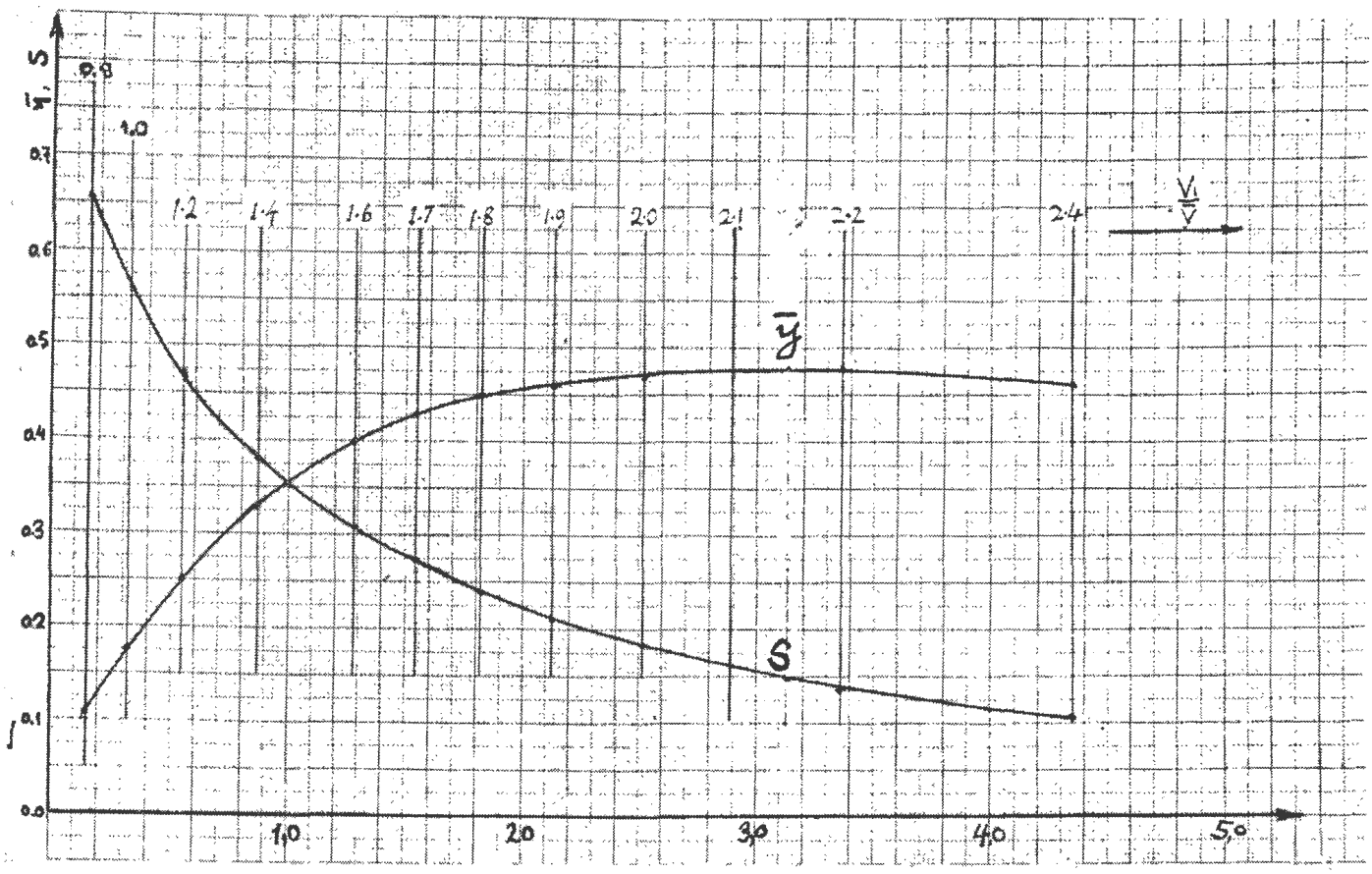


Figure 8

It was found that most practical results fell between, and on average midway between, the two curves given by $n = 1$ and $n = 2/3$, for which λ assumes the values :

$$\lambda_1 = \sqrt{\pi}$$

$$\lambda_{2/3} = \frac{\sqrt{\pi}}{\Gamma\left(\frac{s}{6}\right)} = \frac{\sqrt{\pi}}{1.1288}$$

The value chosen for Z is the mean of the two values of the functions given by substituting 1 and 2/3 for n in equations 14-18. Thus, if Z_1 and $Z_{2/3}$ are these two functions

$$Z = \frac{1}{2}(Z_1 + Z_{2/3}) \qquad [18]$$

The resulting function Φ required to calculate the mean output of a windmill generator is given by

$$\Phi\left(\frac{V}{\bar{V}}\right) = \int_{\frac{V}{\bar{V}}}^{\infty} \left(\frac{V'^3}{\bar{V}^3} - \frac{V^3}{\bar{V}^3}\right)\left(-\frac{dz}{dv'}\right) dV' \qquad [19]$$

Substituting from earlier equations and re-arranging

$$\therefore \Phi = \frac{\pi}{2}\left[(1 + \chi_1^2)e^{-\chi_1^2} + \frac{1}{(1.1288)^3}\left\{\chi_{2/3}\, e^{-\chi^2_{2/3}} + \frac{\sqrt{\pi}}{2} Z_{2/3}\right\}\right]\left(\frac{V}{\bar{V}}\right)^3 Z \qquad [20]$$

The functions Z and Φ are shown in figures 6 and 7.

APPENDIX C

Variation of specific output and mean efficiency with the ratios $E_R/E_{\bar{V}}$ and $V_1/\bar{V}$

Assuming the following typical values

$$\lambda = 0.138 \qquad k = 0.365$$

and the function Φ deduced in appendix B, calculations have been made of the values of the ratios

$$s = \frac{\bar{E}}{E_R} \qquad \bar{y} = \frac{\bar{E}}{E_{\bar{V}}}$$

for various values of $V_1/\bar{V}$ and hence of $E_R/E_{\bar{V}}$ using equations 12 and 13. The results are shown in figure 8.

Summary

The wind-driven generator system considered in this paper comprises a fixed-pitch windmill mechanically coupled (through a step-up gear) to an A.C. generator directly feeding into an A.C. network. The matching problem may be expressed as follows : given (*a*) the windmill diameter[2] and (*b*)

[2] Equally, the rated power could be taken as one of the given conditions and an optimum choice sought for the windmill diameter.

the mean wind speed at the site, what is the optimum choice of (*a*) the gear ratio between windmill and generator and (*b*) the rated power of the generator.

Many factors enter into the matching problem; some can readily be expressed in mathematical terms, others cannot. The purpose of this paper is to consider a few of the more obvious ones which can be so expressed.

The problem is one of matching three sets of physical characteristics, namely, the power output of the windmill as a function of wind speed, the electrical power output of the generator as a function of the input mechanical power and the speed-duration function of the wind at the chosen site.

Power output from a windmill

In presenting results of windmill performance, the author considers it better to reduce power and speed to non-dimensional terms and to plot the resulting power coefficient

$$C_p = \frac{P}{\frac{\pi}{8} c\rho n^3 D^5}$$

against the cube of the non-dimensional wind-speed parameter, i.e. against

$$\left(\frac{V}{n D}\right)^3$$

where P = output power of windmill measured in electrical units
c = the factor required to convert mechanical units into electrical units
ρ = the density of air
n = the rotational speed of the windmill rotor
D = the windmill diameter
V = the speed of the wind

Results, presented in this form and obtained from tests made by Fragoianis in the low-speed subsonic wind-tunnel at the Training Center for Experimental Aerodynamics, are given in figure 5.

In using results of windmill tests to calculate the output of a windmill-generator set, the windmill power equation is written:

$$\frac{P}{E_{\bar{V}}} = k_W \left(\frac{V^3}{\bar{V}^3} - \lambda_W \frac{V_1^3}{\bar{V}^3}\right) \qquad \text{for } 0 \leqslant V \leqslant V_1$$

$$\frac{P}{E_{\bar{V}}} = \frac{P_1}{E_{\bar{V}}} = k_W (1 - \lambda_W) \frac{V_1^3}{\bar{V}^3} \qquad \text{for} \qquad V \geqslant V_1$$

where

$$E_{\bar{V}} = \frac{\pi}{8} c\rho \, \bar{V}^3 D^2$$

and $\bar{V}$ is the mean (annual) wind speed.

Coupling an A.C. generator to the windmill

The function of a generator is to convert the mechanical power P delivered by the windmill into electrical power E, the efficiency of the process being less than unity; or if P and E are measured in the same units, $E < P$.

In this analysis, it is assumed that E and P are connected by the equation

$$E = k_G P - \lambda_G E_R$$

where E_R is the rated output and $\lambda_G E_R$ is the mechanical input corresponding to zero electrical output. Very roughly λ_G is a constant for a given order of magnitude of E_R; it decreases from, say, 0.20 for 1 kW to, say, 0.05 for 100 kW.

Matching the windmill to the generator simply requires that $P = P_1$ when $E = E_R$. Substituting this relationship into the previous equation, we obtain:

$$(1 + \lambda_G) E_R = k_G P_1$$

Combining the above four equations:

$$\frac{E}{E_{\bar{V}}} = k \left(\frac{V^3}{\bar{V}^3} - \lambda \frac{V_1^3}{\bar{V}^3}\right) \qquad \text{for } 0 \leqslant V \leqslant V_1$$

$$\frac{E}{E_{\bar{V}}} = \frac{E_R}{E_{\bar{V}}} = k (1 - \lambda) \frac{V_1^3}{\bar{V}^3} \qquad \text{for} \qquad V \geqslant V_1$$

where

$$k = k_W k_G$$

$$\lambda = \frac{\lambda_W + \lambda_G}{1 + \lambda_G}$$

The wind-speed-duration function

As shown in figure 3, the effect of increasing V_1 is to reduce the output at low speed and to increase it at high speed. The relative importance of these loss and gain increments depends upon the relative frequency of low and high wind speeds, that is, upon the shape of the speed-duration function. This function $Z(V)$ is defined as the proportion of time (over a whole year) in which the wind speed exceeds V. Thus, for a small value of δV, the proportion of time during which the wind speed lies between V and $V + \delta V$ is

$$-\frac{dz}{dv} \delta V$$

Assuming that the windmill generator is cut out at wind speeds for which the generator output would be negative, the mean (annual) output $\bar{E}$ is given by

$$\frac{\bar{E}}{E_{\bar{V}}} = k \, \Phi \left(\lambda \frac{V_1^3}{\bar{V}^3}\right) - \Phi \left(\frac{V_1^3}{\bar{V}^3}\right)$$

where

$$\Phi \left(\frac{V^3}{\bar{V}^3}\right) = \int_V^\infty \left(\frac{V'^3}{\bar{V}^3} - \frac{V^3}{\bar{V}^3}\right) \left(-\frac{dz}{dv'}\right) dv'$$

It appears from the available statistics of wind-speed duration at various sites that Z, as a function of $V/\bar{V}$, taken over a year, varies very little from site to site. In figures 6 and 7, a representative form for $Z(V/\bar{V})$ is given and also the corresponding values of Φ.

The mean value $\bar{E}$ can be expressed as two figures of merit, one as a fraction of E_R and the other as a fraction of $E_{\bar{V}}$, namely, the specific output:

$$S = \frac{\bar{E}}{E_R} = \frac{1}{1-\lambda} \cdot \frac{\left\{ \Phi\left(\lambda \frac{V_1^3}{\bar{V}^3}\right) - \Phi\left(\frac{V_1^3}{\bar{V}^3}\right) \right\}}{\frac{V_1^3}{\bar{V}^3}}$$

and the "mean efficiency":

$$\bar{y} = \frac{\bar{E}}{E_{\bar{V}}} = k \left\{ \Phi\left(\lambda \frac{V_1^3}{\bar{V}^3}\right) - \Phi\left(\frac{V_1^3}{\bar{V}^3}\right) \right\}$$

In appendix C, values of s and $\bar{y}$ based on the assumed Z function are deduced for typical values of k and λ.

CENTRALE ÉLECTRIQUE A ÉNERGIE ÉOLIENNE BRANCHÉE DIRECTEMENT SUR UN RÉSEAU DE DISTRIBUTION EN COURANT ALTERNATIF — PROBLÈME DE L'APPAREILLAGE

Résumé

Le système de génératrices éoliennes que l'on étudie dans la présente communication comprend un moulin à vent à pas fixe qui est mécaniquement couplé (par un engrenage multiplicateur) à une génératrice de courant alternatif directement branchée sur un réseau de distribution en alternatif. Le problème de l'appareillage peut être posé comme suit : si l'on donne *a*) le diamètre de l'éolienne[1] et *b*) la vitesse moyenne du vent au site considéré, quel est le choix idéal *a*) du rapport de multiplication entre l'éolienne et la génératrice et *b*) de la puissance nominale de cette génératrice.

Nombre de considérations interviennent dans ce problème, dont certaines peuvent facilement se réduire à des expressions mathématiques. D'autres ne le peuvent pas. On se propose, dans la présente communication, d'étudier l'une des plus évidentes, parmi ces considérations, qui peuvent s'exprimer de la sorte.

Le problème consiste à appareiller trois jeux de caractéristiques physiques, à savoir : le débit énergétique des systèmes en fonction de la vitesse du vent, le débit d'énergie électrique de la génératrice en fonction de l'énergie mécanique qu'elle reçoit et la fonction vitesse-durée du vent au lieu choisi.

Puissance débitée par un moulin à vent

En présentant les résultats des calculs faits sur le rendement d'une éolienne, l'auteur estime qu'il est préférable de ramener la puissance et la vitesse à des expressions non dimensionnelles et de tracer une courbe donnant le coefficient de puissance correspondant :

$$C_p = \frac{P}{\frac{\pi}{8} c\rho n^3 D^5}$$

en fonction du cube du paramètre du vent (non dimensionnelle), c'est-à-dire en fonction de

$$\left(\frac{V}{nD}\right)^3$$

expression dans laquelle

P = puissance de sortie de l'éolienne, mesurée en unités électriques
c = facteur nécessaire pour convertir les unités mécaniques en unités électriques
ρ = densité de l'air
n = vitesse de rotation du rotor de l'éolienne
D = diamètre de l'éolienne
V = vitesse du vent

Les résultats, présentés sous cette forme et obtenus au moyen d'essais faits par Fragoianis dans le tunnel aérodynamique subsonique à faible vitesse du centre d'instruction aérodynamique expérimental, sont donnés en figure 5.

Quand on se sert des résultats des essais des éoliennes pour calculer le débit d'un groupe électrogène à aéromoteur, l'équation de la puissance s'écrit :

$$\frac{P}{E_{\bar{V}}} = kW\left(\frac{V^3}{\bar{V}^3} - \lambda W \frac{V_1^3}{\bar{V}^3}\right) \text{ pour } 0 \leqslant V \leqslant V^1$$

$$\frac{P}{E_{\bar{V}}} = \frac{P_1}{E_{\bar{V}}} = kW(1-\lambda w)\frac{V_1^3}{\bar{V}^3} \text{ pour } V \geqslant V_1$$

expressions dans lesquelles :

$$E_{\bar{V}} = \frac{\pi}{8} c\rho \bar{V}^3 D^2$$

et $\bar{V}$ est la vitesse moyenne (annuelle) du vent.

Couplage d'une génératrice à courant alternatif sur l'éolienne

La génératrice a pour fonction de convertir l'énergie mécanique P, fournie par un moulin à vent, en énergie électrique E, le rendement du processus étant inférieur à l'unité ou, si on mesure P et E dans les mêmes unités, $E < P$.

Dans cette analyse, on admet que E et P sont reliés par l'équation

$$E = k_G P - \lambda_G E_R$$

dans laquelle E_R est le débit calculé et $\lambda_G E_R$ la fourniture d'énergie mécanique qui correspond à un débit électrique nul. En très grossière approximation λ_G est constant pour un ordre de grandeur donné

[1] La puissance nominale pourrait également être prise comme l'une des données, tandis que l'on chercherait une solution idéale pour le diamètre de l'éolienne.

de E_R; sa valeur décroît de 0,20 pour 1 kW, à 0,05 pour 100 kW, par exemple.

Pour appareiller l'éolienne à la génératrice il suffit que $P = P_1$ quand $E = E_R$. Si on introduit ce rapport dans l'équation précédente, on obtient :

$$(1 + \lambda_G)\, E_R = k_G\, P_1$$

En combinant les quatre équations ci-dessus :

$$\frac{E}{E_{\overline{V}}} = k \left(\frac{V^3}{\overline{V}^3} - \lambda \frac{V_1^3}{\overline{V}^3}\right) \text{ pour } 0 \leqslant V \leqslant V_1$$

$$\frac{E}{E_{\overline{V}}} = \frac{E_R}{E_{\overline{V}}} = k\,(1 - \lambda)\, \frac{V_1^3}{\overline{V}^3} \text{ pour } V \geqslant V_1$$

expressions dans laquelle

$$k = k_W\, k_G$$

$$\lambda = \frac{\lambda_W + \lambda_G}{1 + \lambda_G}$$

Fonction vitesse du vent-durée

Ainsi que l'indique la figure 3, augmenter V_1 a pour effet de réduire le débit à basse vitesse et de l'augmenter à grande vitesse. L'importance respective de ces pertes et de ces gains dépend de la fréquence relative des vitesses de vent (grandes et petites), c'est-à-dire de la forme de la fonction vitesse-durée. Cette fonction est définie comme étant la proportion du temps (sur une année entière) pendant laquelle la vitesse du vent dépasse V. De la sorte, pour une petite valeur de δV, la proportion du temps pendant laquelle la vitesse du vent est comprise entre V et $V + \delta V$ est :

$$-\frac{dz}{dv}\, \delta V$$

En admettant que la génératrice de l'éolienne entre en fonctionnement à des vitesses du vent pour lesquelles son débit serait négatif, le débit moyen annuel $\overline{E}$ est donné par l'expression

$$\frac{\overline{E}}{E_{\overline{V}}}\, k\, \Phi \left(\lambda \frac{V_1^3}{\overline{V}^3}\right) - \Phi \left(\frac{V_1^3}{\overline{V}^3}\right)$$

dans laquelle

$$\Phi \left(\frac{V^3}{\overline{V}^3}\right) + \int_V^\infty \left(\frac{V_1^3}{\overline{V}^3} - \frac{V^3}{\overline{V}^3}\right) \left(-\frac{dz}{dv^1}\right) dV^1$$

Il ressort des statistiques disponibles sur la vitesse du vent et sa durée en divers lieux que Z, fonction de $V/\overline{V}$ pendant une année, varie fort peu d'un lieu à l'autre. Aux figures 6 et 7, on donne une forme type de $Z\ (V/\overline{V})$ ainsi que les valeurs correspondantes de Φ.

La valeur moyenne $\overline{E}$ peut s'exprimer sous forme de deux coefficients de mérite, l'un est fraction de E_R et l'autre fraction de $E_{\overline{V}}$, à savoir le débit spécifique

$$S = \frac{\overline{E}}{E_R} = \frac{1}{1 - \lambda} \frac{\left\{\Phi \left(\lambda \frac{V_1^3}{\overline{V}^3}\right) - \Phi \left(\frac{V_1^3}{\overline{V}^3}\right)\right\}}{\frac{V_1^3}{\overline{V}^3}}$$

et le rendement moyen :

$$\bar{y} = \frac{\overline{E}}{E_{\overline{V}}} = k \left\{\Phi \left(\lambda \frac{V_1^3}{\overline{V}^3}\right) - \Phi \left(\frac{V_1^3}{\overline{V}^3}\right)\right\}$$

A l'appendice C, on déduit, à partir de valeurs type de k et de λ, des valeurs de s et de y basées sur la fonction z supposée.

SMALL WIND-ELECTRIC PLANT WITH PERMANENT MAGNETIC GENERATOR

Franz Villinger *

Much progress has been made in the last decades in supplying densely populated areas with electrical energy through public or private networks. There still exists, however, an extensive demand for power plants to supply houses in remote areas. These plants should be able to provide lighting and make possible the use of small appliances such as radios and television sets.

Small electric plants driven by internal combustion engines are generally used for this purpose. They have a rather low initial cost but need a constant supply of fuel as well as maintenance at frequent intervals by skilled mechanics if they are to last many years. Furthermore, the loud noise of the engines is distracting. To stop the noise, at least during the night, the plants are usually provided with batteries for the storage of electric energy. The batteries are then alternately charged to capacity and fully discharged while the engines rest. Such a mode of operation is of course detrimental to the life expectancy of the storage batteries.

In areas with sufficient average wind velocities, i.e. of at least 4 to 4.5 m/sec, small wind-electric plants (so-called "wind chargers") may be used instead of, or in addition to, the usual set-up to provide single houses with electric energy. These wind chargers must in all cases be used in connection with storage batteries so as to produce a sufficiently constant voltage for lighting purposes, despite more or less prolonged fluctuations in wind velocity. This operation in shunt connection with the wind chargers is much less harmful to the batteries than that described in the preceding paragraph. When output and consumption of electric energy are almost equal, the batteries are relatively little involved and may last 10 years or more. The higher initial cost of the wind-driven electric plant is compensated for by independence from a permanent fuel supply and by almost automatic operation and little noise.

In an attempt to keep the initial cost of the wind chargers as low as possible, a large number of them have been produced and sold in many countries during the last decades, but they have failed to meet the requirements of undisturbed operation under all atmospheric conditions. Many of them, indeed, failed after a relatively short time. On several trips to Algeria and to the Sahara for purposes of building larger wind power plants for water pumping, the author found that many wind chargers had completely broken down in so ideal an area for wind power plants. The experience gained on these trips led soon afterward to the development of the new wind chargers.

The new plants were based on the fact that long and satisfactory service, without constant maintenance, can only be achieved through a very simple design, a very sturdy construction, a reliable automatic regulation, and without regard to apparently cheap initial costs. Another highly desirable feature would be the ease of construction and removal of the wind chargers without complicated tools anywhere.

Consequently, the new types of wind chargers, WL 250 and WK 500, are fitted with two-bladed rotors designed for a high running speed rate ($c_L = U/V$ = velocity of wing tips / wind velocity = 8.0) which drive the movable part of the generator directly, without gearing.

As the collectors and brushes in the well-known D.C. generators of wind chargers need most careful maintenance and are a frequent cause of breakdowns, the new models have specially designed disc-shaped magnetic generators. They combine a ring of permanent magnetic bars with alternating polarity and a corresponding ring of bobbins with soft iron cores which are adjacent to the magnetic bars on the head of the wind charger and remain in a fixed position. As soon and as long as the rotor with the magnetic system is running, an alternating voltage is induced in the bobbins.

The disc shape was chosen for the generator in order to obtain as high a relative speed as possible between the magnets and the bobbins, and, in addition, it was chosen to obtain a simple method for adjusting the air space between the magnets and the bobbins.

Formerly, an automatic clutch was placed between the rotor hub and the magnetic system for a particularly easy start of the wind charger, in spite of the relatively high torque needed for breaking the magnetic system from the bobbins. The individual magnets and the bobbin cores were made of square sections. In the new models, the centrifugal clutch was eliminated, and the magnets and bobbin cores now have round sections. This results in a smaller torque in the braking point because of only a pointed spot of overlapping at the last moment.

The A.C. voltage rated at 110 V and induced in the bobbins with a frequency proportional to the rpm of the rotor is transmitted to the tower of the wind charger by an insulated peak barrel and an elastic

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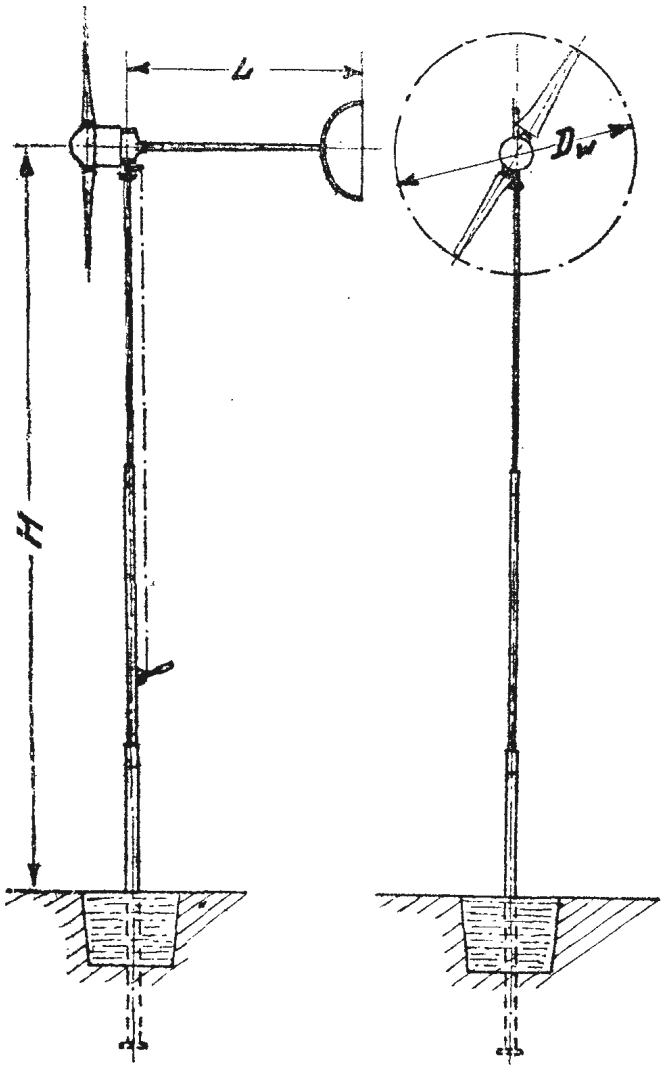


Typ	WL 250	WL 500
N	200 W	500 W
H	5,0/7,5/10,0 m	7,5/10,0/12,5 m
D_W	2,50 m	5,00 m
L	~ 2,50 m	~ 4,00 m

Figure 1

guidance bushing. The A.C. then travels through a cable of double wire and to a transformer combined with a two-way rectifier. At that point, the current is transformed into D.C. which can be stored in a battery with any voltage needed between 12 and 220 V according to the proportion of the transformer. Thus, the rectifier works also as a current valve and prevents the discharge of the battery through the generator when the charging voltage falls below the voltage of the battery. Any risk of overloading the battery can be avoided by the use of a manually or automatically adjustable transformer.

The blades of the new wind chargers consist of glass fibres in molded plastic. They will be manufactured by placing single bundles of glass fibres and integrated joining sockets into half-shells. The method for this procedure was developed several years ago by U. Hütter and E. Hünle. It makes it possible to obtain very light and strong blades of moderate cost even when only small numbers are produced. The blades are also thoroughly weatherproofed and need no additional protection of their surface for the duration of their life-span. This is particularly helpful for operation in areas of high humidity and heavy rainfall.

As a protection against overloading due to extremely high wind velocities, the rotor blades have an adjustable pitch and can turn in their bearing boxes about their axis. This automatically adjusts them to a smaller angle of attack, throttles the performance of the wind chargers and adjusts the number of revolutions of the rotor as soon as it exceeds the specifications. For this purpose, the bearing boxes of the wing roots are attached to the hub by two pairs of parallel levers and they are held in their normal operating position by governor springs with adjustable initial stress against the centrifugal forces acting on the blades. As soon as the rated number of revolutions is reached, the blades and their bearing boxes begin to move radially outwards and thereby function as centrifugal weights of a centrifugal governor. At the same time, they are shifted about their axis to a throttling position by operating rods which extend from an eccentrically arranged pivotal point at the wing roots to pivot points at a governing fulcrum of the hub.

When at a stand-still, the rotor blades and their bearing boxes are moved still farther inward on the hub by a pair of additional springs prestressed much lower than the main regulator springs mentioned above. In this way, the blades are shifted quite automatically about 30° in respect of their operating position and into a starting position.

The governing fulcrum on the hub is also manually adjustable along the axis against the force of a return spring by means of a push-rod which penetrates the hub and the head box at the center, and by means of an adjusting linkage on the tower. This makes it possible to turn the wind charger on and off at any time by moving the blades to their various positions.

An ordinary wind vane automatically adjusts the wind charger to the direction of the wind. It consists of the vane itself and a supporting arm which, for shipping purposes, can easily be separated from the wind charger as well as from the vane itself. The wind vane also acts as a counterweight for the rotor with hub and generator arranged on the windward side of the tower in an undisturbed air flow. The wind charger as a whole is thus supported about its vertical axis; this results in relatively small friction torques.

Another new feature is a tower that can be telescoped. This tower consists of a variable number of tubes of different diameters tapered on the inside at the upper end and on the outside at the lower end. At the upper end of the widest tube, which also constitutes a tower base in the earth, there are two brackets on opposite sides for two double levers of different lengths. Step by step these levers elevate,

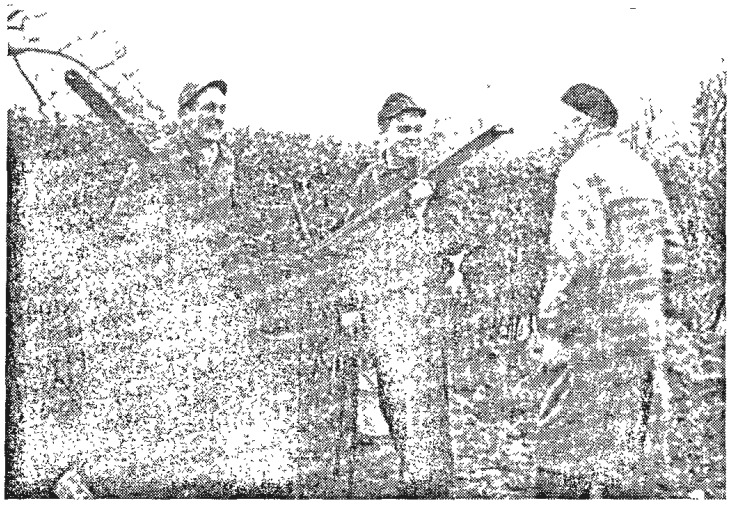


Figure 2

one after the other, the tubes as well as the wind charger which is fully mounted on the innermost tube. For this purpose, gripping jaws are mounted on the top of short push-rods which can lift and alternatively hold and once more grip the tubes. As soon as one tube is fully extended, its outward tapered lower end is placed against the inward tapered upper end of the next wider tube. It is then lifted a little and is rigidly coupled with the other tube so as to make bending or pushing impossible. The outer ends of the double levers are then pushed down simultaneously and pulled up alternately to hold and to grip the tubes anew until all of them are lifted into their highest position and locked together. Once a year, when the wind charger has to be serviced or otherwise repaired, the telescopic tower can be lowered by the opposite operation of the double levers. When telescoped, the tower has only the bulk of the lowest tube which results in favorable freight costs. The total height of the tower is optional and depends on the number of tubes. In every case, the narrowest ones will be at the top of the tower and the wider ones at the bottom. The tube with the smallest diameter, directly beneath the head of the wind charger, has a flange which is bolted to a corresponding flange at the lower end of a supporting tube in the wind charger's head. As the tower has a built-in erection mechanism, the plant can be assem-

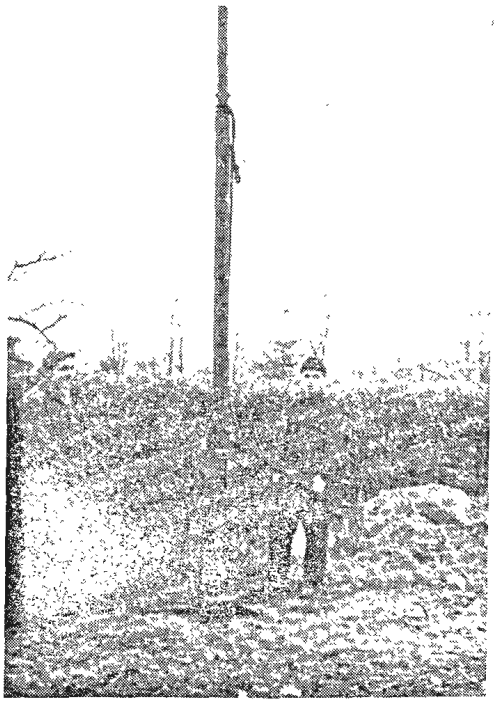


Figure 3

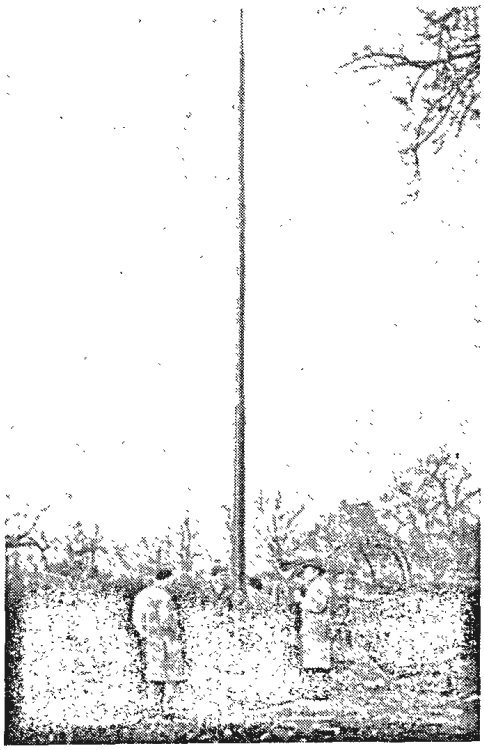


Figure 4

bled on the ground, in any location. Only two men and no special tools are needed. The position of the wind charger on top of the telescopic tower eliminates the necessity for climbing the tower. This should please most owners of isolated houses, as the owner has found them to be generally fearful of maintaining their wind chargers in this manner.

The need for more material and labor in the production of a reliable wind power plant inevitably results, as has been noted above, in much higher initial costs than those of an electric plant run by a small internal combustion engine. The price of the new wind chargers is not yet known; it depends on the number to be manufactured. It is hoped that the larger one with a rotor 5 m in diameter will cost about U.S. $1 000 while the smaller model with a 2.5 m diameter will cost $750.

In order to take good advantage of the generator output, and to hold the initial cost of the battery down to a minimum, the generators have been rated for a much lower output in relation to the diameter of the rotors than those for other wind electric plants. Thus the WL 250 reaches its rated output of 500 watts at a wind velocity of about 5.5 m/sec (12.5 m/h), while the smaller model, the WL 250, reaches its output of 200 watts at a wind velocity of about 6.9 m/sec. (15 m/h).

By rating the new wind chargers so unusually low, the generators achieve a much higher efficiency in the most important field of the lower and medium wind velocities than do generators rated for higher but only rarely occurring wind velocities. The comparatively low rated output of the wind chargers already becomes available in lower wind velocities. This also makes it possible to operate the plants with rather small storage batteries whose minimum capacity is limited by the maximum permissible amperage during charging.

If a life-span of ten years and 1 000 and 500 generated kWh per year are taken as a basis for the two models, 1 kWh costs about $0.15 and $0.22, respectively, without the battery, and $0.20 or $0.275, respectively, with the battery, the cost of which is taken at 15 per cent per year for depreciation and interest. These figures cannot, however, be compared with those of other wind electric plants because, as a rule, a much higher output per rotor area is taken as a basis for the calculation.

The wind chargers described above are still in the testing stage. Only recently has the author been able to find a manufacturer who was willing and able to build at least one plant for testing purposes in accordance with the designs perfected by the author in his spare time. In the past four years, not even one test plant was manufactured, despite promises from several manufacturers. The start of practical work was delayed time and again in favor of the more conventional products because factory capacities were strained in Germany.

The main obstacle to the setting-up of production of the wind chargers in Germany is certainly the absence of a worth-while local market, as Germany has a close-meshed electric network. It seems therefore advisable to study the possibility of producing these plants in the areas concerned and to have the more complicated parts, such as the permanent magnets, the rotor blades and the roller bearings, supplied by more industrialized countries.

Summary

The new types of small wind power plants have been designed for the transformation of a natural source of energy, namely wind, into electric current. Isolated houses that until now could not be supplied with electricity at all or only at great expense can now, with the additional help of a storage battery, be provided with enough for the lighting of rooms and for certain small appliances such as radios, television sets, etc.

Many years' experience with different kinds of wind power plants in various countries has gone into the design of these wind chargers. Special stress was laid on great simplicity and reliability, a minimum need for servicing and ease of installation.

In view of these aims, the wind chargers consist of a rotor with two blades and a fairly high speed rate of blade tip, speed/wind velocity ratio (c_L) and of a permanent magnet generator with a direct drive, that is, without gearing. This generator is based on a series of magnets which turn with the rotor, and bobbins at the resting case. (All moving parts for transmitting current, such as collectors, between the armature and the stator of the generator have been eliminated.) It provides an A.C. of uniformly high voltage but of variable frequency. The current can be transformed to any voltage needed by means of an ordinary transformer and changed into storable D.C. in a dry rectifier. This rectifier also functions as a current valve which prevents any discharge of the storage battery through the generator when the charging voltage falls below the battery.

The rotor blades are made of fibre-glass in molded plastic and are weatherproofed. The blades have adjustable pitch, turn about their axis and can be set automatically for starting, normal working conditions or throttling in high wind velocities. They can, however, also be set by hand by means of an adjusting linkage at the foot of the tower so that the plant can be started or stopped at any time.

A specially designed telescopic tube tower makes it possible to assemble the wind chargers on the ground and without mounting tools, and to install it on the lowered tower. Only when this has been done is the tower vertically extended, step by step, by

a simple mechanical lifting device. The wind charger will be on top of the narrowest and innermost tube. This tube and others of over larger diameter are rigidly locked together to prevent pressing and bending. For the yearly servicing, the tower and the wind charger can be lowered by the same operation so that the tower itself need never be climbed at all.

The dimensions and capacities of both models are shown in figure 1. Their initial cost is estimated to be about $1 000 and $750, respectively.

GROUPE ÉLECTROGÈNE A ÉNERGIE ÉOLIENNE DE PETITES DIMENSIONS DU TYPE A MAGNÉTO

Résumé

Les deux modèles de petites centrales éoliennes récemment mis au point sont destinés à transformer la forme d'énergie naturelle que représente le vent en courant électrique. Ces centrales permettent de fournir du courant à des maisons isolées dont l'électrification serait soit impossible, soit trop coûteuse pour éclairer les pièces et couvrir les besoins de force motrice, par exemple pour les postes de TSF ou de télévision, etc. Le tout s'installe en liaison avec une batterie d'accumulateurs.

De nombreuses années d'expérience, acquise avec différents modèles de centrales éoliennes dans divers pays ont permis de réaliser semblables installations d'aéromoteurs. On s'attache particulièrement à une grande simplicité et une parfaite régularité de marche, combinées avec la réduction au minimum des frais d'entretien et avec la plus grande facilité d'installation.

Pour réaliser ces objectifs, les éoliennes employées sont du type à deux pales avec une vitesse linéaire des bouts de pales assez élevée par rapport à la vitesse du vent (c_L) et du modèle à commande directe, c'est-à-dire sans train d'engrenage. Elles entraînent des génératrices à aimant permanent. Celles-ci débitent du courant alternatif en liaison avec un système d'aimants qui tourne avec l'hélice. Les enroulements sont montés sur le boîtier et il n'y a pas de pièces mobiles telles que collecteurs et autres entre l'induit, ou rotor, et le stator. Ce courant alternatif, dont la tension est élevée mais la fréquence variable, peut être ramené à la tension voulue à l'aide d'un transformateur de type classique et servir ensuite à la charge d'une batterie par l'intermédiaire d'un redresseur du type sec. Ce redresseur sert également de conducteur unidirectionnel qui s'oppose à toute décharge des accumulateurs par la génératrice quand la tension de charge tombe au-dessous de celle des accumulateurs.

Les pales de l'éolienne sont en fibre de verre agglomérée par un produit plastique, qui est éminemment résistante et à l'épreuve des intempéries. Ces pales s'articulent sur leur moyeu de manière à pouvoir pivoter sur leur axe longitudinal, si bien que le pas est automatiquement réglé, et ce d'une façon totalement automatique, à diverses valeurs pour le démarrage, la marche normale et la mise en drapeau aux grandes vitesses de vent. On peut également régler le pas à la main au moyen d'une timonerie depuis la base de la tour pour arrêter ou démarrer à volonté.

Il est possible de monter ces aéromoteurs au sol et de les installer sur une nouvelle tour télescopique tubulaire qui, elle aussi, a été mise au point récemment pour les modèles WL250 et WL500, avant de la déployer. Ceci fait, la tour est élevée verticalement, avec son aéromoteur tout installé, au moyen d'un dispositif mécanique simple qui permet de la déployer progressivement. L'éolienne repose sur le tube de plus petit diamètre et les autres sont verrouillés les uns aux autres, de manière à résister aux sollicitations verticales et aux moments fléchissants. Pour les besoins des travaux d'entretien — qui ne doivent normalement s'exécuter qu'une fois par an — on peut également faire descendre l'ensemble tour-aéromoteur, si bien qu'il n'y a jamais lieu de monter au sommet de cette tour.

On donne les cotes principales et les caractéristiques des deux modèles d'éolienne, dont la construction est identique, quant au principe, à la figure 1.

Les frais de premier établissement de ces machines sont évalués respectivement à 1 000 et 750 dollars environ.

TESTING OF THE GEDSER WIND POWER PLANT

V. Askegaard *

The experimental plant of the Danish Wind Power Committee, the Gedser mill, is equipped with a measurement cylinder which makes it possible to measure the influence of the wind on the mill. The measurement cylinder is placed between the tower and the machine cabin (figure 1).

The measurement cylinder

The measurement cylinder was designed by Dr. B. Højlund Rasmussen and constructed and mounted by the firm of Aarhus Maskinfabrik. The measurement cylinder (figure 3) has a wall thickness of 3 mm, a radius of 700 mm and a height of 450 mm. The cylinder is welded together in the direction of the cylinder generators.

Along its lower rim, the cylinder is welded on a circular ring-shaped steel plate. This plate is fixed to the top of the concrete tower by means of eighteen bolts.

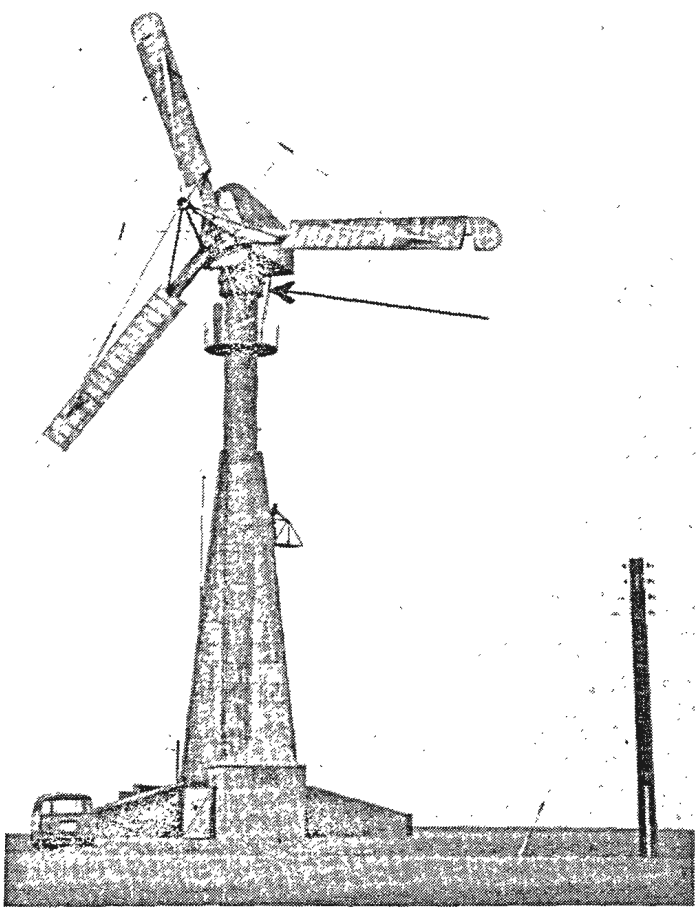
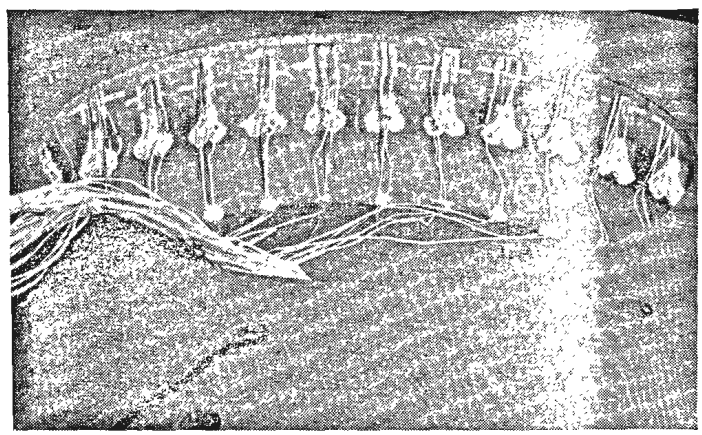


Figure 1. Position of the measurement cylinder immediately between tower and machine cabin



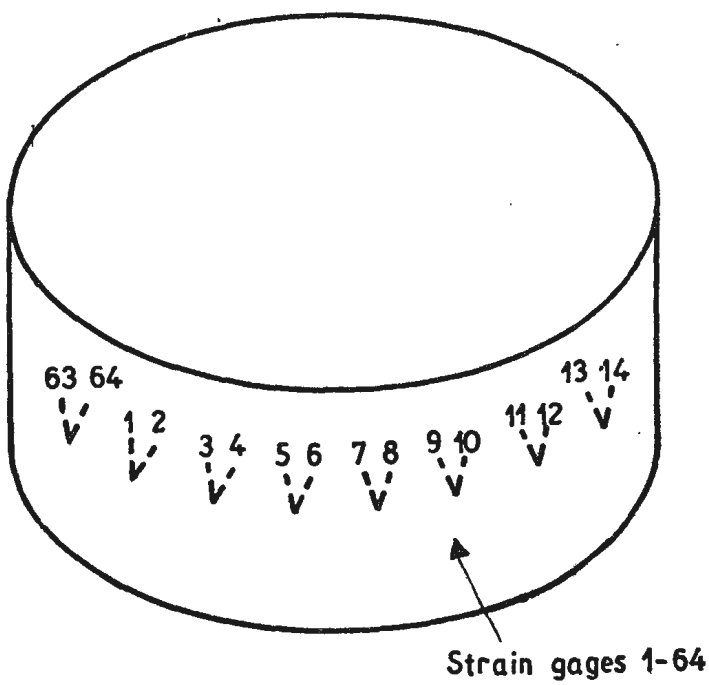


Figure 2. On the inside of the measurement cylinder are pasted 64 wire resistance strain gauges, which are placed at an angle of 45° between their longitudinal direction and the generators of the cylinder and in such a way that any two successive gauges are perpendicular to each other

* Civil Engineer, Wind Power Committee, Association of Danish Electricity Works, Copenhagen.

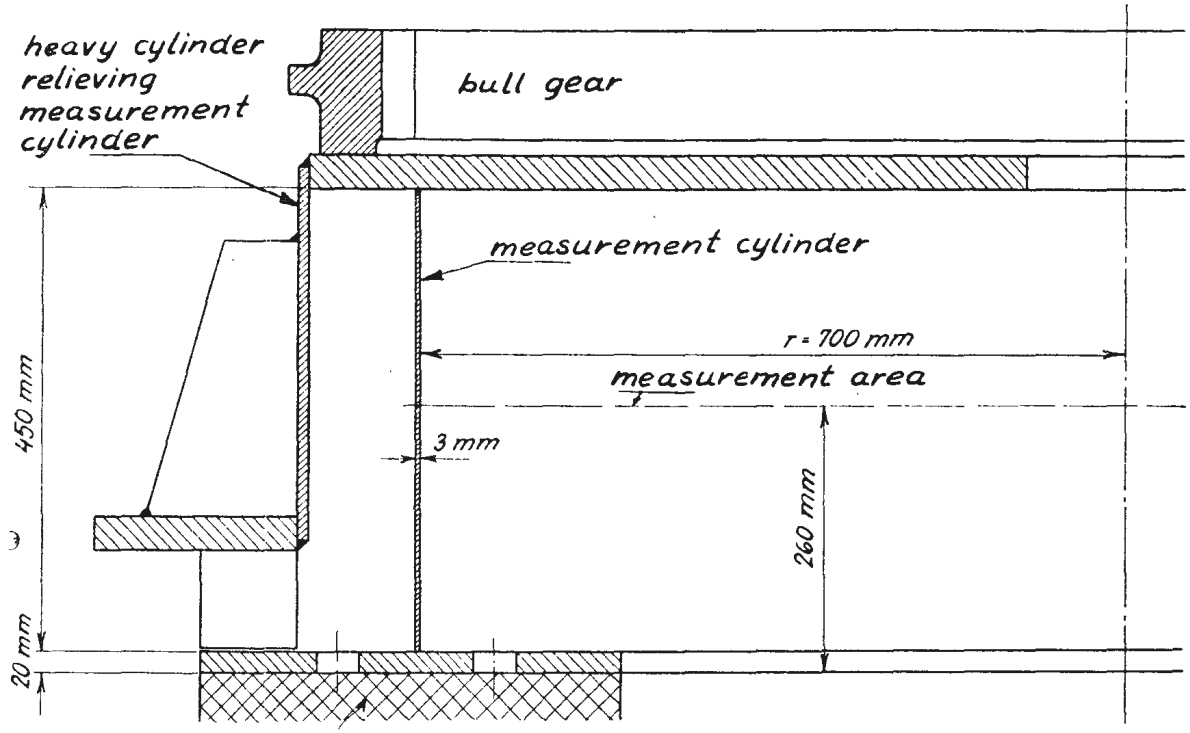


Figure 3. Cross-section of measurement cylinder. Along its lower rim the cylinder is welded to a circular ring-shaped steel plate. Eighteen bolts hold it to the top of the concrete tower. The top edge of the cylinder is welded to a circular steel plate carrying the bull gear and, thus, also the machine cabin, which can turn

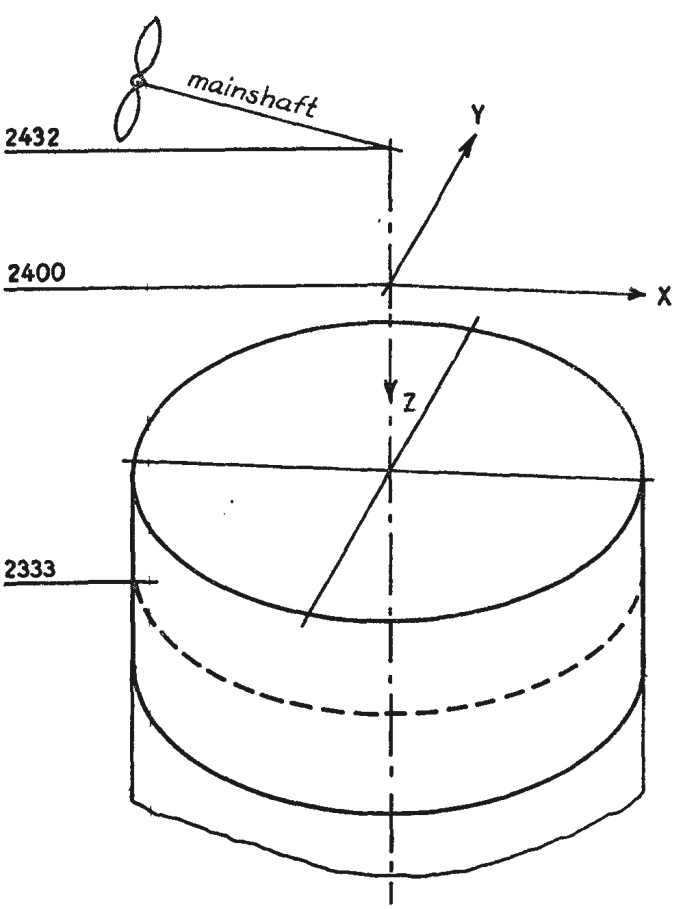


Figure 4. The measurement cylinder is calibrated for various moments of force : P_x, M_y and M_z. The system of co-ordinates shown is fixed in relation to the machine cabin

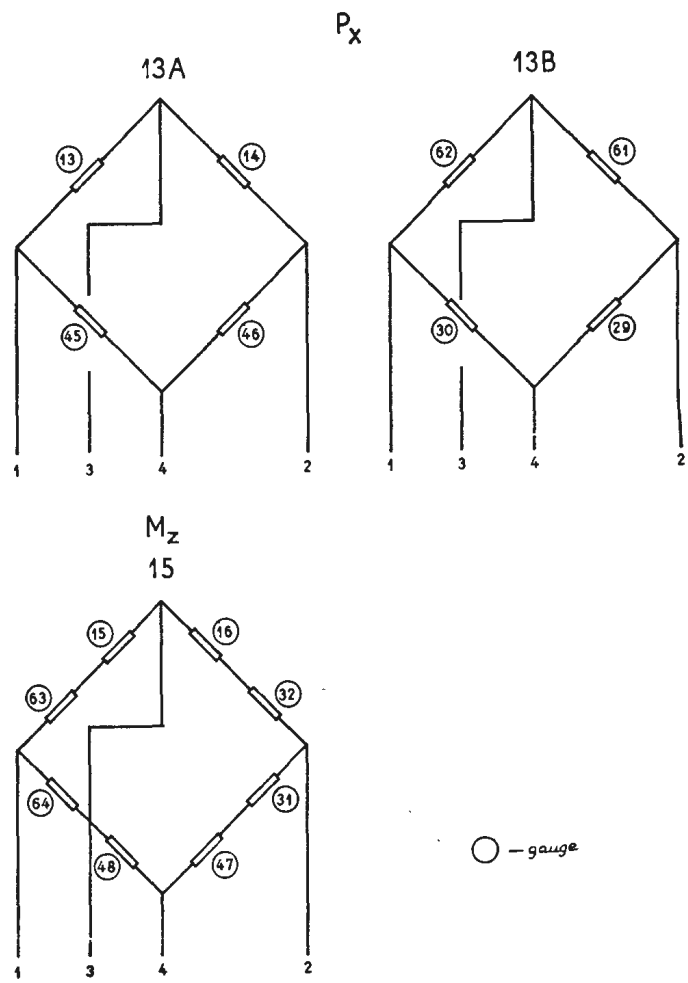


Figure 5. Measuring combinations which show the gauges used by measurement of P_x and M_z

The top edge of the cylinder is welded to a circular steel plate carrying the bull gear and, thus, also the revolving machine cabin. Around the outside of the measurement cylinder is another cylinder that serves to relieve the pressure on the measurement cylinder whenever measurements are not being taken. The top edge of the external cylinder is welded to the same plate as the measurement cylinder, and its lower edge can be locked to the circular, ring-shaped steel plate by insertion of a row of bolts.

Measuring

The measurements were taken by the Laboratory of Building Technique of the Technical University of Denmark.

The state of deformation of the measurement cylinder depends upon the forces (strength and direction) acting upon the blades and the machine cabin. This state of deformation is determined by means of wire resistance strain gauges. Altogether, sixty-four strain gauges are pasted on. They are placed on the inside of the cylinder at angles of 45° between their longitudinal direction and the cylinder generators and in such manner that any two successive gauges are perpendicular to each other (figure 2).

Before it was mounted on the tower, the measurement cylinder was calibrated on a clamping stand, for various moments of force: P_x, M_y and M_z (figure 4), corresponding to the stresses for which the dimensions of the tower were calculated.

The system of co-ordinates shown in figure 4, in relation to the machine cabin, is fixed. Because of the shape (small height) of the measurement cylinder, its state of deformation, when subjected to a certain moment of force, depends upon its conditions of support. Consequently, it has been difficult to obtain a clear differentiation between the magnitude of the signal registered from a strain gauge combination and the magnitude of a component of force. The most reliable combinations were selected, however, and by means of these, the measuring accuracy described below was obtained.

After the measurement cylinder had been mounted on the mill, an after-calibration was carried out, at which the behaviour of the cylinder was ascertained — through measurements of the combinations selected — and it had not changed materially because of the mounting. The after-calibration, however, could only be carried out with regard to the bending moment M_y, this moment being solely due to the eccentric effect of the weight of the machine cabin itself.

The calibration measurements were carried out with a view to later continual measuring, over a prolonged period, of the horizontal force

$$P_x = \sqrt{P_A^2 + P_B^2}$$

of the moment of torsion around the vertical axis of the tower M_z, as well as of the overturning moments M_x and M_y.

The experimental technique, however, was altered so that only the two components of P_x and M_z were determined during the measuring on the mill. The measuring combinations used are shown in figure 5. A permanent measuring arrangement was established, measurements having been taken only on days with the desired wind conditions, however, and signals were then recorded during short periods (about 5 sec) within which the wind velocity might be supposed to be constant.

Thus, measurements were taken during the operation of the mill on 27 October 1959, at 12-20 m/s. Measurements were taken at 5-7 m/s only on 29 October 1959, the mill being stopped at the time. This last measuring formed the basis for determining the readings of the measuring combinations at 0 m/s, which was the basis of determination of the wind forces measured. During these measurings, the mill was standing in the same position.

Correspondingly, measurements were taken while the mill was operating on 2 November 1960 at 10-16 m/s and again, with the mill stopped and in the same position, on 9 November 1960 at 6 m/s. Wind conditions at the same time are shown in figure 6.

While measurements were taken, the wind velocity was read on an instrument connected with a cup-

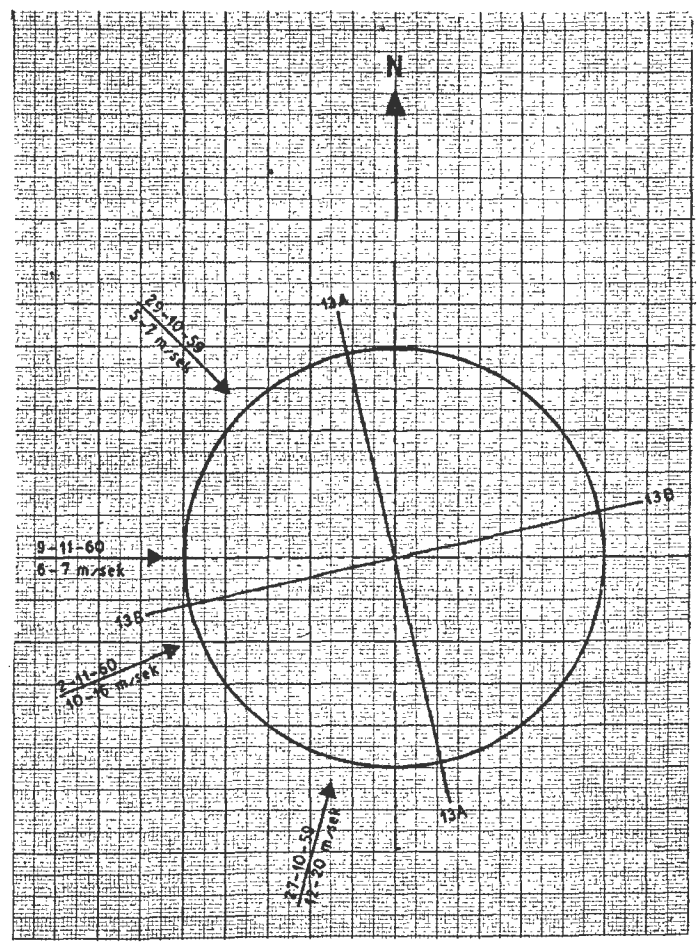
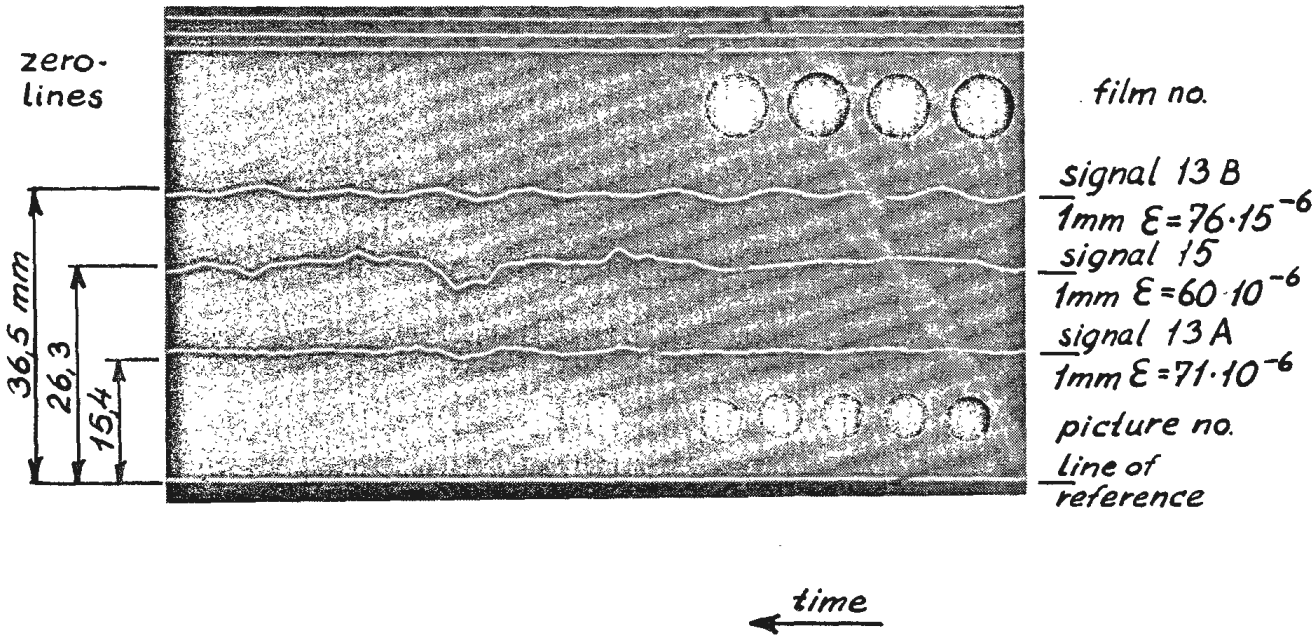


Figure 6. The wind conditions during the taking of measurements



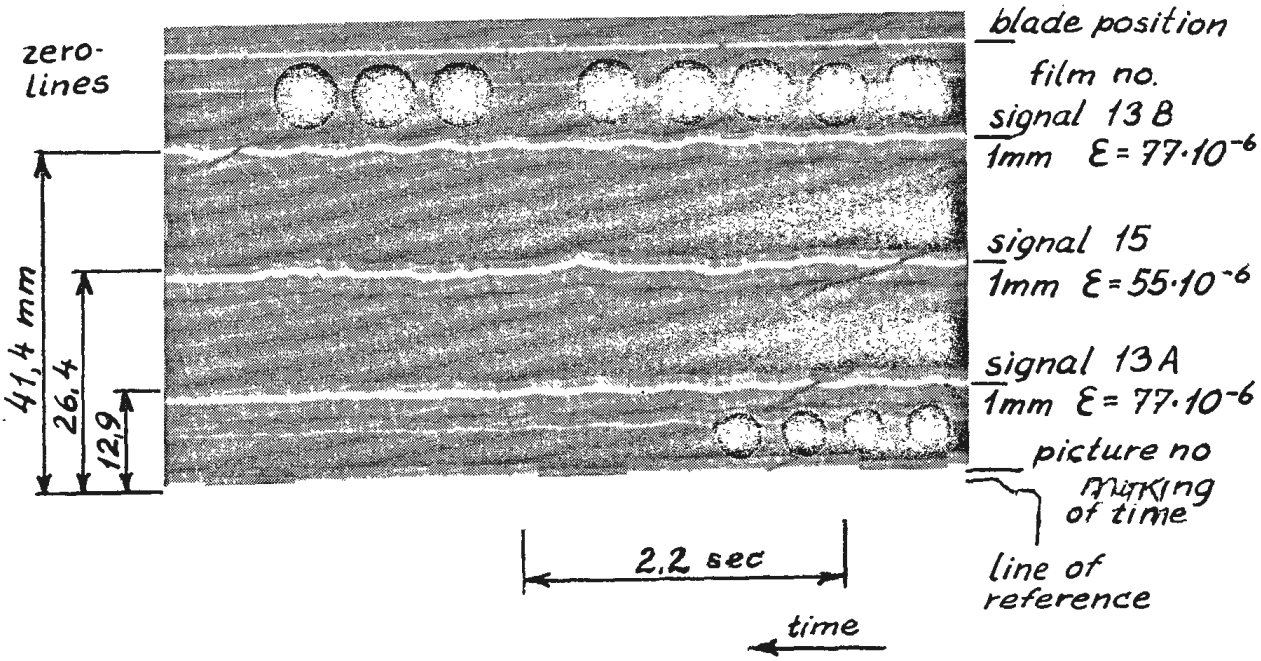


Figure 7. Typical cases filmed during the measurements. The zero lines of the individual signals and the correlation between the amplitude and the measured unit-elongation ε are shown

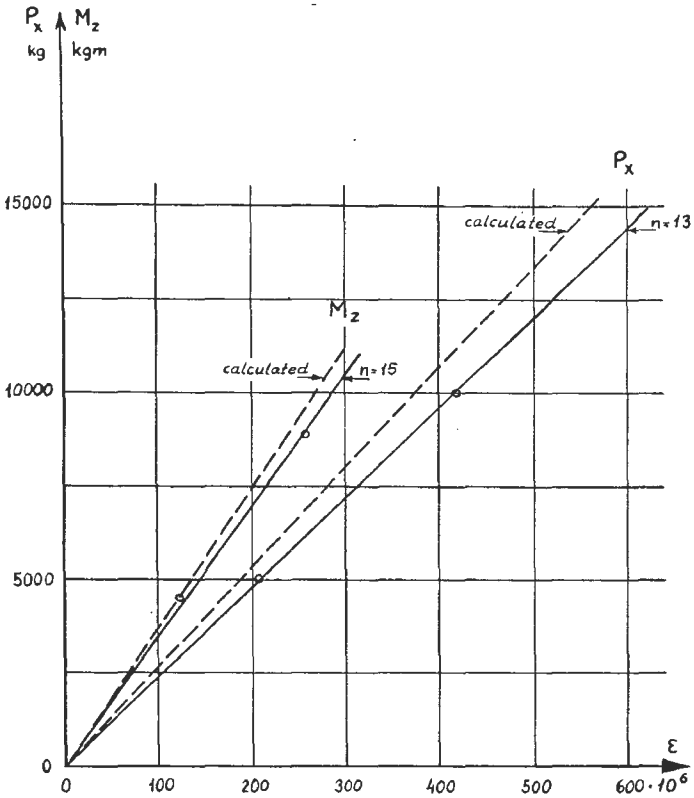


Figure 8. The correlation between P_x, M_z and the measured values of the unit-elongation ε (*n* is the measuring combination)

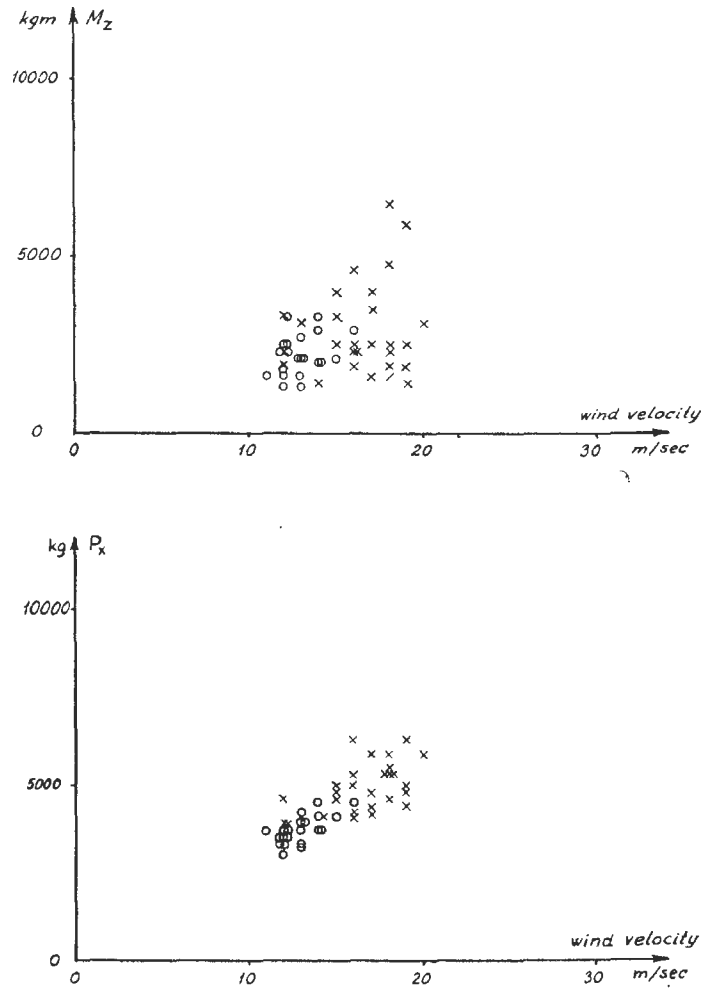


Figure 9. The measurement points indicate the maximum values in measuring periods of about 5 sec duration (*x* = measurement on 27 October 1959; *o* = measurement on 2 November 1960)

contact anemometer placed about 25 m to the west of the mill at a height of about 10 m.

Measurement results

During the measuring, films of a duration of a few seconds were taken. Typical cases are shown on the films in figure 7. The zero lines of the individual signals, laid down after correction for effects of wind direction and wind velocity, as well as the correlation between the amplitude and the measured unit-elongations, ε, are shown. The correlation between ε and the wind forces measured appears from the calibration curves in figure 8.

On the film shown in the lower half of figure 7, the position of the blades has been recorded by means of a contact device on one of the blades.

The total number of measurement results (i.e., the maximum value in each period of measuring) as regards P_x and M_z are sketched in figure 9. The average inaccuracy of the individual measurements is 700 kg and 700 kgm, respectively.

For comparison it may be noted that the tower is calculated for P_x = 15 000 kg and M_z = ± 5 000 kgm. Although measurements so far have only been taken at wind velocities up to 20 m/s, there appears to be a great safety margin for P_x. As for M_z values, they were measured in this wind speed interval, which exceeded the one deciding the dimensions, and are in this case only of importance for the bull gear.

Summary

The experimental wind power plant of the Danish Wind Power Committee, the Gedser mill, is designed to make possible the measurement of pressures and torsional forces acting upon it.

A measuring cylinder is fixed on top of the tower, and the machinery is mounted pivotally on top of that.

The dimensions of the measuring cylinder are the following: diameter, 1 400 mm; height, 450 mm; and wall thickness, 3 mm.

The cylinder is fixed by welding between two horizontal circular plates; the bottom one is bolted to the tower and the top one carries the bull gear and, thus, also the revolving machine cabin.

The forces acting upon the blades are absorbed by the measuring cylinder. By placing a suitable number of resistance wire strain gauges on the surface of the measuring cylinder, the static as well as the dynamic effects can be registered electrically.

Before the measuring cylinder was mounted on the tower, a calibration of it was undertaken on the testing stand of the Laboratory of Building Technique at the Technical University of Denmark. The measuring cylinder was mounted on the wind power plant and a recalibration was made at which it was ascertained that the behaviour of the measuring cylinder had not materially altered because of being mounted.

Measurements have been taken at a wind velocity of 10-20 m/s. It was not yet possible to take measurements at 20-30 m/s.

The 10-20 m/s measurements were registered during short periods (about 5 seconds); within that space of time, the wind velocity may be supposed to be very nearly constant.

The action of thrust on the blade hub, as well as the influence of torsion around the vertical axis of the tower, have been registered. Although measurements so far have only been taken at wind velocities up to 20 m/s, there appears to be a great safety margin for the action of thrust on the blade hub. As for the torsion around the vertical axis of the tower, values were measured in this wind speed interval. They exceeded the ones deciding the dimensions, and are in this case only of importance for the bull gear.

ESSAIS SUR LES CENTRALES ÉOLIENNES GEDSER

Résumé

L'installation expérimentale d'énergie éolienne de la commission danoise chargée de cette source de force motrice, — la Centrale de Gedser — a été conçue de manière à permettre la mesure des pressions et des couples qui agissent sur ses éléments constitutifs.

On trouve, au sommet de la tour, un cylindre de mesure qui porte les machines nécessaires, montées sur un pivot.

Les dimensions du cylindre de mesure sont les suivantes : diamètre, 1 400 mm; hauteur, 450 mm; épaisseur de paroi, 3 mm.

Le cylindre est fixé, par une soudure à l'autogène, entre deux plaques circulaires horizontales. Celle du bas est boulonnée à la tour et celle du haut porte l'engrenage d'entraînement, ainsi que la cabine de la machine, qui est capable de tourner.

Les réactions créées par les forces qui agissent sur les pales sont absorbées par le cylindre de mesure. On peut, en installant un nombre suffisant de calibres de déformation à fils sur la surface du cylindre à mesurer, enregistrer électriquement les effets statiques et dynamiques.

Avant l'installation du cylindre de mesures sur la tour, son étalonnage a été entrepris au banc d'essais du laboratoire d'architecture de l'université technique du Danemark. Une fois le cylindre de mesure installé sur l'aéromoteur, on procéda à un second étalonnage, qui révéla que son comportement n'avait pas été modifié dans une mesure appréciable par l'installation.

On a pris des lectures pour des vitesses de vent s'échelonnant de 10 à 20 m/s. Celles que l'on comptait exécuter dans la gamme allant de 20 à 30 m/s n'ont pas encore été possibles.

Les mesures faites entre 10 et 20 m/s ont été enregistrées pendant de brèves périodes (cinq secondes environ) pendant lesquelles on peut admettre que la vitesse du vent restait très sensiblement constante.

On a enregistré l'action de la poussée sur le moyeu des pales, ainsi que l'effet de torsion sur l'axe vertical de la tour. Bien que les mesures n'aient été faites, jusqu'à présent, qu'à des vitesses de vent de 20 m/s au maximum, il semble y avoir une large mesure de sécurité quant à l'action de la poussée sur le moyeu de la pale. En ce qui concerne la torsion autour de l'axe vertical de la tour, on a mesuré des valeurs, à cette gamme de vitesses du vent, qui dépassaient celles qui déterminaient les dimensions, ce qui n'a d'importance, en pareil cas, que pour la roue dentée d'entraînement.

VARIOUS RELATIONSHIPS BETWEEN WIND SPEED AND POWER OUTPUT OF A WIND POWER PLANT

G. Clausnizer *

For the technical and economical valuation of wind power plants, the knowledge of the relationship between wind speed and power output, the so-called power characteristic, is of greatest importance. This characteristic varies according to the type and magnitude of the wind power plants, as well as to the rated output of the generator. Furthermore, the mode of operation of wind power plants marked by the two extremes, i.e., loading of batteries on the one hand, and synchronous interaction with an electrical network on the other hand, has a significant influence on the characteristic.

Fundamental difficulties are encountered in measuring the relationship between wind speed and power output. The magnitude of wind speed close to the ground varies very rapidly with time and may be quite different at two locations not far apart. The reason for this is the turbulence produced by obstacles in the path of the air-stream. Recordings of sensitive anemometers therefore show the well-known zigzag curves. As a wind power plant is mostly within the turbulence zone of the free atmosphere, it is thus exposed to velocities varying to a great extent both temporally and locally.

The generated power therefore also shows great variations, although the often considerably large swept circle and the inertia factor of the rotating masses of the plant produce a certain smoothness of the power performance. Comparing temporally correlated instantaneous values of wind velocity and power output, a field of widespread points is obtained from which the connection sought after cannot be determined in a satisfactorily exact manner.

The simplest way to overcome this difficulty is the temporal mean value of velocity and power. Hourly and, to a much greater extent, daily, mean values lead to a sufficiently exact reproducible relationship between wind speed and power output. The determination of the power characteristic in hourly or daily mean values is, therefore, up to the present common practice.

In examining the economic possibilities of installing a wind power plant at a certain place, the wind conditions in hourly or daily mean values must be sufficiently known. This necessitates some expenditure as to personnel and measuring equipment which is not always available at very remote places. Fortunately, the annual mean value of the wind velocity is specifically constant at each place; moreover, it is easily determined by simple integrating anemometers. Besides, maps on which points with the same annual mean value of wind velocity are connected are available for many parts of the world. Therefore, it is necessary to know the power characteristic of a wind power plant in annual mean values, because with this characteristic it is possible to state the average annual output. Thus, the energy production from the annual mean velocity for a given place can be found and it is possible to estimate whether the installation of wind power plants at that particular place is economically feasible.

An experimental determination of the characteristic in annual mean values for a single plant requires years, and for this reason it is not put into practice. On the other hand, the characteristic in hourly or daily mean values is quite different from the characteristic in annual mean values, since measurements of a wind power plant operating in parallel with an electrical network (1), described below, have shown that the characteristic also changes considerably with the length of the time interval over which the mean value was taken (measuring time interval δ).

Measurements

The a/m measurements were carried out on the Stötten test field of the Studiengesellschaft Windkraft e. V. Stuttgart, under the guidance of Dr. Hütter. A two-bladed Allgaier-Hütter wind power plant, with a rotor 10 m in diameter and a three-phase induction generator of 8.8 kW, operated parallel with an electric network. At sufficient wind speed, an automatic device connected the plant parallel to the grid and disconnected it again at power reflux. A cup-anemometer was positioned at 50 m distance from the wind power plant, at the same level as the rotor axis, 10 m above ground. The anemometer made a contact on a Tritschler-quantum recorder every 20 m run-of-wind.

In this device, each pulse is forwarding a paper tape by 0.2 mm. At the end of 2.5 min, a time marking is perforated on the tape, so that the length of tape between two markings indicates directly the wind velocity existing during this interval. The power output was recorded on a second quantum recorder; an electric meter made a contact every 0.44 kWh. Here also the metering interval was 2.5 min. In both quantum recorders, the perforation was simultaneous.

* Hamburgische Electrizitäts-Werke AG, Hamburg.

Naturally, it is the aim to keep the measuring time interval as short as possible in order to be able to obtain in a short time many measurings of both wind velocity and power output. During the tests in Stötten, it became evident, however, that it is not advisable to pass over to measuring time intervals shorter than 2.5 min at 50 m distance. Otherwise, the time lag of air between the anemometer and the wind power plant, as well as the influence of the wind direction and the already mentioned influences of turbulence, have an impermissibly strong effect on the result. The minimum measuring time interval required can be roughly estimated according to the formula

$$\delta \min \approx \frac{d}{6 \cdot v_{\min}} [\min]$$

where d is the distance between anemometer and wind power plant in meters, and $v_{\min}$ is the lowest wind velocity in m/sec, the exact measurement of which is still of interest.

With the equipment described, the characteristic of a wind power plant in mean values of 2.5 min was obtained in the short period of three days. The evaluation was made largely automatically by mechanical scanning of the munched tapes.

By taking the moving mean, the characteristic of the same plant in mean values of 5, 10 and 30 min, as well as 1, 2, 3, 4, 6, 8, 12 and 24 hr, was obtained. The results are shown in figure 1. Two of these curves are drawn separately above a fixed scale of wind velocity (figure 2). Here it becomes evident that the cut-in velocity (intersection of characteristic and velocity axis) decreases with increasing measuring time interval, a fact which results from the frequency distribution of wind velocities within the measuring time interval.

The fact can also be explained in that the characteristic in instantaneous values of a wind power plant connected to a grid is a straight line. Owing to the constant speed of the rotor enforced by the frequency of the network, the c_L vs. tip speed ratio λ curve is swept over at varying wind velocity. This curve is within operating range approximately proportional to λ^2, i.e. proportional to v^{-2}. Therefore, a dominating influence of the linear term of velocity on power remains.

For the testing of wind power plants, the important yield of these measurements is, as already mentioned, that the power characteristic of a wind power plant varies with the length of the measuring time interval. For this reason, the characteristics in daily and hourly mean values are not comparable with each other without considerable error, and the use of these characteristics for annual mean values is absolutely impossible.

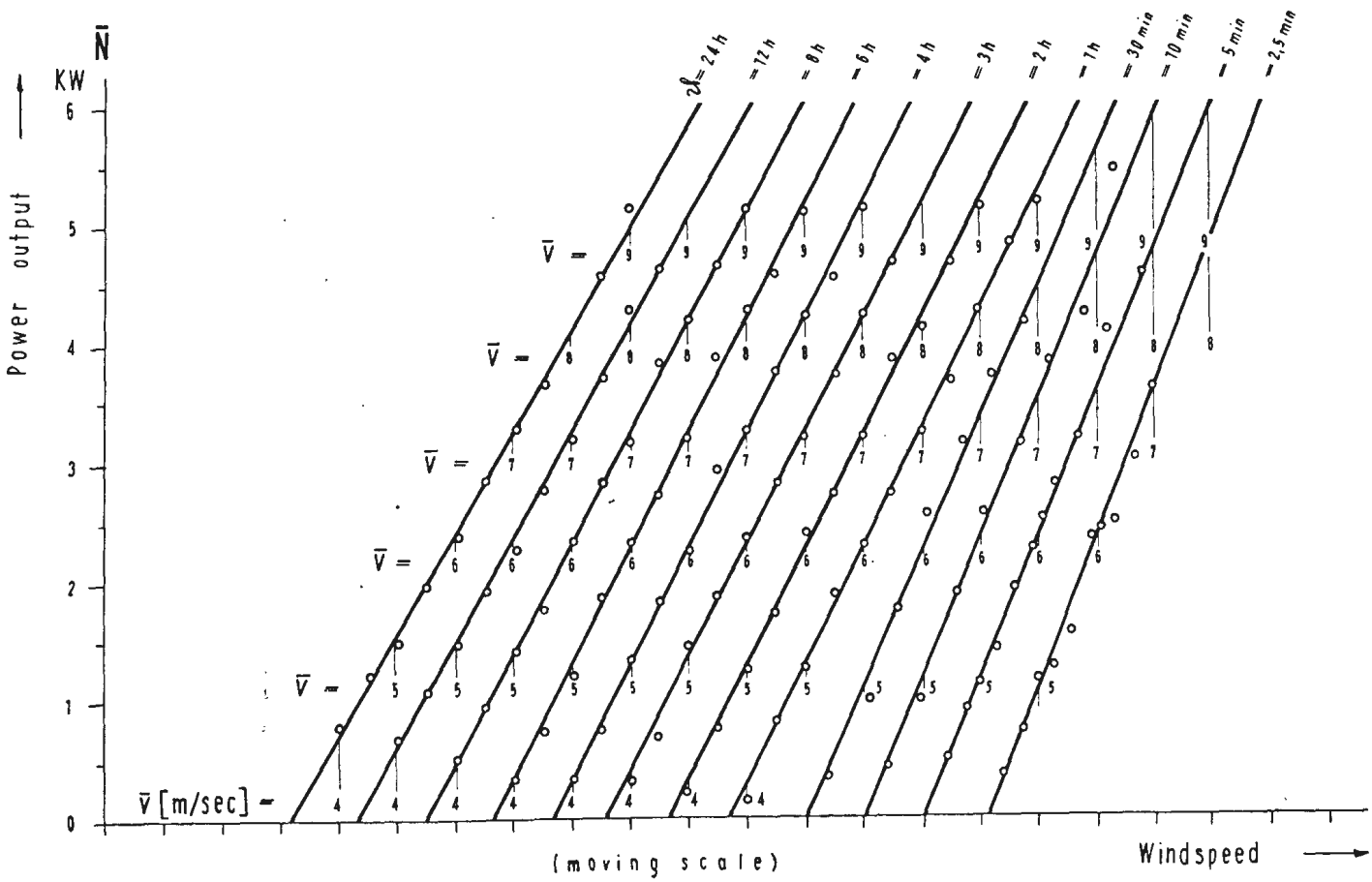


Figure 1. Wind speed/power output relationship for various measuring time intervals δ (experiments)

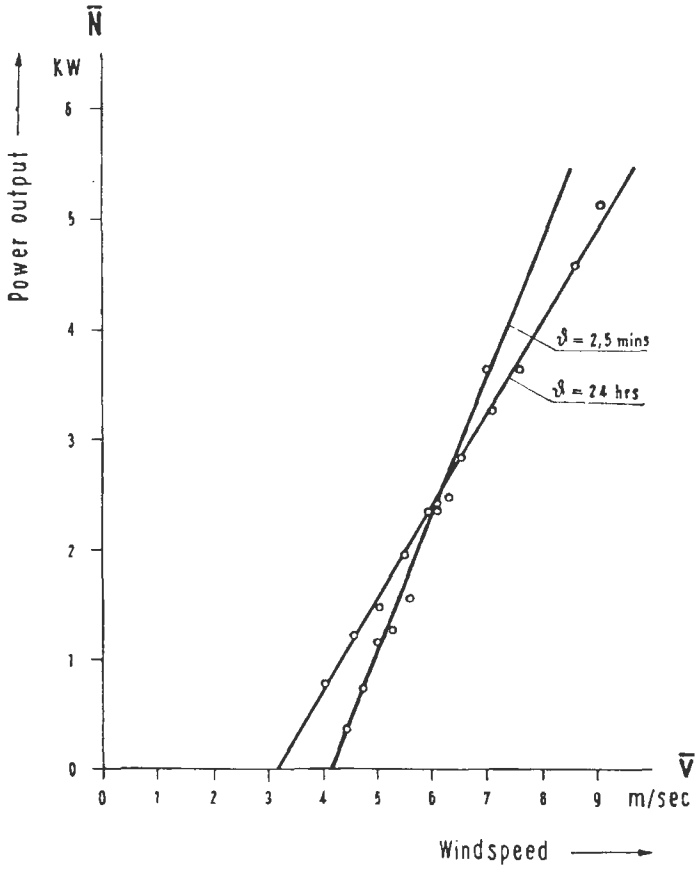


Figure 2. Characteristics in 2.5-min and 24-hr mean values

Measuring equipment

For the purpose of comparing various wind power plants and wind rotor types, uniform test methods are necessary. Here it is important to keep the measuring time interval as short as possible, to reduce the total testing time. It is therefore advisable to approach δ min. Furthermore, the equipment should be both simple and conventional and be adapted easily to testing conditions. The most important factor, however, is that the measuring time interval δ be the same throughout. If this should not be possible, the applied measuring time interval should at least be given with each characteristic.

Considering all these points, the following test method is proposed.

(*a*) The measuring time interval δ for wind rotors of $D \leqslant 10$ m in diameter, shall be $\delta = 2.5$ min. For larger wheels, $\delta = 6$ min is chosen.

(*b*) The totalizing anemometer — a cup-anemometer making contact after 15 m and 36 m run-of-wind, corresponding to the smaller and the larger δ, respectively, should be placed in a stream undisturbed as far as possible and at the same height as the rotor axis. To avoid a reaction from the wind rotor to the anemometer, a distance between these of 5 times the diameter of the rotor is considered to be sufficient (2).

(*c*) The energy produced by the generator is metered and a contact device operated each time a fixed quantity of energy has been produced. This fixed quantity of energy M_E is determined by the required accuracy of the measurement, as

$$M_E \approx \frac{0.5}{3} \cdot N_{\text{inst}} \qquad \text{for } \delta = 2.5 \text{ min}$$

$$M_E \approx 0.4 \cdot N_{\text{inst}} \qquad \text{for } \delta = 6 \text{ min}$$

where N_{inst} is the installed capacity of the generator in kW, and M_E the fixed quantity of energy in Wh/pulse. From this quantity of energy, the necessary constant of the meter used is derived. With

n = counts per disk-rotation (c/rev)
N_{inst} = installed generator capacity (kW)
w = transformer ratio

the constant of the meter in disk-revolutions per kilowatt/hour is

$$c \approx \frac{6\,000}{n} \cdot \frac{w}{N_{\text{inst}}} \qquad \text{for } \delta = 2.5 \text{ min}$$

$$c \approx \frac{2\,500}{n} \cdot \frac{w}{N_{\text{inst}}} \qquad \text{for } \delta = 6 \text{ min}$$

As the quotient of transformer ratio and installed generator capacity $\frac{w}{N_{\text{inst}}}$ is always of the same order of magnitude, the formulae show that the same meter can be used for different installed capacities. Only the transformers have to be replaced, which causes less expenditure and saves time.

(*d*) Run-of-wind and energy pulses are recorded by two synchronized quantum recorders. Their time constants can be changed by simple switching from 2.5 min to 6 min.

With the described measuring equipment , it should be possible to gather within a few days as many measurings as required for a statistical evaluation. The evaluation itself is done by mechanical scanning of the tapes and by classification of the determined values into individual groups, to which mean values of wind velocity and power, respectively, are assigned. From the abundance ratio of the individual groups, duration curves for both wind speed and power can be drawn. If this is done in the way as shown in figure 4, the power characteristic can be easily determined from the two duration curves by graphs.

Thus, in a relatively short time, comparable characteristics of various types of wind power plants can be obtained. The short testing period makes it possible to examine experimentally and to prove the effect of technical improvements on installed wind power plants. This may be of interest for the development of such plants. Furthermore, acceptance tests can be carried out to check the terms of guaranty given.

Power characteristic in annual mean values

The characteristic in short-time mean values is particularly suitable for the technical evaluation of wind power plants, as was previously shown. If,

however, economic aspects are involved, especially the search for favourable sites, it is necessary to know the characteristic in annual mean values. Since the characteristic cannot be determined by experiments, all that can be done is to attempt to calculate its shape from short-time measurements.

This attempt was successfully carried out for a wind power plant connected to a grid (1). The calculation was simplified by the fact that in this case the short-time characteristic is a straight line, as explained above. The results of this work are discussed below.

Starting with the characteristic in mean values of 2.5 min and 6.0 min, respectively,

$$\overline{N} = C\,(\bar{v} - \bar{v}_n)$$

with $\overline{N}$ = mean value of power
$\bar{v}$ = mean value of wind velocity
C = incremental factor of the characteristic
$\bar{v}_n$ = mean value of cut-in wind velocity.

The two "constants" C and $\bar{v}_n$ are functions of the measuring time interval δ. The tests applied have demonstrated that the characteristic in instantaneous values ($\delta = o$)

$$N = C_o \cdot (v - v_{no})$$

is obtained by increasing C and $\bar{v}_n$ by a small percentage :

$$\delta = 2.5 \text{ min};\ C_o = 1.04_4 \cdot C;\ v_{no} = 1.02_8 \cdot \bar{v}_n$$
$$\delta = 6 \text{ min};\ C_o = 1.09_2 \cdot C;\ v_{no} = 1.03_6 \cdot \bar{v}_n.$$

Using an analytical formulation of the annual duration curve of the wind velocity (3)

$$\frac{t}{\delta} = e^{-x} \cdot \sum_{o}^{\chi} p \frac{x}{p!}$$

with

$$x = \frac{v}{\bar{v}}\,(\chi + 1)$$

where χ is a form factor of the order between 1 and 3, leading to the characteristic in annual mean values of the plant connected to a network

$$\overline{N} = C_o \cdot e^{-b} \left\{ (\overline{V} - V_{no}) \cdot \sum_{o}^{\chi} p \frac{b^p}{P!} + \overline{V} \frac{b^{\chi+1}}{(\chi+1)!} \right\}$$

with

$$b = \frac{v_{no}}{\bar{v}}\,(\chi + 1)$$

$$1 \leqq \chi \leqq 3$$

The influence of an overload control is taken into account by the factor

$$R = \frac{\overline{N}_R}{N} = 1 - \frac{t_A}{t_n}$$

whereby t_A is the time during which the overload control was operating and t_n the time during which the plant supplied power to the network. Both times can be calculated easily from the duration curve of wind velocity.

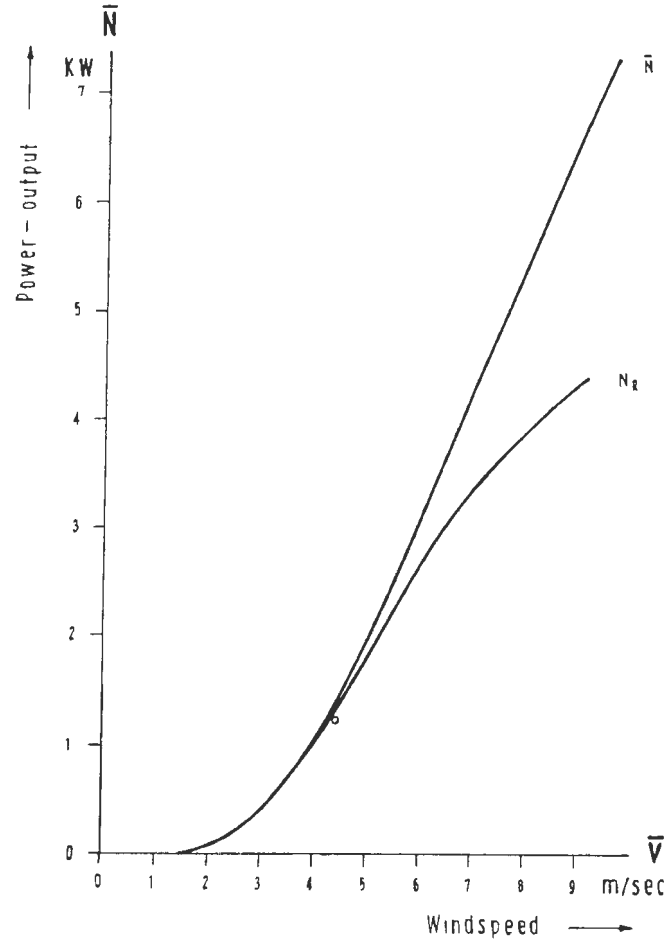


Figure 3. Power characteristic in annual mean values for a two-bladed Allgaier-Hütter wind power plant with a rotor 10-m in diameter and a generator-capacity of 8.8 kW operated in parallel to an electrical network

Figure 3 shows the characteristic $\overline{N}$ in annual mean values calculated for the wind power plant tested in Stötten; the overload control has been considered in the curve $\overline{N}_R$. Two different statements can be obtained from this figure. On the one hand, for each annual mean value of wind velocity, the attainable annual mean power output and, therefore, annual energy generation can be read. On the other hand, it is to be seen that on sites where the annual mean value of the wind velocity is above 5 m/sec, a larger-sized generator could be chosen. For Stötten, however, with an annual mean value of 4.4 m/sec, the rating of the plant was absolutely correct, in order to produce a maximum of electrical energy. Figure 3 also shows the mean power output which resulted during the twelve-month testing period in Stötten. The insignificant deviation can be explained by the outages unavoidable during tests.

For a wind power plant operated for battery loading, it is much more difficult to calculate the characteristic in annual mean values. In this case,

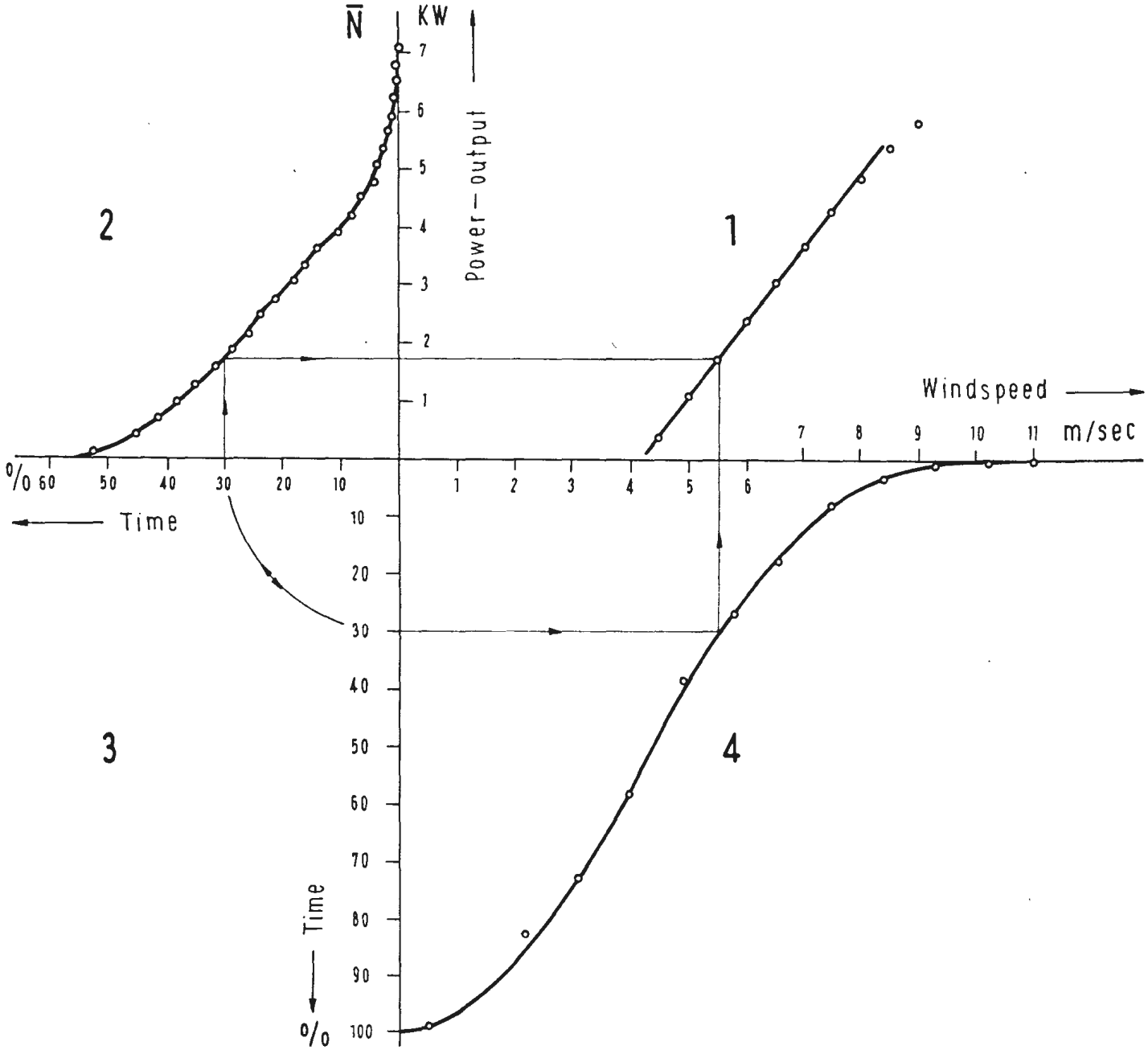


Figure 4. Evaluation of a short-period test
(Total time required for measurement T = 39 hr)

a short-period characteristic must be approximated by a polynomial of a higher order, of which the constants probably all depend on the measuring time interval δ. This dependency must be determined again by experiments. A further difficulty is that the power output of the plant depends on the state of battery charge. This means that the structure of demand is of great significance and may differ largely from one case to another. To what extent it could be posible to agree upon general assumptions cannot be examined here in more detail.

Conclusions

This paper emphasizes the fact that the power characteristic of a wind power plant varies with the measuring time interval and that for the particular case of a plant connected to a network, the characteristic in annual mean values can be determined by short-period tests. A measuring equipment by which the short period characteristic can be quickly obtained could provide a uniform basis for evaluating the productivity of wind power plants.

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Summary

The relationship between wind speed and power output of a wind power plant, the so-called power characteristic, can only be determined by statistical methods. This means that the power characteristic has always to be given in temporal mean values of wind speed and power output.

In this paper, measurements on a wind power plant connected to an electrical network are described. The results show clearely that the characteristic varies with the length of the time interval over which the mean value was taken, i.e. the measuring time interval δ.

For the technical valuation of wind power plants, e.g. for proving the effect of improvements carried out on the plant, it is useful to keep the measuring time interval as short as possible in order to keep the total measuring time short. Various influences, however, do not make it possible to go under a certain limit of δ for which an approximative expression is given.

A simple measuring equipment is proposed for standard short-period tests, consisting of a cup-anemometer, an electric meter and two quantum recorders for both run-of-wind and electric energy. The tapes of the quantum recorders are scanned automatically so that the short-time characteristic of a wind power plant can be determined by this equipment experimentally within a few days.

Finally, a method is dealt with enabling the calculation of the characteristic in annual mean values from such short-period tests for a wind power plant connected to an electrical network. This special characteristic is of interest for the economic valuation of a wind power plant and for the evaluation of a suitable site. This relationship normally can be obtained experimentally only in unreasonably long periods. On the other hand, the annual mean results have shown that characteristics in hourly or daily mean values cannot be used as annual mean values. The outlined calculating method shows the possibility of obtaining, at least approximatively, the characteristic of a wind power plant connected to a network in annual mean values.

QUELQUES RAPPORTS ENTRE LA VITESSE DU VENT ET LA PUISSANCE DISPONIBLE D'UNE CENTRALE ÉOLIENNE

Résumé

Les rapports qui lient la vitesse du vent et la puissance disponible d'une centrale éolienne, en d'autres termes son coefficient de puissance, ne peuvent être établis que par des méthodes statistiques. Ceci revient à dire que ce coefficient doit toujours être indiqué sous la forme de moyennes, par rapport à l'argument temps, de la vitesse du vent et de la puissance disponible.

On décrit, dans le présent mémoire, les mesures effectuées sur une centrale éolienne reliée à un réseau de distribution électrique. Les résultats démontrent clairement que la caractéristique varie avec l'intervalle sur lequel la moyenne est prise, c'est-à-dire avec le temps de mesure.

Pour aboutir à une évaluation technique des centrales éoliennes, par exemple pour mettre en lumière les effets des perfectionnements qui y sont apportés, il est indiqué de rendre la durée de mesure aussi courte que possible, de manière à maintenir le temps consacré à toutes les mesures dans des limites aussi exiguës que possible. Il existe cependant certaines influences en raison desquelles on ne saurait ramener ce temps d'expérience au-dessous d'une certaine limite, dont on donne une expression approchée.

On propose un système de matériel de mesure simple pour les essais standard de brève durée, constitué par un anémomètre à coquilles, un compteur électrique et deux enregistreurs totalisateurs pour l'énergie fournie par le vent et celle de l'électricité. Ces derniers utilisent un ruban à exploration automatique, si bien que la caractéristique à court terme de la centrale éolienne peut être déterminée expérimentalement avec ce matériel en quelques jours seulement.

On mentionne finalement une méthode qui permet de calculer la caractéristique, sous forme de moyennes

annuelles, à partir de ces essais sur de courtes périodes, pour une centrale éolienne reliée à un réseau électrique. Cette caractéristique spéciale présente de l'intérêt pour l'évaluation économique d'une centrale éolienne et celle d'un emplacement approprié. Normalement, ce rapport ne peut être déterminé expérimentalement qu'au prix de périodes indûment prolongées. Les déterminations anciennes de la moyenne annuelle ont démontré toutefois que les caractéristiques tirées des moyennes horaires ou journalières ne peuvent être utilisées à son évaluation. La technique de calcul soumise dans le présent mémoire laisse entrevoir la possibilité d'obtenir les caractéristiques d'une centrale èolienne liée à un réseau de distribution d'électricité pendant une année entière, tout au moins d'une maniète approchée.

MÉTHODES D'ESSAIS EMPLOYÉES SUR L'AÉROGÉNÉRATEUR 100 KW ANDREAU-ENFIELD DE GRAND VENT

F. H. Delafond *

L'aérogénérateur installé à Grand Vent près d'Alger (figure 1) est placé sur une plate-forme triangulaire de 100 m environ de côté dominant un relief aux formes arrondies, mais assez tourmentées. Ce relief crée donc des turbulences notables du vent, turbulences peu favorables aux mesures.

Pour mesurer le vent, un pylône en treillis supporte un anémomètre à la même hauteur que le centre de l'hélice et à une distance de 50 m (deux fois le diamètre de l'hélice). La direction du vent est généralement perpendiculaire à la ligne machine-pylône de mesures.

Du fait de la transmission d'énergie par dépression, nous disposions, en plus de la vitesse du vent et de la puissance produite, de paramètres intermédiaires : vitesse de rotation de l'hélice, dépression en aval de la turbine, débit d'air dans la turbine.

Les instruments de mesure sont groupés dans un pavillon à 50 m de la machine, et à 20 m du pylône. Les dépressions y sont transmises par des tubes souples, et mesurées par des manomètres à eau.

La vitesse de rotation d'hélice est mesurée avec un tachymètre à distance du type Aviation. La puissance est mesurée avec un wattmètre enregistreur ordinaire. Pour le vent, on utilisera d'abord un anémomètre à coupelles de fabrication courante.

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Essais

Premier stade

Quand la machine commença à fonctionner, en novembre 1957, les mesures furent assez grossières, du fait de l'imprécision de l'anémomètre. Les résultats (vitesse du vent-puissance produite) semblaient très dispersés, et on se rendit compte de l'impossibilité de faire des lectures simultanées et fréquentes des cinq appareils de mesure, plus l'heure.

On décide donc de grouper tous les appareils sur un panneau éclairé qu'on photographierait toutes les secondes environ au moyen d'une caméra de 16 mm.

Pour la mesure du vent, nous avons conservé le transmetteur à coupelles, mais remplacé le récepteur par un galvanomètre plus sensible (0,1 mA 1 volt) avec redresseurs au germanium. Pour l'ajuster et l'amortir, nous l'avons muni d'une résistance en série et un condensateur en parallèle.

Deuxième stade d'essais

Cette installation (figure 2) ne fut en état de marche qu'au début de 1959, divers ennuis mécaniques étant survenus entre-temps à la machine.

Nous avons alors pu commencer à faire des enregistrements de mesures d'environ 30 minutes sans interruption. Pour cela nous avions réglé le limiteur de

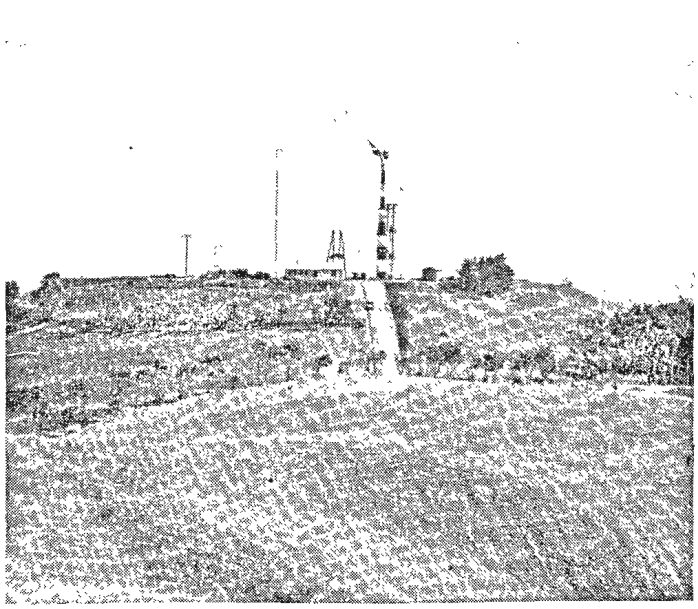

Figure 1

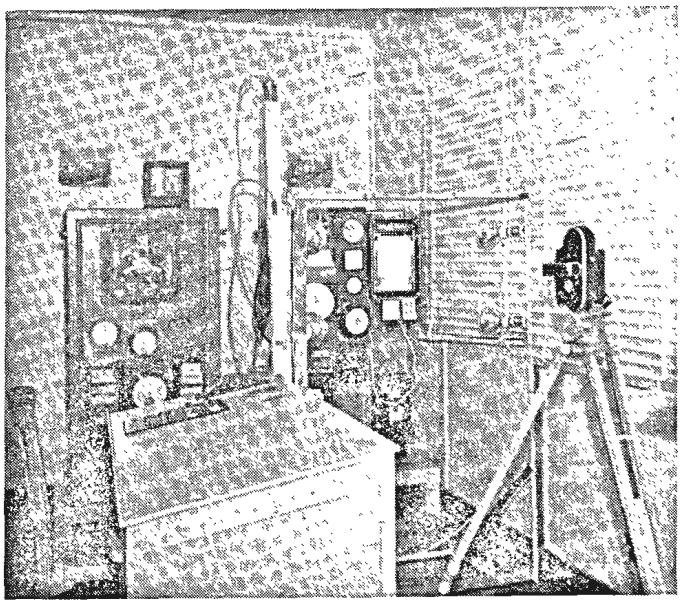

Figure 2

régime d'hélice à 111 t/min au lieu de 100 t/min, pour disposer d'une zone de mesures aussi étendue que possible sans qu'il entre en action.

La première série d'essais fut faite avec un angle de calage des pales de 7°. Puis quatre autres séries d'essais furent effectuées, en réduisant légèrement le calage entre chaque série. On disposa ainsi d'un nombre de mesures considérable (plus de 50 000), mais dont l'analyse était difficile.

En portant sur un graphique les vitesses du vent et les puissances produites, on trouvait un nuage de points d'une largeur considérable (figure 3) qui montre bien la difficulté d'obtenir la loi de corrélation en atmosphère turbulente.

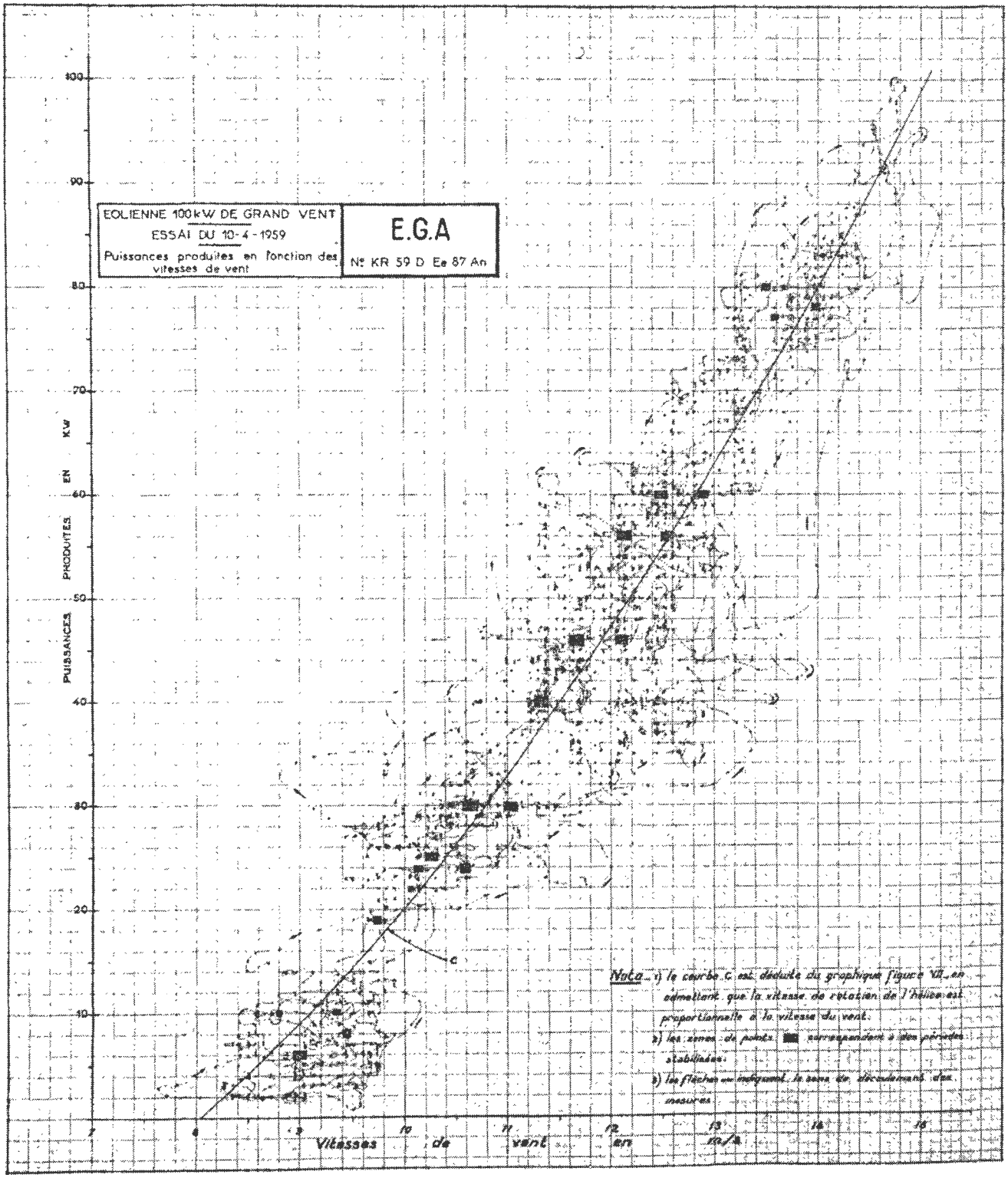

Figure 3

Interprétation des résultats

Méthode du choix

Pour étudier les résultats de ces mesures, on commença par transposer toutes les mesures photographiées, en chiffres, rangés chronologiquement sur des tableaux.

En examinant ces tableaux de chiffres, il fut aisé de repérer les moments où la vitesse du vent et la puissance produite restaient stables pendant 5 à 10 secondes. On peut penser qu'on est alors en régime permanent, et qu'en limitant son choix à ces valeurs on pourra tracer la courbe cherchée.

En fait, les points ainsi obtenus (figure 3, zones ombrées) sont beaucoup moins dispersés que l'ensemble des mesures. L'écart maximum de puissance pour un vent donné est de l'ordre de 10 kW au lieu de 50 kW. Mais on ne peut tout de même pas tracer une courbe qui se rapproche de ces points d'une manière satisfaisante.

Par contre, si l'on considère les relations entre les autres paramètres que le vent, et qu'on limite son choix aux périodes de stabilité, on trouve que tous les points choisis pendant ces périodes sont parfaitement alignés sur des courbes. Deux de ces relations sont particulièrement simples : la dépression est proportionnelle au carré de la vitesse de rotation de l'hélice (figure 4), et le débit d'air est proportionnel à la vitesse de rotation de l'hélice.

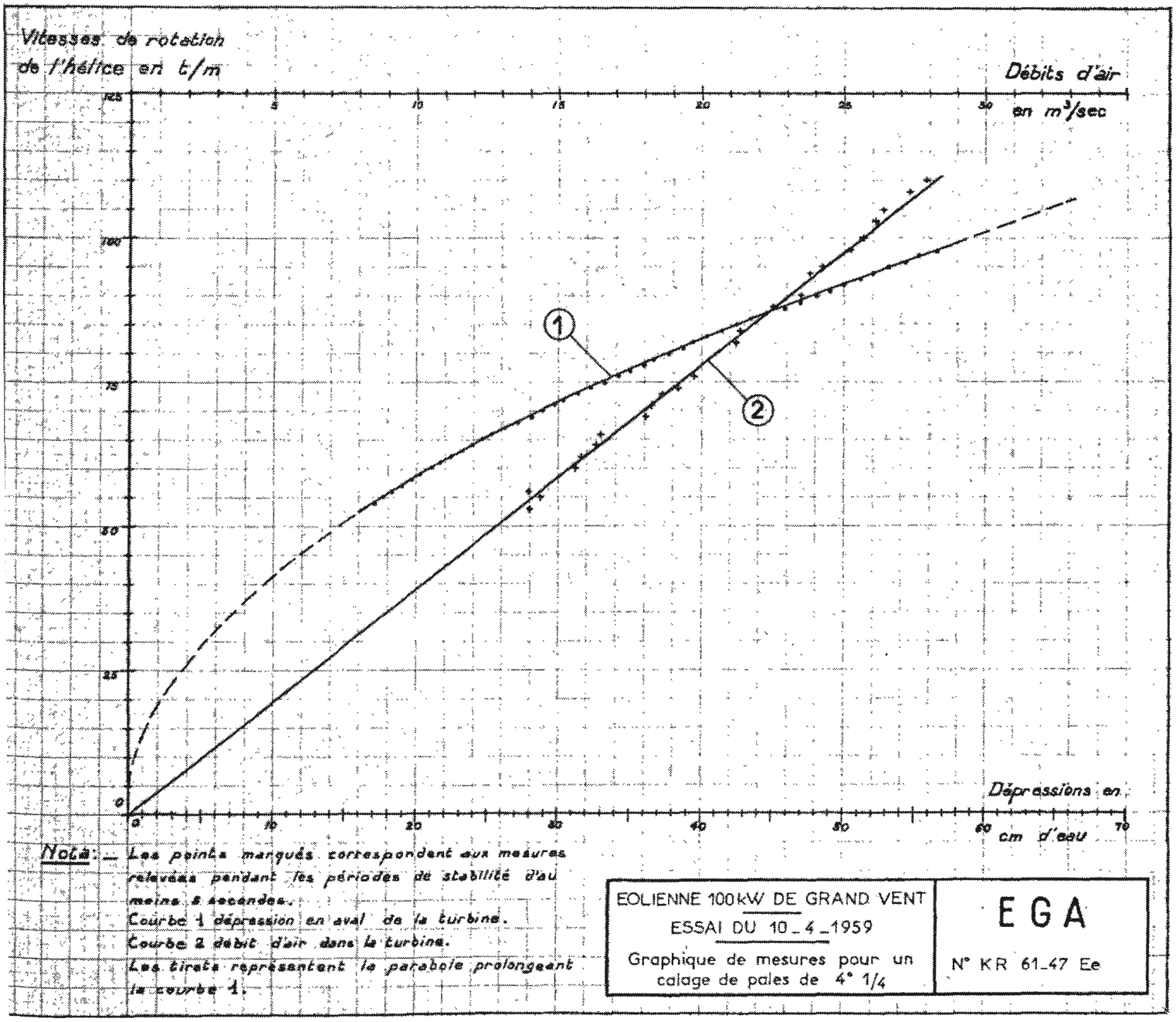

Figure 4

Méthode statistique

N'ayant pas obtenu un si bon résultat pour la relation vitesse du vent-puissance, nous avons cherché à utiliser le grand nombre de mesures dont nous disposions, en employant une méthode statistique.

Pour cela nous avons calculé la moyenne des puissances pour chaque vitesse de vent, ou, plus exactement, pour chaque tranche de vitesse de 0,3 m/s de la largeur. En portant ces résultats sur un graphique, on obtient une série de points (figures 5 et 6) qui permet de tracer une courbe (*a*) plus facilement que la précédente méthode, par le simple fait que les points sont régulièrement espacés en abscisse. Le calcul statistique indique que ces points se rapprocheront d'autant mieux d'une courbe que le nombre de mesures effectuées sera plus grand. L'expérience montre qu'il faut un minimum de 50 mesures par tranche de vitesse pour avoir un résultat acceptable.

Cette courbe représente-t-elle bien la relation cherchée? Pas exactement, car elle donne seulement la puissance la plus probable pour un vent donné. Inversement, si l'on fait la moyenne des vitesses de vent pour chaque puissance, on obtient une autre série de points, donc une autre courbe (*b*), qui, elle, donne la vitesse de vent la plus probable correspondant à une puissance donnée. La théorie, comme la pratique, montrent que ces deux courbes se croisent aux environs du centre de gravité du nuage de points initial, mais font entre elles un angle d'autant plus

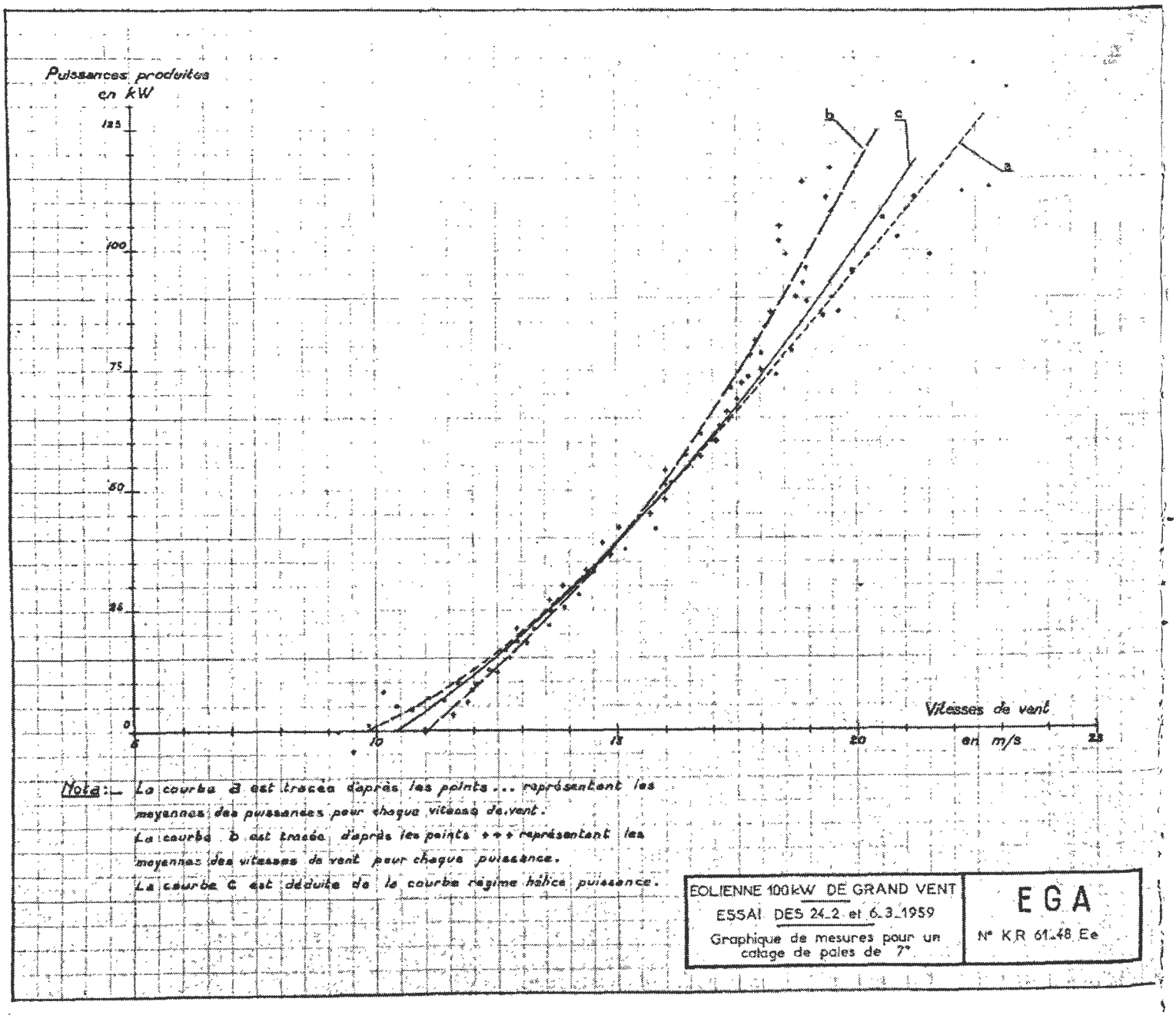

Figure 5

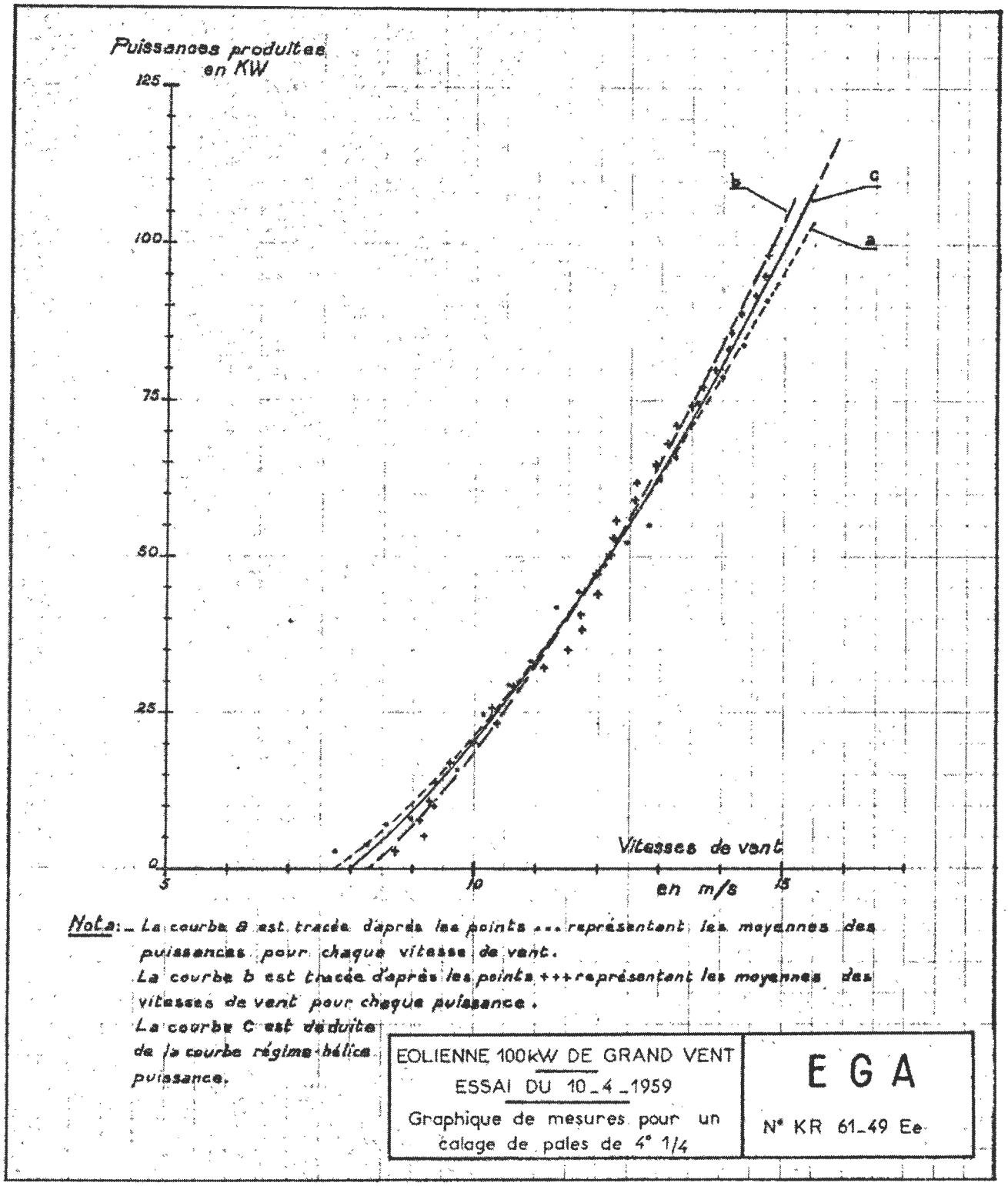

Figure 6

grand que le nuage de points initial est plus large et plus court. Cet angle ne se réduira pas si l'on augmente le nombre de mesures : ceci ne fera que préciser davantage le tracé des deux courbes, en rapprochant les points aberrants. Les seules améliorations qu'on puisse espérer s'obtiendront en allongeant le nuage de points initial, c'est-à-dire la plage des puissances au cours de l'essai (jusqu'en zone négative par exemple) et en diminuant sa largeur, c'est-à-dire en opérant un jour où le vent est aussi peu turbulent que possible. Il faut donc choisir, pour effectuer l'essai, un jour où le vent, tout en étant peu turbulent, couvrira équitablement la gamme des vitesses souhaitées, sans jamais la dépasser ! On conçoit aisément qu'il est rare de rencontrer cette chance, mais on pourra y parvenir plus facilement en opérant en deux ou

trois fois, sans que le résultat final s'en trouve trop perturbé.

Méthode spéciale à l'aérogénérateur Andreau

Nous avons vu que sur la machine du type Andreau nous disposons de trois autres paramètres mesurables, entre lesquels les relations sont bien définies, ainsi qu'avec la puissance produite. Nous avons même signalé que la dépression est proportionnelle au carré de la vitesse de rotation de l'hélice, et le débit d'air proportionnel à cette même vitesse (figure 4), la précision des mesures effectuées étant d'environ 1 et 5 p. 100.

Or, dans les limites où travaille la machine (dépression inférieure à 60 cm d'eau) la puissance disponible dans la veine d'air traversant la turbine est, à 1 p. 100 près, proportionnelle au produit de ces deux grandeurs, donc au cube de la vitesse de rotation de l'hélice.

La puissance disponible dans le vent étant elle-même proportionnelle au cube de la vitesse du vent, cette similitude nous a amenés à penser que, si la machine travaillait en écoulement permanent, la vitesse de rotation de l'hélice devrait être exactement proportionnelle à la vitesse du vent. La courbe représentant cette rotation serait alors une droite passant par l'origine.

Comme nous sommes en régime transitoire, nous trouvons un nuage de points. Mais, avec l'hypothèse de proportionnalité, il devient inutile, pour obtenir

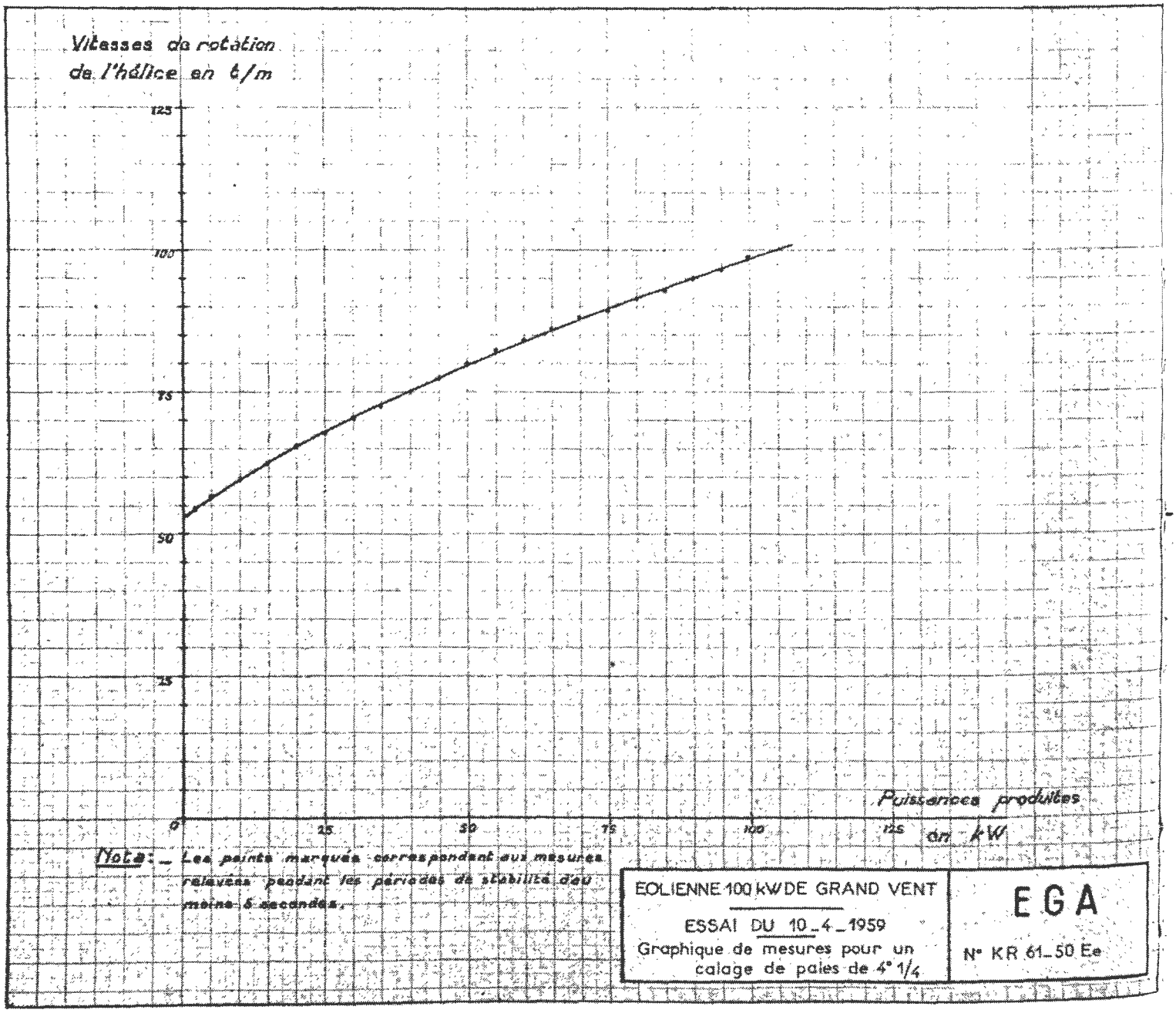

Figure 7

cette relation, de faire des moyennes pour chaque tranche de vitesses, car nous savons que la droite de régression est celle-ci qui joint le centre de gravité de ce nuage de points à l'origine. L'ambiguïté se trouve levée et les calculs de dépouillement, notablement simplifiés.

Connaissant alors la relation entre la vitesse du vent et la vitesse de rotation de l'hélice, et, par les mesures citées plus haut, la relation entre cette dernière et la puissance produite (figure 3), il suffira d'éliminer la vitesse du vent pour obtenir, sans ambiguïté, la relation entre la vitesse du vent et la puissance produite.

Nous avons donc tenté de démontrer que la vitesse de rotation de l'hélice, en régime permanent, doit bien être proportionnelle à la vitesse du vent.

Pour cela il faut admettre que pour un angle d'incidence donné, la portance et la trainée de chaque élément de pale sont proportionnelles au carré de la vitesse relative, ce qui semble valable dans l'intervalle considéré, 25 à 125 m/s environ.

Nous ne reproduirons pas la démonstration, qui est fastidieuse, mais, intuitivement, on comprend facilement que, les lois d'écoulement de l'air étant supposées les mêmes à l'extérieur de l'hélice et à l'intérieur de la machine, le rapport de ces deux vitesses d'écoulement reste constant.

Pour obtenir la relation vitesse du vent-vitesse de rotation de l'hélice, il suffit donc de calculer la valeur moyenne de toutes les mesures effectuées sur ces deux grandeurs. On en déduit la valeur moyenne du rapport vitesse vent/vitesse hélice, puis, dans la relation vitesse hélice-puissance (figure 7), on multiplie la première par ce rapport pour obtenir la relation vitesse vent-puissance produite (figures 5 et 6, courbes *c*).

Critique des méthodes d'interprétation des essais

La méthode du choix présente l'inconvénient d'un certain arbitraire, de ne donner qu'un petit nombre de points de la courbe, que ces points sont très inégalement répartis, et enfin assez dispersés. Il est difficile de tracer une courbe prétendant à quelque précision à partir de ces résultats.

La méthode statistique supprime l'arbitraire, et donne le nombre de points désirés, régulièrement répartis. Par contre, elle nécessite un gros travail de dépouillement, et la dispersion, même avec plus de 50 mesures par point, reste notable. On voit qu'elle est plus grande sur le graphique de la figure 5 (essai effectué en deux fois) que sur le graphique de la figure 6, qui résulte d'un essai ininterrompu.

Les courbes *a* et *b* sont cependant plus faciles à tracer que par la méthode du choix (zones ombrées, figure 3) à cause de leur répartition régulière des points. Mais le gros inconvénient est l'introduction d'une ambiguïté d'autant plus grande que le vent est plus irrégulier.

La méthode nouvelle que nous avons employée pour la machine du type Andreau supprime l'ambiguïté, la dispersion des points, et simplifie le dépouillement, ce qui rend possible l'utilisation d'un plus grand nombre de mesures, d'où un meilleur résultat statistique.

Elle est néanmoins discutable, car elle est fondée sur une démonstration basée elle-même sur des données qu'on sait être légèrement inexactes (erreurs de l'ordre de 2 p. 100 dans l'intervalle de mesures considéré).

La meilleure vérification de son exactitude est sa comparaison aux résultats des méthodes précédentes : elle donne une courbe beaucoup mieux définie, située entre les courbes de la méthode statistique (figures 5 et 6) et voisine des points choisis (figure 3).

Son intérêt semble très limité, puisqu'elle ne peut s'appliquer qu'aux machines du type Andreau. Mais elle permet de juger, par comparaison laquelle est la plus valable parmi les méthodes précédentes, et d'étendre ce jugement aux essais d'autres machines.

Méthode d'essais proposée

Choix de la méthode d'interprétation

Pour les raisons exposées ci-dessus, nous ne conseillons pas la méthode du choix, à moins qu'elle ne donne de meilleurs résultats en des sites où le vent est moins turbulent.

La méthode nouvelle que nous avons employée peut être conservée pour les machines du type Andreau, puisqu'elle donne un résultat qui semble bon, et en tous cas sans équivoque.

Pour les autres machines, il faut donc se reporter à la méthode statistique. Mais comme elle conduit à deux résultats (courbes *a* et *b* des figures 5 et 6) d'autant plus différents que la turbulence du vent est plus grande au moment de l'essai, et que le résultat exact se situe sensiblement à mi-distance entre les deux précédents (courbe *c*), nous proposons de considérer comme exacte la courbe obtenue à partir des courbes *a* et *b* en prenant la moyenne des vitesses de vent pour chaque puissance.

Conditions dans lesquelles les mesures doivent être effectuées

Les mesures doivent être régulièrement espacées dans le temps, à environ 1 seconde d'intervalle et rigoureusement simultanées. Pour cela, la photographie d'appareils à lecture directe semble très préférable à un enregistreur multiple.

Il faut disposer d'au moins 2 000 mesures consécutives et bien réparties sur la gamme des puissances, de manière à pouvoir la diviser en 30 tranches égales comportant chacune plus de 50 mesures. Si on ne peut rencontrer les conditions de vent nécessaires pour effectuer cet essai en une seule fois, on pourra utiliser

deux ou trois périodes d'essai, à condition d'effectuer séparément les corrections de densité d'air. Pendant ces essais, la puissance peut devenir négative, mais il faut alors que le wattmètre puisse la mesurer. Aucun limiteur de puissance ne doit entrer en action pendant ces périodes.

Pour éviter les perturbations dues aux micro-turbulences, l'anémomètre doit avoir un temps de réponse d'au moins une seconde, sensiblement égal à celui du wattmètre, compte tenu de l'inertie de l'hélice. Ces temps de réponse doivent être égaux à la montée et à la descente.

L'anémomètre doit être placé à même hauteur que l'axe de l'hélice. La distance entre l'anémomètre et le centre de l'hélice doit être environ égale au double du diamètre de cette dernière, pour éviter son interaction, tout en restant aussi près que possible.

Au cours d'un essai, l'anémomètre doit toujours être en dehors de l'angle de 120° en aval de l'hélice, pour ne pas être influencé par son sillage.

Résumé

Les premiers essais de la machine ont montré une grande dispersion dans les résultats de mesures. De plus, il était impossible de faire une lecture simultanée de tous les appareils à une cadence assez rapprochée.

On a donc installé une caméra qui photographie toutes les secondes le tableau des instruments de mesure.

On dispose alors de mesures très nombreuses et parfaitement objectives. Parmi ces mesures, on peut choisir celles qui correspondent à des périodes de stabilité de 5 à 10 secondes.

Ce choix réduit notablement la dispersion dans la relation vitesse du vent-puissance produite, et la supprime entièrement dans les relations entre le régime d'hélice, la dépression, le débit d'air et la puissance produite.

- Le grand nombre de mesures permet également de faire la moyenne des puissances pour chaque vitesse de vent, ou inversement, la moyenne des vitesses de vent pour chaque puissance. Les deux courbes obtenues sont légèrement différentes et se croisent aux environs du centre de gravité du nuage des points mesurés.

Enfin, sur la machine Andreau, du fait qu'on dispose de paramètres intermédiaires et que les lois d'écoulement de l'air sont les mêmes (régime turbulent) pour le vent extérieur à l'hélice et pour le circuit intérieur à la machine, on a pu démontrer que la vitesse de rotation de l'hélice devrait être sensiblement proportionnelle à la vitesse du vent, en régime permanent. Ceci permet de lever le doute signalé plus haut, et d'obtenir une courbe bien tracée, qui se situe entre les deux précédentes. Cette méthode n'étant applicable qu'aux machines de ce type, il est nécessaire d'adopter une autre solution permettant de comparer les résultats d'essais des diverses machines.

La meilleure méthode semble être de tracer les deux courbes précédentes (moyenne des puissances et moyenne des vitesses) puis, entre ces deux courbes, de faire une moyenne des vitesses de vent pour chaque puissance.

A cela, on pourrait ajouter les conditions suivantes :

a) L'intervalle entre chaque mesure doit être de l'ordre de la seconde et chaque tranche doit comporter au moins 50 mesures;

b) L'ensemble des mesures couvrant toute la gamme des puissances de la machine doit être effectué si possible au cours d'un même essai, ou au maximum en trois essais, sans qu'aucune mesure ne soit éliminée entre le début et la fin d'une période d'essai;

c) L'anémomètre doit avoir un temps de réponse d'au moins 1 seconde sensiblement égal à celui de Wattmètre, et ces temps de réponse doivent être égaux à la montée et à la descente;

d) L'anémomètre doit être placé à même hauteur que l'axe de l'hélice à une distance de la machine égale au double du diamètre de l'hélice. Au cours d'un essai, il ne doit jamais se trouver dans l'angle de 120° à l'aval du centre de l'hélice.

TEST METHODS APPLIED TO THE ANDREAU-ENFIELD 100 KW WIND-DRIVEN GENERATOR AT GRAND VENT

Summary

The first tests of this generator gave results with a great scatter. Moreover, simultaneous readings of all the instruments could not be taken at sufficiently short intervals.

A camera was therefore installed, and the instrument panel was photographed at one-second intervals.

Very numerous measurements, all of them perfectly objective, have thus been made available. Among them, we may select series corresponding to periods of stability lasting 5 to 10 seconds.

This selection sharply reduces the scatter in the relation between wind speed and power output,

and suppresses it entirely in the relations between propeller régime, depression, air flow and power output.

The large number of measurements likewise makes it possible to average the power output for each wind speed, or to average the wind speed for each power-output level. The two curves obtained differ slightly, and intersect near the center of gravity of the cloud of measured points.

Finally, owing to the availability of intermediate parameters for the Andreau generator, and to the fact that the laws of airflow are the same (turbulent conditions) for the external wind outside the propeller and for the internal circulation in the machine, it could be demonstrated that the propeller speed must be substantially proportional to the wind speed under steady conditions. This eliminates the above uncertainty and gives a reliable and definite curve located between the two original curves. Since the method is applicable only to generators of this type, a different solution must be adopted for comparing the test results of different machines.

The best method appears to be to plot the two curves just mentioned (the mean of the power outputs and the mean of the wind speeds) and then, between these two curves, to plot the mean wind speed for each value of the power output.

The following conditions may be imposed.

(*a*) The interval between the measurements of each parameter should be of the order of one second, and each section should consist of at least 50 measurements.

(*b*) The set of measurements covering the entire power-output range of the generator should be made, if possible, during a single test, or at most in three tests, without eliminating any measurement at all between the beginning and end of a test period.

(*c*) The anemometer should have a response time of at least one second, substantially equal to that of the wattmeter, and these response times must be the same for increasing and decreasing wind speeds.

(*d*) The anemometer should be placed at the same height as the propeller shaft at a distance from the generator equal to twice the propeller diameter. During a test it must never be at an angle of 120° downwind from the propeller centre.

THE TESTING OF A WIND POWER PLANT

J. G. Morrison *

The investigations described in this report were made at the request of the scientific division of the Ministry of Power and were carried out at the Electrical Research Association's windmill testing station at Cranfield. The station is situated on top of a small plateau, 350 ft. above sea level, and is open to winds from the south and south-west, the prevailing wind direction.

The tests were conducted to establish methods for measuring the stresses set up in the windmill blade system and the output of the machine over short periods of time. The information to be obtained and methods adopted from these tests were required in connection with the design and testing of various wind power plants then under construction for the Ministry of Power.

Description of the plant and test equipment

Wind power plant

The windmill on which the tests were conducted was coupled to a 10 kW asynchronous alternator, the output of which was fed directly into a 3-phase, 50 c/s 440 volt network. The two 10-ft blades were constructed of laminated Douglas fir and designed to run down-wind of the tower structure. Provision was made for automatic pitch changing, but throughout the tests described, the blades were locked in the fine pitch position when the blade angle, at 0.75 radius, was $+2°$ to the plane of rotation. Static tests were conducted to determine the natural period of the blades in flexure and torsion, and records of these tests are shown in figure 1.

The machine was mounted on a lattice tower at a hub height of 45 ft (figure 2) and could be yawed in any direction by means of an electric motor.

The power output of the windmill alternator was measured by an auto-repeater, which is a quick response device for obtaining a direct current proportional to the power in an A.C. circuit. For recording purposes, the output of the auto-repeater was connected to one channel of a two-channel pen recorder.

Anemometers

Two omni-directional anemometers were used for measurement of wind speed — a highly responsive gust anemometer (1), and a small windmill-type anemometer fitted with balsa wood blades (2). The response of the former was of the order of 0.1 seconds and its output was recorded, in analogue form, on the second channel of the pen recorder. The windmill anemometer had a response time of approximately 0.25 seconds and its output, a series of pulses for a given short period-run-of-wind, was reproduced on one of the channels of a 5-channel photographic recorder together with the strains set up in the blades (figures 3, 4 and 5).

Strain measuring equipment

Strain gauges were attached to the blades to measure flexure and torsion at five positions along their length. The arrangement and positioning of the strain gauges are shown in figure 6. The supply to, and output from, the strain gauges, was transmitted *via* a multi-cored screened cable and 18-channel slip-ring assembly. The screened cable was supported and held clear of the rotating blades by means of a steel hawser anchored, at one end, to the non-rotating part of the slip-rings, and at the other, to a stake fixed in the ground at a suitable distance from the base of the tower.

The signals from the strain gauges, for alternating stresses, were amplified by four audio-frequency amplifiers and then recorded on the photographic recorder. In order to record average or steady stresses, the output signals from the strain gauge bridges were "chopped" (short-circuited) at a frequency ten times greater than the alternating stress frequency (figure 5).

Blade position marker

A micro-switch fixed to the housing of the windmill and operated once per revolution by a cam on the blade system gave an indication, on the records, of the blade position. The cam was arranged to operate the switch when one of the blades was at bottom-dead-centre, i.e. vertical. The switch, when "made", short-circuited the output from the windmill anemometer for a fraction of a second, appearing on the record as a short break in the wind-speed trace (figures 4 and 5).

Testing methods

As already stated, the generator output and signal from the gust anemometer were recorded side-by-side on a high-speed pen recorder. The blade stresses from four selected positions and wind-speed signal

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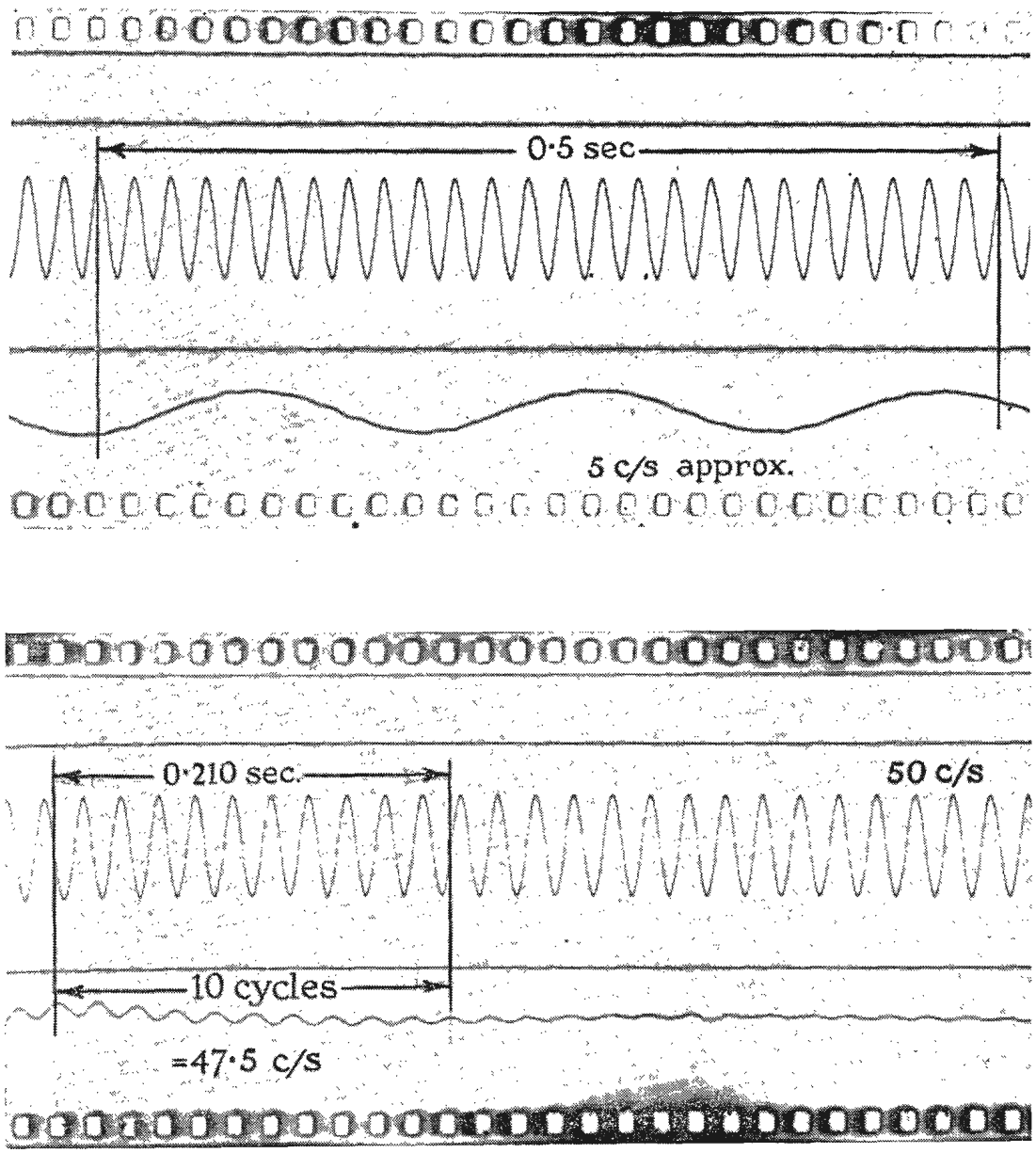

Figure 1. Natural period of blade in flexure (above) and torsion (below)

from the balsa mill anemometer were recorded simultaneously on the photographic recorder. A marker, common to both recorders, could be put in operation when it was desired to compare the two records over definite time periods. During analysis of the records, allowance was made for the displacement, up-wind, of the anemometer from the windmill.

Generator output

Analysis of early records showed that the response of the windmill to gusts of reasonable magnitude was sluggish, and in order to obtain a true wind-speed/generator-output characteristic, it was necessary to select points from the records when the wind speed had been steady, within ± 3 mph for periods of at least 3 seconds, and then take the average wind speed over the last 0.25 second of this period. The generator output corresponding to this wind speed was taken as the mean of that indicated at the end of the period.

Correlation of blade stresses with wind speed

Various methods of correlating blade stresses with wind speed were tried out initially, but the final method adopted was as follows:

(*a*) Alternating stress : the range of stress between the trough, caused by the reduction in wind velocity behind the tower, and the peak, due to the increase in wind velocity as the blade cleared the tower;

(*b*) Average stress : the algebraic sum of half the alternating stress, defined as above, and the minimum value of stress.

The reasons for adopting these methods are fully explained below.

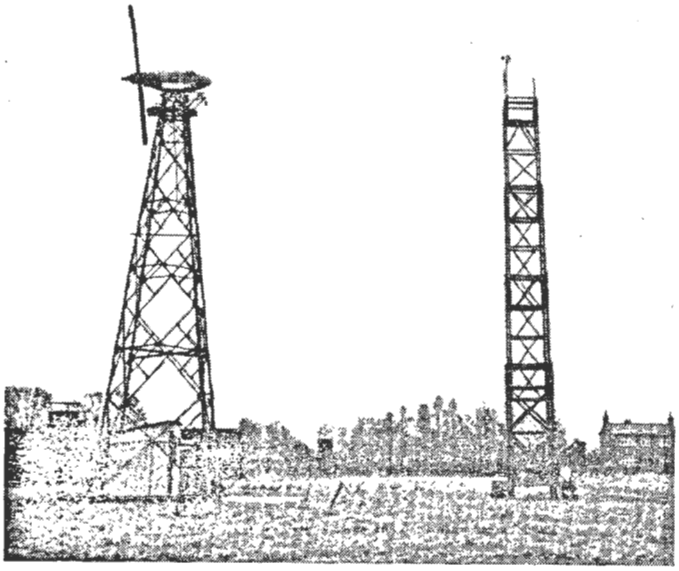

Figure 2. View of windmill and anemometer mast

The stress values thus obtained were related to wind speeds averaged over 0.25-second intervals and selected at points on the records where, again, the wind speed had been reasonably steady for a period of at least 3 seconds.

Results

The records from which the test results were extracted cover a mean wind-speed range of 18 to 38 mph, and a generator output of 0 to 10 kW. These tests were made over a period of 7 months and represent approximately 100 hours of running.

Midway through the tests, it was seen that the maximum stress in flexure was occurring at the 0.3 radius station (figure 3), and, in view of this, it was decided that all future investigations would be concentrated at this position on both blades, especially as it was obvious that there were no nodes along the blade length. At the same time, it was decided to discontinue measurements of blade torsional stresses because of their very small amplitude throughout the wind-speed range.

Interpretation of stress records

From the records it was observed that the cyclic variations of stress experienced by the blades was due almost entirely to the reduction in wind speed behind the tower. Figure 7 shows stress changes taking place at the root of the blade, due to this effect, during one revolution. The wind speed during the period considered had remained steady at 24 mph for 3 seconds, and the machine output was 3 kW.

Commencing at the point where the blade is at bottom- dead-centre (0°) and is experiencing a reduction in wind speed due to the tower structure ("tower shadow"), it will be seen that the alternating stress does not reach its minimum value, or trough position, on the stress curve, until it has rotated a further 31°. At some short period of time later, the blade receives the full force of the wind and commences to absorb this force in bending, until the maximum stress, or peak, position is reached. This change in wind velocity can be looked upon as an artificially created gust having a value equal to the wind velocity in the unscreened portion of the swept circle, minus the wind velocity behind the tower structure. In other words, the blades are subjected to a forcing vibration with a frequency of once per revolution, and the blades then vibrate at their natural period until, once again, the tower shadow intervenes and the cycle is repeated.

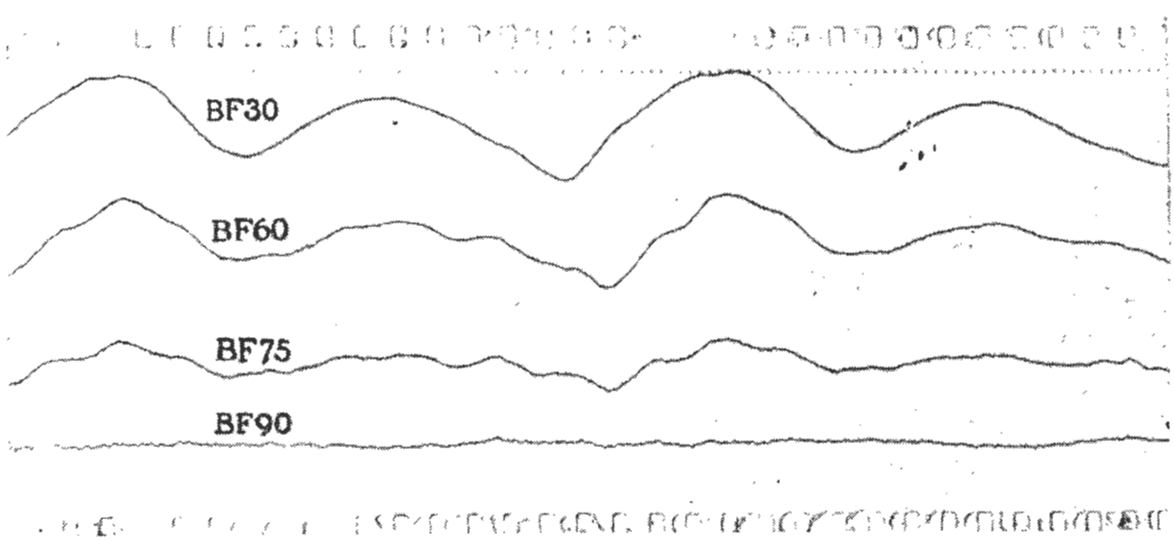

Figure 3. Flexural stress records along the length of one blade

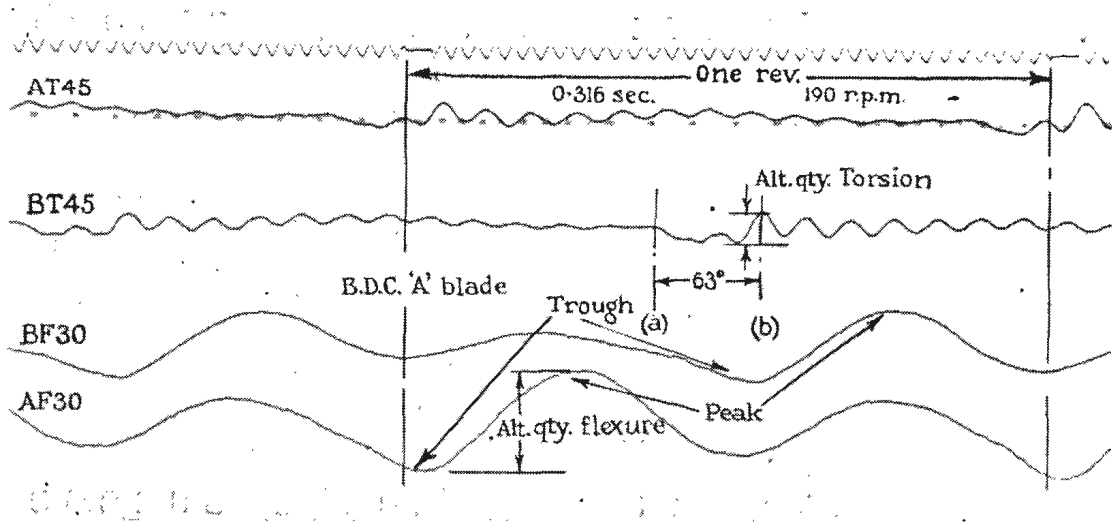

Figure 4. Alternating stresses in flexure and torsion

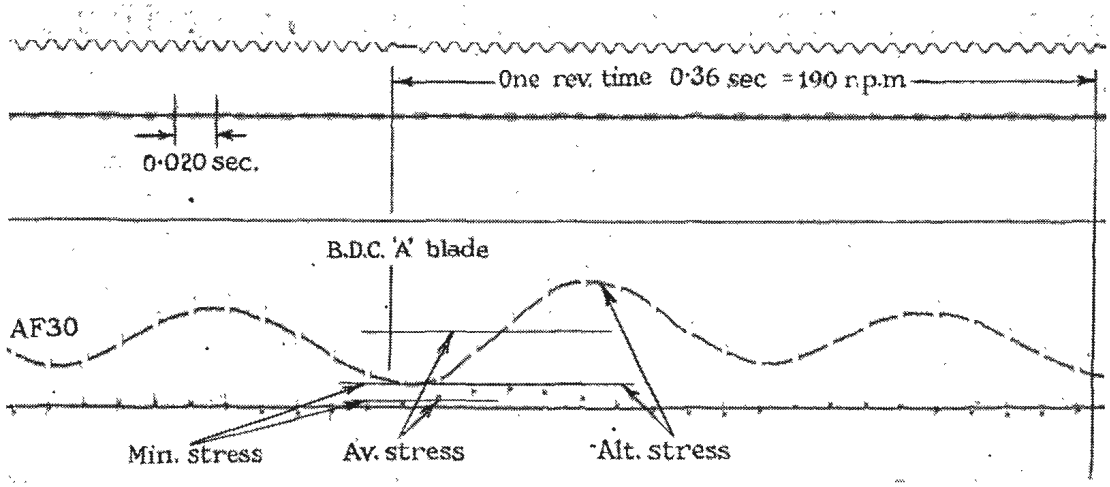

Figure 5. Typical record of "chopped" signal to give average stress value

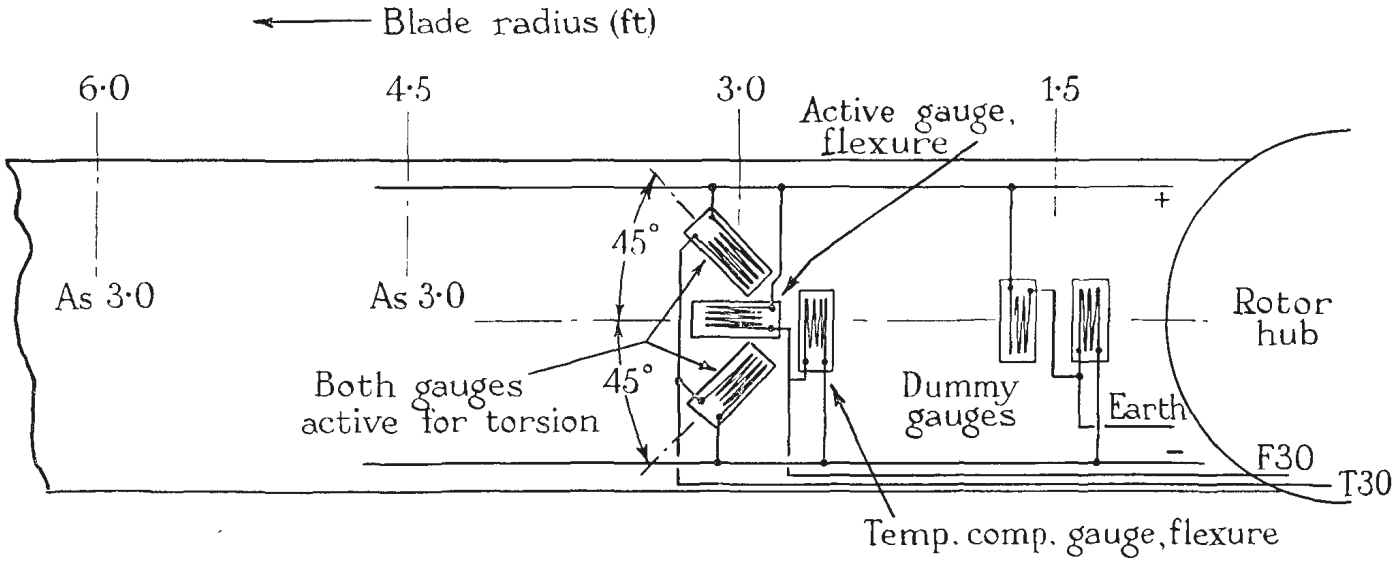

Figure 6. Arrangement and positioning of strain gauges

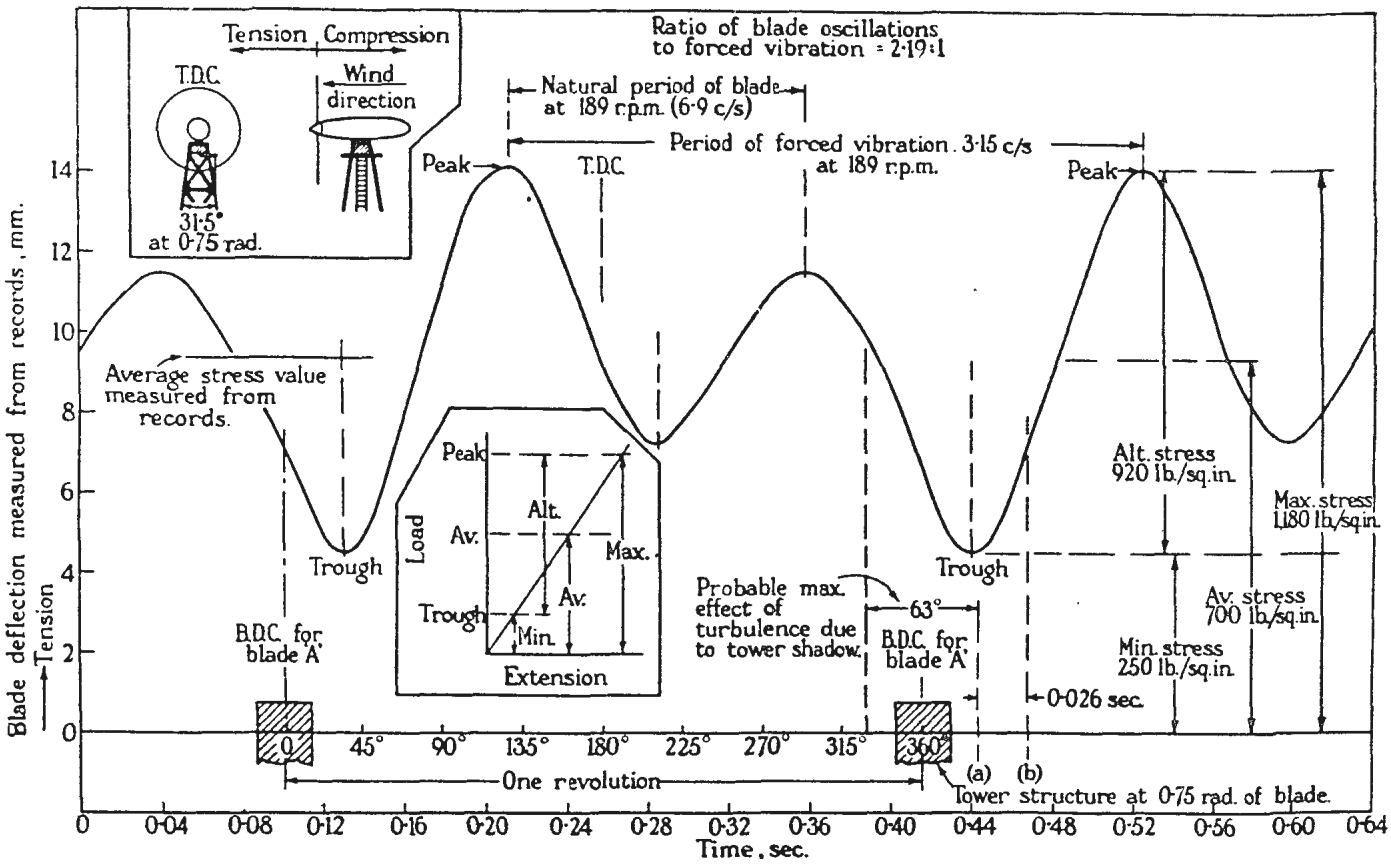

Figure 7. Stress experienced by a windmill blade during one revolution

Generator-output/wind-speed relationship

The generator output is related to wind speed in figure 8; the output and wind-speed values were measured as described under "Generator output" above. The small cyclic pulsations in the power output were thought to be due to the blades passing through the shadow of the tower, but tests carried out at a later date, when the blades were run up-wind of the tower, tended to disprove this (see "Discussion of results" below). The amplitude of these pulsations remains constant over the range of power output and has an approximate value of 0.5 kW.

Blade stress results

In figure 9, the combined average and alternating stresses in flexure, for a strain gauge position situated at 0.3 radius on one of the blades, are shown plotted against wind speed. They are mean values derived from a large number of readings covering the stress values over the wind-speed range 18 to 36 mph.

The wind speed as measured by two anemometers, the generator output and the average and alternating blade stresses at 0.3 radius, are shown plotted against time in figure 10. This represents a period when the wind speed is subject to fairly rapid changes with subsequent changes in the generator output.

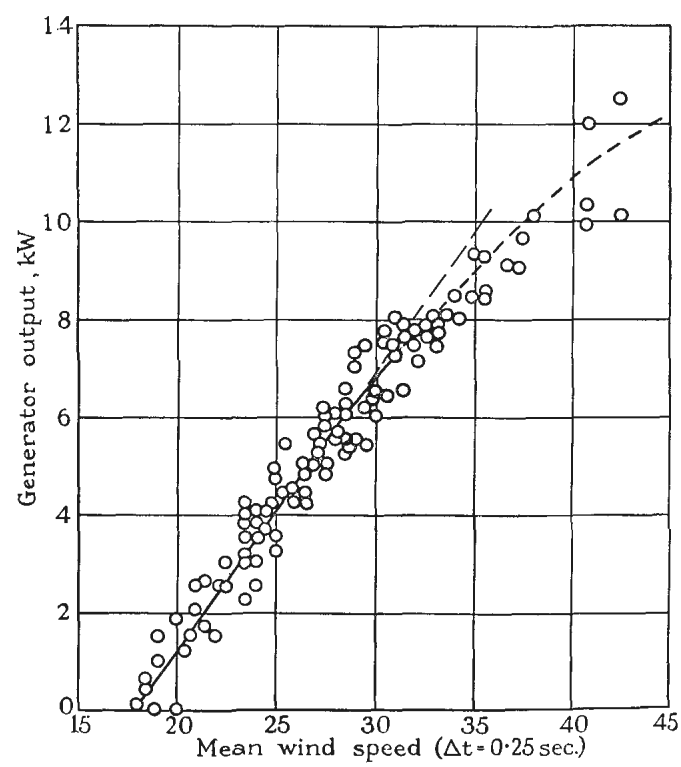

Figure 8. Generator output/wind-speed curve

Discussion of results

The scatter present on the generator output curve (figure 8) is most probably due to the fact that prior to each test, the windmill was fixed in yaw with the wind rotor normal to the mean wind direction, so that any large change in wind direction would affect the output of the machine. The anemometer, on the other hand, was of the omni-directional type and measured maximum wind speed irrespective of wind direction.

The method adopted of selecting reasonably steady wind-speed conditions, prior to taking readings from the records, is satisfactory, as this period of time, 3 seconds, ensures that the wind speed acting on the anemometer and windmill are of the same order when their outputs are compared, provided, of course, there has been no major change in the wind direction. It also allows the output of the generator to settle down to the particular value of wind speed under consideration.

The cyclic variation in the power output, two per revolution of the wind rotor (figure 11 (*a*)), was at first thought to be due to the effect of the tower shadow on the blades, but tests at a later date, when the blades were run up-wind of the tower, gave a cyclic variation in the power output of once per revolution (figure 11 (*b*)), and a reduced value of alternating blade stress (figure 12).

Further tests were made where the upper portion of the lattice tower was blanked-off to simulate a solid tower and another where the bottom half of the swept area was screened with fine mesh expanded aluminium. During these tests, the amplitude of the power fluctuations (figures 11 (*c*) and (*d*)) increased slightly but with a smoothing effect in one case (figure 11 (*d*)). The main effect, however, was to reduce the mean power output of the generator for a given wind speed, and in the case of the latter test, where half of the swept area was screened, the windmill output was reduced by approximately 20 per cent. The alternating stress level at the blade roots,

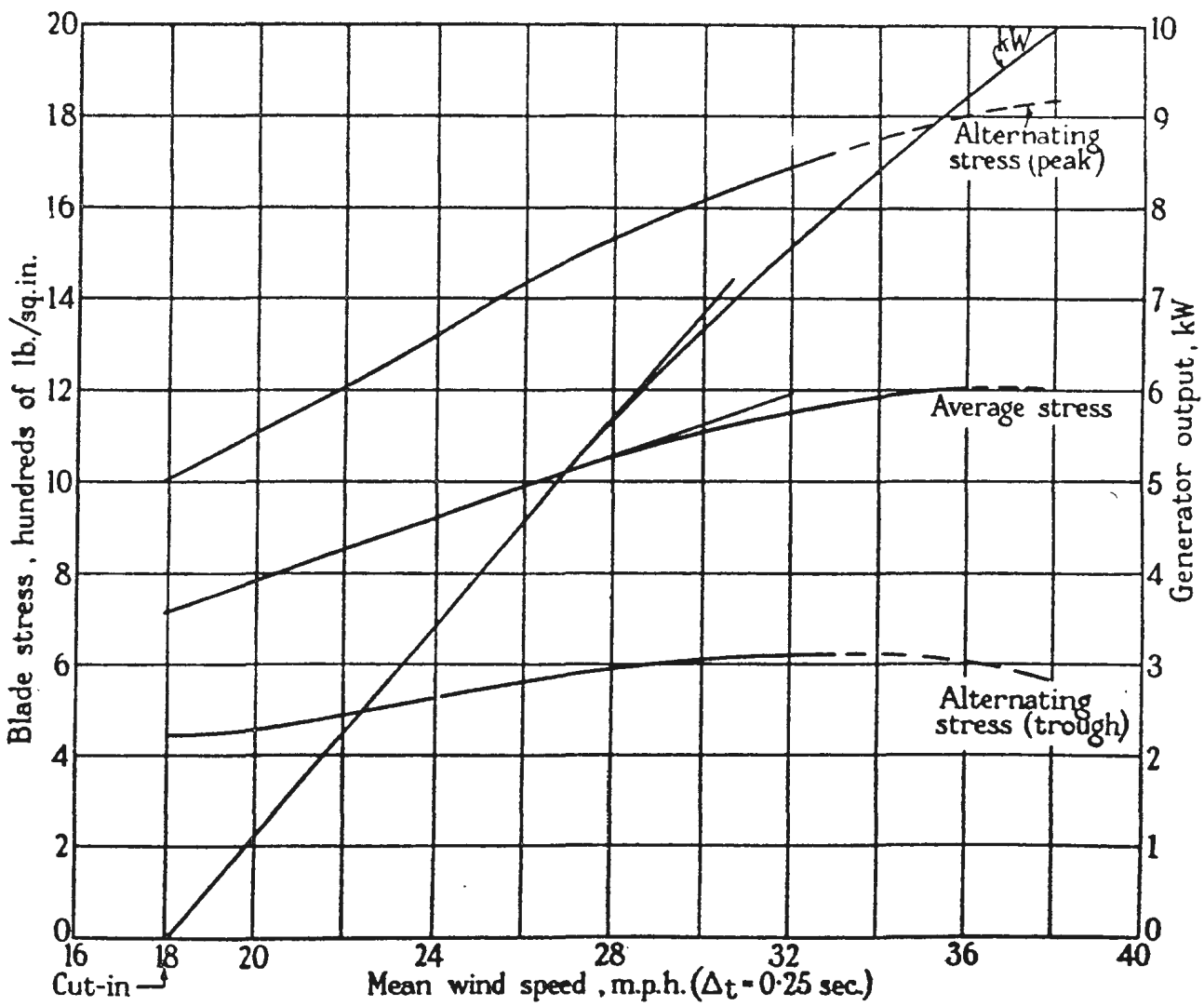

Figure 9. Combined alternating and average stress values in flexure for one blade

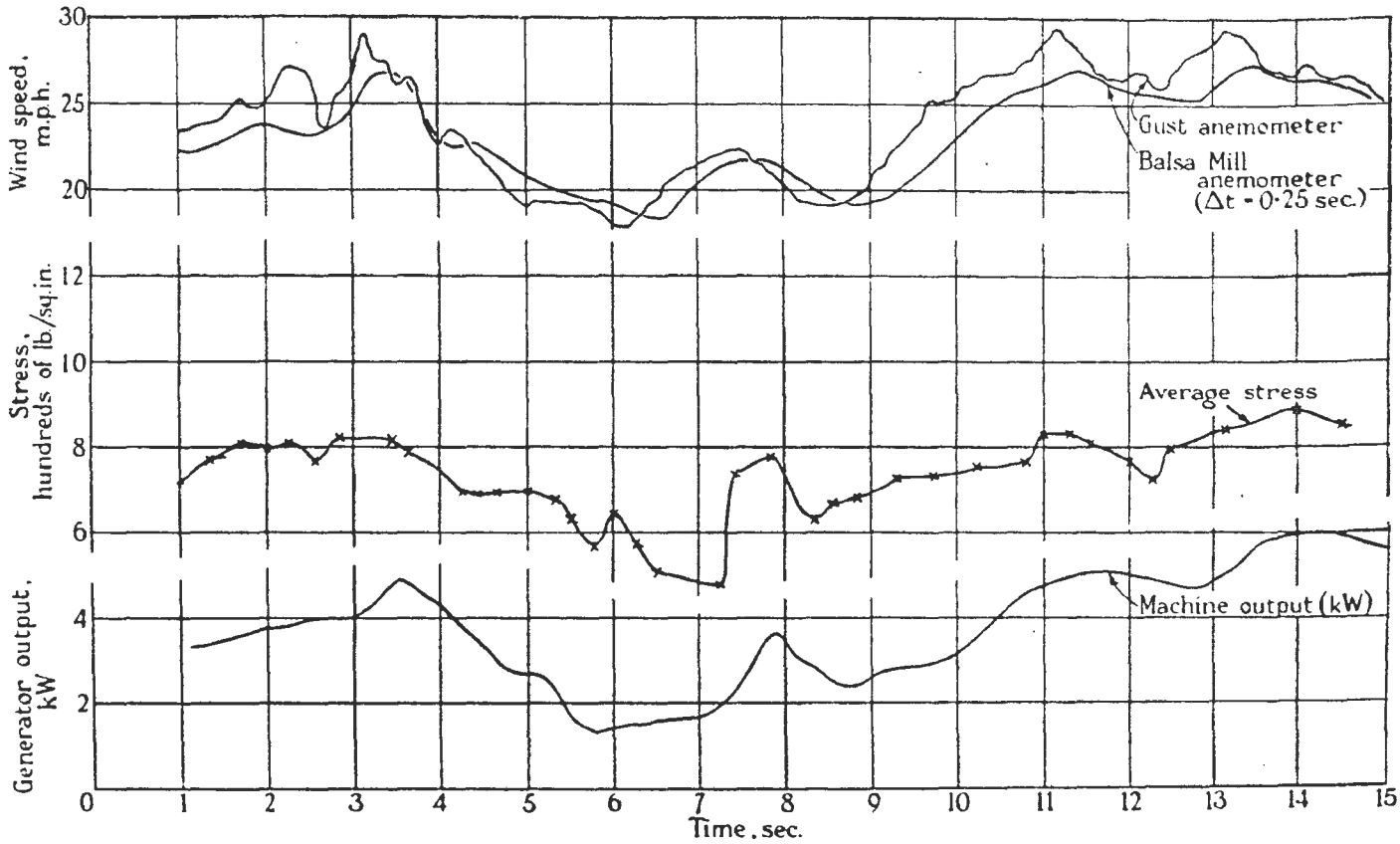

Figure 10. Wind speed, generator output and blade stresses over a short period of time

on the other hand, increased rapidly (figure 12), until, in the final condition, the strain gauges were ruptured.

Although the machine was locked in yaw during these tests, there was a small cyclic variation of the windmill head in this plane which was due to backlash in the bullring and yawing motor gears. The amount of angular movement was approximately 10° and occurred with a frequency of once per revolution of the wind rotor. A small unbalance in the blade system could account for this movement, and it is thought that it is this effect, when transmitted to the plane of rotation of the wind rotor, that is mainly responsible for the power fluctuations in the generator output.

The fact that the alternating stress level at the blade roots increases rapidly as the tower obstruction increases would suggest that larger power fluctuations could be expected if the tower shadow was responsible. This is not the case, in point of fact: when the blades were run up-wind of the tower, equivalent to reducing the tower obstruction, the alternating stresses were reduced considerably (figure 12) and the amplitude of the power fluctuations increased from 0.5 kW to 1.5 kW (figure 11 (*b*)). One of the most important effects to be made clear by the tests is that of the tower structure on the rotor blades, especially when the blades are run downwind of a solid tower.

The tower shadow effect extends to some distance on either side of the tower and the traces of torsional stress indicate this more precisely than do the traces of flexural stress. In figure 4 it can be seen that the frequency of the blade oscillations in torsion is approximately 6.5 times greater than that in flexure, and it follows that the higher frequency of oscillation will respond more rapidly to a change, such as that created by the tower. The positions (*a*) and (*b*) in figure 4 show, respectively, the release of the torsional stress as the blade enters the tower shadow, and its re-application as the blade leaves the tower shadow. For this particular windmill, the angular extent of the tower shadow was determined as 63°.

Considering the rapid changes in wind speed experienced by a blade under these conditions, the blade, on leaving point (*a*) in figure 7, will have experienced the full change of wind speed by the time it reaches the position (*b*), i.e., after 0.026 second. With a reduction in wind speed, behind the tower, of 20 per cent in a 24 mph wind (3), the rate of change will correspond to a gust of 4.8 mph in 0.026 second or 185 mph/second. This rate of rise is much greater than any gust so far measured at the Cranfield site, and no doubt the higher the average wind speed the greater the rate of rise will be due to the tower shadow effect.

Suggestions for the standardization of testing methods for wind power plants over short periods of time

Testing methods for obtaining the output characteristics of normal prime-mover-generator combinations are already well established, but during these tests the input power is usually under the control of the investigator so that a large number of different steady-state operating conditions can be produced merely by altering the input power to the prime mover and allowing the machine to settle down to its new steady-state condition. In the case of the windmill, however, the input power is not under control and is, in point of fact, extremely variable, remaining steady only for very short periods of time.

At the commencement of the tests described, it was realised that to obtain a steady-state relationship between output and input it would be necessary to measure the wind speed, generator output and blade stress values, during these small periods of steady-state wind speed conditions, and that highly responsive instruments and recording equipment

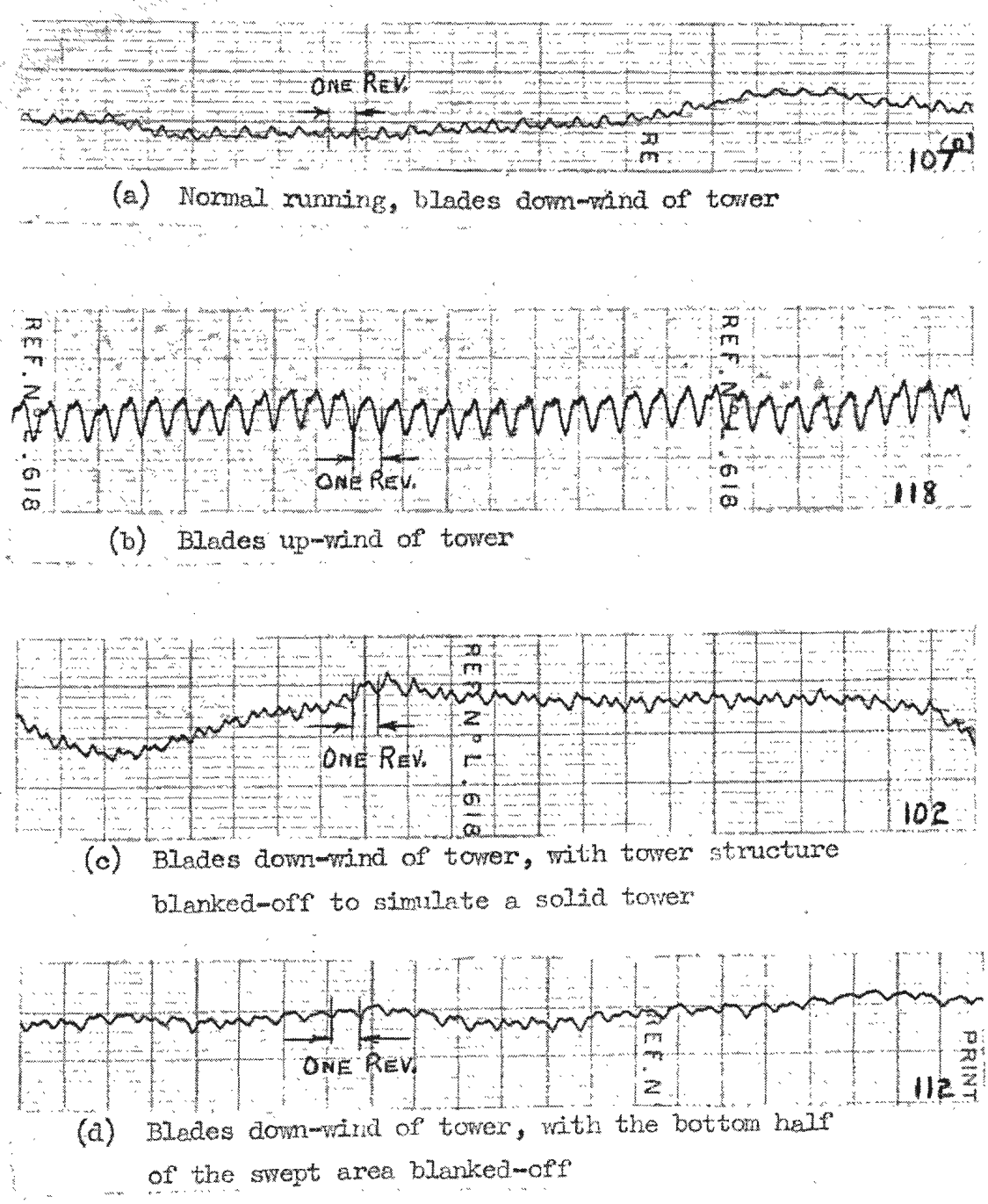

Figure 11. Generator output records of the 10 kW machine under various operating conditions

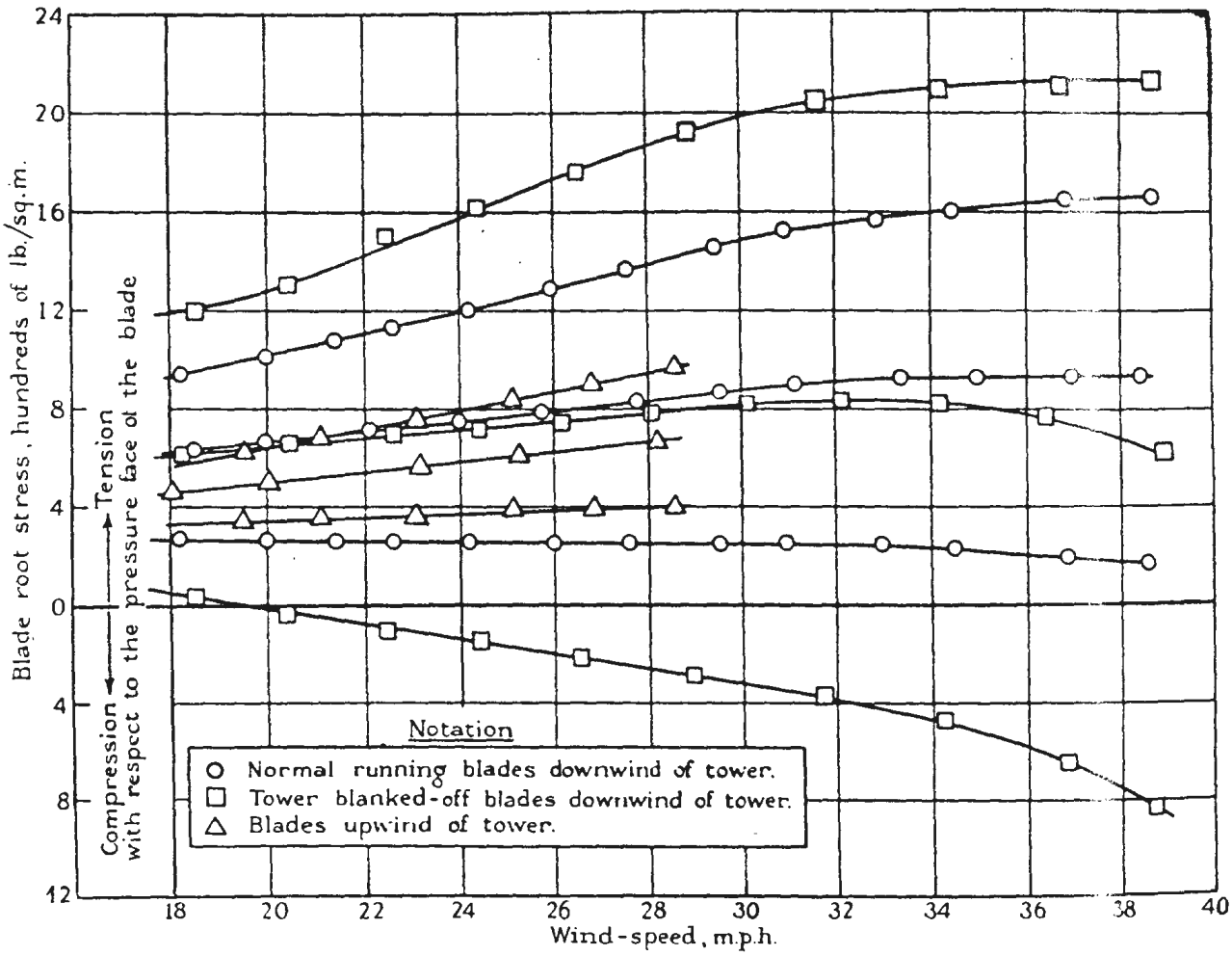

Figure 12. Combined stress loads with the machine under various operating conditions

would be required for this purpose. It was decided that test equipment already to hand would be suitable and that the various testing methods could be developed in the light of results obtained.

An ideal method of recording, but very expensive and scarcely justified at this stage, would have been one where all the variables were recorded side by side on a multi-channel recorder having a common time base. Nevertheless, the methods used were satisfactory, and, with a few modifications as suggested below, they could, in the author's opinion, form a basis for the standardization of wind power plant testing methods over short periods of time.

Measurement of wind speed

In order that the wind speed measured is free of all turbulence created by the windmill rotor or supporting structure, the anemometer must be at least two diameters of the wind rotor, up-wind of the machine, and fixed at some height to come well within the area of the swept circle and preferably within the upper half of this area. This latter position will be more representative of the wind speed acting on the rotor, as, in the lower half of the swept circle, the rotor blades will be subject to turbulence caused by the tower structure even when the rotor is up-wind of the tower.

The type of anemometer used will depend upon the scope of the tests, i.e., purely power-output/wind-speed relationship or a combination of these and measurements of stresses in various parts of the machine. In the first case, the anemometer should have a response of 0.25 second to enable selection of reasonably steady wind-speed periods and, in the latter case, the instrument should be able to respond to a gust of 0.1 second duration. The anemometer should in either case be of the uni-directional type having the same sensitivity to change of wind direction as the windmill under test.

One anemometer should be sufficient for testing wind power plants on the small and medium scale, i.e. 10 to 100 kW, but for machines with output in excess of 100 kW, two or even more may be required.

The mast supporting the anemometer should be of slim dimensions to cause minimum disturbance in the air flow immediately up-wind of the rotor; if fully portable, it will allow easy alignment.

Measurement of generator power output

The majority of wind power plants are fitted with some means of automatic yawing to allow for changes

in the wind direction over long periods of time. The response of these systems is usually very slow and cannot hope to follow the normal gusty directional deviations present in a mean wind speed of 25 mph or above, with the result that the machine is continually yawing from side to side, admittedly by a small amount, but seldom is it directly in step with the wind direction. If, however, before each test, the windmill rotor is placed normal to the mean wind direction and then locked in yaw, the air-flow affecting the rotor will be the same as that measured by the uni-directional anemometer. The readings obtained by this method will have the effect of reducing the scatter which is present on most curves showing wind-speed/generator-output characteristics.

This is a precise method of obtaining the wind-speed/output characteristics of a machine under steady wind speed conditions and is the only method which enables quick tests to be made to check the effect of modifications to a machine, such as a change in the blade pitch, or of the tests referred to earlier in this paper.

As, by this method, no account is taken of gustiness in the wind, it is not expected that the average output of the machine over a given period, in hours, days or weeks, when related to the mean wind speed over the same period, will be the same as that predicted by the short-term measurements.

Stress measurement

The methods developed and described under "Strain measuring equipment" above for measurement of stress in the rotor blades were considered satisfactory, but again, more accurate results, in the wind-speed/stress relationship, would be expected if a fast response uni-directional anemometer was used. The measurement of these stresses over the wind speed range of cut-in to rated value is considered essential for any new design of wind power plant. This information, when coupled with a knowledge of the blade material and of the wind regime, as expressed by the velocity/duration curve (4) for the windmill site, makes it possible to estimate the life of the blades.

The number of stress investigation points and their positioning along the length of a blade will depend upon (*a*) the length of the blade, (*b*) the construction of the blade, i.e., solid, or hollow with a main spar, and (*c*) the construction of the rotor as a whole, i.e., whether fitted with blade interconnecting straps and stay-wires. In the latter case, it is advisable to take direct measurements of stress and vibrations set up in the blade interconnecting straps and stay-wires as these, when superimposed on the blade stresses, tend to mask the actual blade alternating stress frequency.

The stress level at the blade root in the plane of rotation is also of importance, especially where a machine has been designed to shut down automatically, in an emergency, by the application of a disc or band brake on the wind-shaft. The loads experienced at the blade roots and wind-shaft under these conditions can exceed those normally experienced in the plane of the wind.

It should only be necessary to investigate one blade of the rotor system extensively with a few check points on the remaining blades situated where the major stress concentrations are expected.

Methods used for relating machine output to wind speed over long periods of time are given in a paper by Tagg.[1]

[1] Paper W/12, under agenda item II.B.1 above.

References

1. Electrical Research Association, Technical Report C/T 106.
2. Electrical Research Association, Technical Report C/T 114.
3. Electrical Research Association, Technical Report C/T 117.
4. Electrical Research Association, Technical Report C/T 108.

Summary

During the past ten years, the Electrical Research Association, in co-operation with other bodies, has been wholly or partly responsible for the testing of various wind power plants ranging in size from 10 to 200 kW.

These tests were conducted to determine (*a*) the power-output/wind-speed relationships and (*b*) the stress levels, both average and alternating, in various parts of the blade system.

For the purposes of this paper, the relevant information obtained from tests made on a 10-kW machine is given, but the information and experience gained over the past ten years has been taken into account in the suggestions made for standardization of testing methods and measurements.

The methods used for measuring wind speed, generator power-output and blade stress over short periods of time are given.

The results of tests are included where the wind plant was operated with (*a*) the lattice tower blanked-off to give the equivalent of a solid tower, (*b*) the bottom half of the swept area blanked-off to simulate a much wider and solid tower, and (*c*) the blades running up-wind of the tower structure.

Power fluctuations in the generator output and their probable cause are discussed, together with the effect of the tower structure on the rotor blades. The amplitude of the power fluctuations was of the order of 0.5 kW throughout the generator range of 0 to 10 kW, so that, at the lower levels of power output, the fluctuations could be a very high percentage of the total power output. The effect of the tower structure on the blades commonly referred to as the "tower shadow effect", can, in the author's opinion, seriously limit the life of the blades, especially when they are running down-wind of the tower. A precise method for the measurement of the angular extent of the tower shadow effect is discussed.

ESSAIS D'UNE CENTRALE ÉOLIENNE

Résumé

Au cours de ces dix dernières années, l'association des recherches électriques, en collaboration avec d'autres organismes, s'est chargée, pour tout ou partie, de mener les essais sur diverses centrales éoliennes dont la puissance s'échelonnait de 10 à 200 kW.

On a exécuté ces essais pour déterminer *a*) les rapports qui existent entre le débit d'énergie et la vitesse du vent et *b*) les sollicitations qui apparaissent — valeurs moyennes ou instantanées, par alternances — dans diverses parties du système de pales.

Pour les fins de la présente communication, on donne les renseignements pertinents qu'ont fourni des essais exécutés avec une machine de 10 kW mais les données recueillies et l'expérience acquise au cours de ces dix dernières années ont été prises en considération dans les recommandations faites pour la standardisation des mesures et des méthodes d'essai.

On indique les méthodes dont on se sert pour la mesure de la vitesse du vent, le débit d'énergie de la génératrice et les sollicitations auxquelles sont soumises les pales pendant de brefs laps de temps.

Les résultats des essais s'appliquent aux configurations suivantes : *a*) tour à croisillons masqués pour donner l'équivalent d'une tour massive; *b*) masque sur la moitié inférieure de la surface balayée pour simuler une tour beaucoup plus large et massive, et *c*) pales tournant au vent de la structure de la tour.

On passe en revue les fluctuations de débit de la génératrice, leurs causes probables ainsi que les effets de la structure de la tour sur les pales du rotor. L'amplitude des fluctuations d'énergie a été de l'ordre de 0,5 kW sur toute la gamme de puissance des génératrices, soit de 0 à 10 kW, si bien qu'aux faibles niveaux de fourniture d'énergie, les fluctuations pourraient représenter un très gros pourcentage du débit total de force motrice. L'effet de la structure de la tour sur les pales, que l'on désigne habituellement sous le nom de « effet d'ombre de la tour » limite sérieusement la durée de service de ces pales, de l'avis de l'auteur, particulièrement quand elles sont sous le vent de cette tour. On passe en revue une méthode directe de mesure de l'ouverture angulaire de l'effet d'ombre de la tour.

Agenda item II.B.3

RECENT DEVELOPMENTS AND POTENTIAL IMPROVEMENTS IN WIND POWER UTILIZATION:

(*a*) For household and other individual uses

(*b*) For community purposes (isolated units and units in combination with conventional power sets)

(*c*) For use in connexion with electrical networks

Point II.B.3 de l'ordre du jour

UTILISATION DE L'ÉNERGIE ÉOLIENNE: PROGRÈS RÉCENTS ET AMÉLIORATIONS POSSIBLES:

***a*) Usages domestiques et autres usages individuels**

***b*) Services collectifs (installations isolées et installations associées à des centrales de type classique)**

***c*) Interconnexion avec les réseaux électriques**

Chairman — Président

Peder Gerhard POULSEN-HANSEN

Rapporteur

Ulrich HÜTTER

RECENT DEVELOPMENTS AND POTENTIAL IMPROVEMENTS IN WIND POWER UTILIZATION

Ulrich Hütter *

During the last decades of the nineteenth century, at least 30 000 windmills were being operated in Denmark, northern Germany, the Netherlands and England.

These mills had a wing-wheel diameter of 18 to 24 metres. Therefore, the circular areas swept by the wind blades amounted to about 250 to 450 m^2 per unit. At equal number and equal dimensions, the total energy output of these windmills would amount to more than 10 000 000 mWh (10 million megawatt hours) if the figures specified in the paper by J. Juul (W/20) for the measured specific energy gain at the experimental wind power plant at Gedser are taken into account.

The operational experiences realized by Juul (Papers W/20 and W/21, and Paper W/17 under agenda item II.B.2 above) at three experimental plants of different size (Vester Egesborg, Bogø and Gedser) represent only one part, although a very essential one, of the knowledge which was gained as secured experience for the exploitation of energy from the wind by several countries actively engaged in this Conference.

By taking into account the breadth of the subject and the variety of test methods and results, the very interesting papers on hand can give only limited, so-to-speak accidental, insights into the entire problem of wind energy utilization, restricted to typical special problems.

In addition — especially in the application — the layout, as well as the constructive design of wind power plants, is so closely connected with the kind and economy of utilization that to gain a completed picture of this section, the discussion cannot be restricted to the papers cited under the present agenda item.

The papers presented by Frenkiel (W/6), Jacobs (W/22), Walker (W/29), Stam, Tabak and van Vlaardingen (W/38) and Venkiteshwaran (W/25) deal with typical problems of utilization of electrical energy for individual uses, whereas Stam (W/40), Nilakantan, Ramakrishnan and Venkiteshwaran (W/23), as well as Havinga (W/32, under agenda item II.B.2 above), suggest and discuss the question of the optimum layout and design of wind pumps in types of construction, the production of which is possible even with a lack of modern production techniques.

Walker (W/18) describes an installation of the Electrical Research Association which offers considerable improvements for individual uses as well as for community purposes with regard to the following :

(*a*) The full utilization of the energy offered by the wind power plant;

(*b*) The correct usage according to arbitrarily eligible preferences;

(*c*) A remarkable extension of the energy balance and, with it, a considerable revalorization of the usefulness of the available energy.

Arnfred (W/1) communicates the experiences of half a century of practical application of medium-sized wind power plants with conventional thermo-electric stand-by units.

The papers submitted by Juul (W/20, W/21 and, under item II.B.2, W/17), as well as by Delafond (W/8 and, under II.B.2, W/9), cleverly complemented, under II.B.2, by the papers of A. Ledacs-Kiss (W/36) and Armbrust (W/34), on the use of A.C. wind power plants in connexion with electrical networks, show us that nearly all basic problems of parallel operation of such plants with powerful electrical networks may be considered as cleared, in that, with a further development of the existing experimental plants, reliable machines may be expected within a short time. These, being produced in quantity as fuel savers, would be able to feed low-cost electrical energy into existing public networks.

Present wind power utilization

In order to understand entirely the technical background upon which potential improvements in wind power utilization may be developed in the future, we should not overlook the following.

(*a*) In the western part of the United States, in South America, in the Mediterranean, in Australia and in South Africa, several hundred thousand wind pumps of conventional multi-winged design have contributed essentially to the utilization of semi-arid deserts and for many decades have been the very precondition for the possible existence of life on farms in these regions.

(*b*) Denmark, during both world wars, was able to improve the energy supply of its rural counties a great deal (Arnfred, W/1) on the grounds of experiences gained by Poul La Cour at his wind power test plant in Askov, by the installation of a large

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number of rural power stations with stand-by diesel-electric machines, as well as by countless wind power plants installed on farms.

(*c*) From the middle twenties to the middle fifties of this century, many thousands of so-called "wind chargers" from the United States were delivered, installed and used for the supply of farms with electrical energy, mainly for illumination and the operation of radios (Jacobs, W/22).

(*d*) For about three decades, experimental wind power plants with a rated output ranging from 10 to 1 000 kW and with fast turning wing wheels (wheels with high rated speed) designed according to the realizations of modern aerodynamics, have proved in years of service in the Soviet Union, the United States, Denmark, France, England and Germany, that electrical energy can be fed into public networks with full automation.

We therefore need no renewed proof that the utilization of wind energy upon certain premises — premises such as are often found in industrially under-developed countries — is technically feasible and economically justified.

Energy quality and cost

In judging the usefulness and economy of an energy source, the following aspects are dominant :

(a) *The energy quality*, which is to be understood as : (i) the degree of time independence of the energy offer, and (ii) the extent of adaptability of the apparatus producing the energy to reliably cover top needs as they sometimes occur;

(b) *The energy cost*, which is the total expenditure for the provision of energy in relation to the energy unit;

(c) *The operational reliability* of the equipment under all possible conditions to be expected in practical, long-term operation.

The aspect of energy quality has taken precedence over the aspect of energy cost not only because the equipment for improving the energy quality crucially influences the energy cost, but also because the question of whether wind energy can be applied in the right way, under the premises being discussed within the framework of this Conference, is a question in the first place of energy quality — in the sense of the above definition — and only in the second place a question of the energy cost.

The crude energy offer from the wind varies steadily because of the continuous fluctuation of the wind speed. The amplitudes of fluctuation often surpass the value of the average figures of the wind speed. The fluctuation frequencies vary from parts of seconds to months. But not all fluctuations have the same consequences for the energy quality.

(*a*) The turbulence-caused, short-time (from split-seconds to five minutes from maximum to maximum) fluctuations of the wind speed create only minor technical difficulties and have little influence upon the energy quality and cost. They may be eliminated without large extension of the investments required for the plants because of the infinitely small storage capacities necessary for their balance.

(*b*) In comparison with it, the fluctuations of wind speed, and thus of the energy offer reaching from half-hourly intervals to the duration of ten days, cause quite considerable difficulties in view of the technical apparatus needed for their compensation, as well as of the economic consequences following upon storage and governing requirements.

(*c*) Over a long period of time, the energy offer from the wind is not only extraordinarily uniform, more uniform than the energy offer from water power plants, but it also shows — as is pointed out by Juul (W/21) in agreement with considerations by H. Honnef in his book *Windkraftwerke* in 1932 — that the monthly energy offer in the course of a year yields a fascinating conformity with the oscillation lapse of the energy need of a country in the middle latitudes of the northern hemisphere, as demonstrated by the load on large energy supply centres. The water passage of large streams, and thus the energy offered by river power stations, behaves in a contrary manner in these regions, as shown by Juul and Honnef.

Necessary energy storage capacity

In the planning of wind power plants it is therefore necessary to deal only with the fluctuations of the energy offer resulting from wind speed changes over average time interval figures.

In endeavouring to lay out the total installation of wind power plants for the purpose of a minimum energy cost and availability of the energy in optimum form, one faces the following problems.

(*a*) By comparing the energy gain of plants of different layout with that which is obtained with the assumption of constant optimum energy conversion from watched wind frequency distributions, the gain distinctly becomes a function of the average wind speed and the specific swept circular area power (table 1). The specific circular area power is the quotient of the installed capacity of the plant divided by the circular area swept by the wing blades.

(*b*) On the other hand, the size of the energy accumulator required for a certain amount of uniformity of the energy gain is also a function of the long-time average wind speed, as well as of the specific swept circular area power. The quotient of the difference of maximum and minimum power of the plant and its average power is chosen as a measure for the uniformity of the output. All three figures may be taken from the power duration curve of the plant. It is suitable to relate the size of the required energy accumulator to the size of the long-term daily average of energy output to be expected. By it we express the storage size in accordance with the time during which the accumulator alone is

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3	180	20 to 120	230	140 to 240
5	410	140 to 340	740	410 to 580
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9	680	380 to 700	1 800	1 200 to 1 640
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$$E_{\text{th}} = \frac{8\,760 \text{ hours per year}}{102 \text{ mkp per kW sec}} \cdot 0.596 \cdot \frac{\delta}{2} \cdot \left[\int_0^{t_{v_1\,\max}} v^3 dt + (1 - t_{v_1\,\max}) \cdot v_1^3{}_{\max}\right]$$

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able to supply the consumer with energy at energy delivery with constant power (table 2).

From table 2 we recognize that at larger mean speed values — at equal layout — the requirements for the accumulator become smaller than at smaller mean values in relation to the mean energy utilization.

(*c*) The total cost of a wind power plant is the sum of the costs for the engine itself, i.e. wind wheel, gear, generator, wind direction servo-mechanism, tower, fundaments, etc., the expenditure for erection and installation including switch and load selection equipment (according to Walker, W/18) and the costs for the energy accumulator.

(*d*) Under agenda item II.B.1 there is a discussion of the extent to which the long-term average of the wind speed depends not only on the meteorologically large-scale given value, but also on the local, topographic properties.

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It is certain that a relation between the layout of the plant, the size of the accumulator, and the average wind speed exists, which must be optimized at a given design conception and at prescribed uniformity of the energy output, with a view to energy costs as well.

With regard to individual uses, the position of the optimum was, until lately, more or less a matter of personal opinion, and also of the personal experience of designers and constructors of wind power plants. Here and there, sales-psychological effects, as well as economic factors, may have had an undesirable influence.

Not only the size of the required accumulator, but also the kind has an influence on the optimum of the total expenditure. E. W. Golding and the present author of this section, as well as several other authors, have early pointed out this circumstance. Their hints originate from the thought that the required energy is only a means to get certain effects and to enable the provision of certain products necessary for life, and are therefore not of primary interest.

Energy requirement structure: automatic load choice and total use of the energy offer

When in the process of planning, one should therefore prepare an analysis of the *need structure* as well as an analysis of the *need volume*. In many cases, the final product, to the provision of which

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energy is needed, may be stored with essentially less expenditure than the energy itself.

This is especially true of heat and water. The present author had access to investigations on the energy-need-structure of agricultural installations in Germany that had been undertaken between 1930 and 1938 by the *Deutsche Gesellschaft für Technik in der Landwirtschaft* and between 1946 and 1948 by the *Energieversorgung Schwaben*.

In both cases, surprising results were obtained, as the following examples indicate.

(*a*) Only 8 to 16 per cent of the total energy is needed for illumination, radios and small appliances, and also for such uses as milking machines and milking centrifuges, operating daily, at fixed times. Only these appliances need the energy "on demand", as Walker says (W/18).

(*b*) The energy needed for mechanical drives such as wood circular saws, hay lifts, small corn mills, etc., is in the same size category. Mechanical drives of this kind are needed to convert products in storage, and to store them again. It is not absolutely necessary, therefore, to take care of these tasks during calm periods at an agricultural installation, and it is possible to wait for periods of sufficient wind without disadvantage.

(*c*) Seventy per cent to more than 80 per cent, however, was used up for thermal devices such as heating, electrical stoves, cooling, refrigerators, hot-water storage, etc. In these, very large amounts of energy are rather simply stored and with considerably less cost than with storage of electrical energy in lead-acid batteries.

(*d*) The same is true for water pumping. Water can be stored in large containers or, in the case of irrigation devices, in the earth itself, without considerable additional expenditure.

The very interesting and, for the methods of practical application of wind energy, immensely informative and valuable paper by Walker (W/18) not only reports on the practical results of an extensively automatic installation for the energy supply of a medium-sized farm, with the aid of wind energy by the use, basically, of the above-mentioned philosophy, but also on the consequences resulting from the provision of many possibilities for the use of energy, in order to exploit the offered energy.

It can be gathered from the exact measurements by Frenkiel (W/6) at the wind power plant at Eilat, covering a duration of three years (a machine which was developed and described by Jacobs, W/22) that in spite of careful precautions, only 2 750 kWh out of 4 200 kWh offered by the wind annually, or 65.5 per cent, in fact, could be used. Since the energy price results almost entirely from the stock costs of the installation of the plant, the part exploitation of an existing plant in the form described by Frenkiel means a rise in the energy price of about 50 per cent.

The procedure of the Electrical Research Association (E.R.A.) described by Walker provides for an automatic control system for the complete installation designed to be operated by a non-technical user and, at the same time, giving the user full control over the selection of the priorities of the various loads.

The load-distributing device, operating on variations in the voltage of the wind-driven alternator, consists basically of a moving coil relay supplied, through a rectifier, from the alternator. Increases or decreases of alternator voltage cause the moving contact of the relay to energize and operate a small motor which drives, through gearing, a series of twenty-eight cams. The cams are arranged to close one micro switch for every 6 degrees of shaft rotation. A single pole supply, taken from the three phase bus bars, is fed, *via* the microswitches, to a vertical row of twenty-eight sockets.

The number of cams, micro-switches, sockets, etc., is entirely dependent upon the number of installed loads. The sockets are so connected that an increase in the output voltage — and therefore power — of the wind power plant causes them to be energized in an ascending order, a decrease in output voltage de-energizing them in the reverse order.

By inserting the plugs into the vertical row of sockets, the operator can select at will the order in which the loads are to be connected to the supply as the energy becomes available.

This basic design of the load-selector system can be applied to any type of medium-sized machine up to, say, 50 kW capacity, provided that the rating and number of load contactors is adjusted to suit any specific requirement.

Conventional thermo-electric stand-by machines

At wind power plants of a magnitude enabling them to supply medium-sized farms or small communities with sufficient energy, the provision of a standby machine may, under circumstances, create extraordinarily favourable conditions in view of operational reliability and the economy of the total installation (Papers W/1 and W/18).

Such thermo-electric stand-by machines offer the following advantages.

(*a*) It offers emergency electricity supply in the case of especially long calm periods. Calm intervals of medium duration, i.e. from one to a maximum of 48 hours, are extraordinarily frequent, but calm periods — as a consequence of stable weather conditions, for instance — of more than two days' duration are quite rare. It is uneconomical and senseless to lay out the energy storage equipment for an especially unfavourable situation occurring only two or three times annually. On the contrary, it makes more sense to transfer such rare cases to the stand-by machine.

(*b*) The stand-by machinery takes over the entire provision of the consumer when repair or maintenance work at the wind power plant or energy accumulator becomes due.

(*c*) At seasonal, large, short-term top power consumption (for instance, threshing of the harvest), the stand-by plant, energy accumulator, and wind power plant together can supply the net, thus taking over unusual and high load demands.

The experimental installation erected by the E.R.A. in Scotland, as well as a wind power plant operated by the *Wasser- und Schifffahrtsamt* in Kiel on the pilot's island, Schleimünde, for the supply of the lighthouse and several houses (reference 4 in W/6), had been equipped with Diesel stand-by machines for the support of the Allgaier-wind power plant of 10 m wind-wheel diameter and 6 kW and 7.5 kW rated output, respectively.

In both cases, it was proven that the diesel stand-by generator was needed quite seldom during several months of operation. At Schleimünde the wind power plant produced 94.5 per cent of the needed energy and at the E.R.A. installation as much as 98.6 per cent, although at the latter the annual average hourly mean wind speed amounted to only 3.8 m/sec.

In the face of this quite small contribution of stand-by units to the entire energy production, Walker says that the stand-by unit could take the form of a portable petrol-driven generator having a capacity of 12 to 20 per cent of the rated output of the wind power plant.

Energy costs in competition with those from conventional power sets

In judging the energy prices for individual use, as well as for community purposes, we must bear in mind that in all cases in which the use of wind or solar energy is being evaluated, the energy price does not compete with those of public networks in industrially highly developed countries, but with that of local thermo-electric plants. Table 3 gives a general view of those figures of energy-producing costs which are contained in the papers of this section, and compares the data given by Golding.[1]

[1] Golding, E. W., Power from Local Energy Resources, *Proceedings of the United Nations Conference on New Sources of Energy, 1961*, vol. 1, agenda item II.D.1, paper GEN/5.

It must not be overlooked that the figures shown in Paper W/21 are valid for plants which are operated in parallel with public networks. The figures taken from Paper W/1 may rely upon procurement prices for wind power plants that date back so far that they can no longer be realized, as the devaluation of currency in the last twenty years has to be considered.

Even when considering these different assumptions, the enormous divergence of the data being cited as energy price is conspicuous. This divergence reflects an uncertainty in the pre-calculation of the energy costs which becomes still larger when we consider that, besides the varying average values of wind speed on which the cost investigations in Papers W/21, W/18, W/22 and W/6 are based, all those uncertainties are added of which Stam speaks in Paper W/40 : "the prices of products, shipped outside the normal routes of world trade multiply..."

The wind power plants described in Papers W/22 and W/6 are identical as to make and type. As the same mean wind speed was assumed for both energy price investigations, the energy cost relation is remarkable.

Water-pumping with wind power plants

Unfortunately, only two papers in this section — W/40 and W/23 — refer to water pumping with mechanically driven pumps. Both papers report on efforts to create the premises for the production of such plants in countries without highly developed industries by means of simple technical solutions in design.

For reasonable planning of large-scale irrigation projects in the course of settling projects or in the course of programmes aiming to enlarge the return on the land of already settled areas by artificial irrigation, it is indispensable that the following data be compiled by meteorologic observations and test drills :

(*a*) Weekly and monthly average values, respectively, of the wind speed over several years;
(*b*) Weekly average values of rainfall;
(*c*) The depth of the ground water level below ground;

Table 3. Comparison of energy costs on the basis of 10-year amortization at total energy sale

Author	*Paper*	*Rated output*	*Windwheel diameter*	*US$ per kWh*
Juul	W/21	200 kW	24 m ⌀	0.00105
Arnfred	W/1	30 kW	18 m ⌀	0.00073
Walker	W/18	7.5 kW	10 m ⌀	0.041
Jacobs	W/22	3.0 kW	4.5 m ⌀	0.028 (factory price of plant considered)
Frenkiel . . .	W/6	3.0 kW	4.5 m ⌀	0.100 (price of plant at the very place considered)
Frenkiel . . .	W/6	3.0 kW	Diesel electric units	0.18
Golding	GEN/5	50 kW		0.073
Golding	GEN/5	100 kW		0.051
Golding	GEN/5	200 kW		0.042

(*d*) The maximum ability of the boring well to yield.

It seems that the wheel size of the multi-winged wind pumps has arisen from the mean well-yield ability — until dry operation of the well — and the mean depth of the groundwater level in the semi-arid steppe areas in which these wind pumps are spread so far apart.

On the other hand, the ground-water level and possible well-yield ability are regionally so different that it pays, upon opening up areas, to make careful climatic and hydrologic examinations in the course of planning, and to design the plant size and layout, as well as the optimum irrigation system, with the values obtained.

Wind-driven water pumps represent a peculiarity, as do the open gutter pump described by Stam (W/40) or the drainage windmills described by Havinga (II.B.2, W/32), in that they have to take care of only a very low hoisting depth at large interspersing water volumes. Water pumps of this type have already been used to keep dry low grounds enclosed by dikes in northern Germany and the Netherlands, for the reclamation of settling country from river mud sedations in Camarque, in southern France, and for irrigation and draining purposes in the delta areas of large streams, where they have their own typical tasks.

Hydroelectric sets in water provision systems

Often the opening up of settling areas with the aid of wind energy will have to start with the provision of the water that is so vitally necessary. The storage of water in corrugated sheet steel containers or earth cavities, made by earth dams, offers the possibility of producing electric energy for illumination, and the operation of radios and small household appliances, by means of small hydroelectric sets at the water-flow from the container to the consumer (W/18) or at the return of surplus water into the well (W/40). This has been suggested by Walker (W/18) as well as by Stam (W/40), and also by the present author during his lectures in Bangalore, India, in January 1961.

The installation of a water-distributing network with the aid of plastic pipes embedded in the soil and with the provision of hydroelectric sets to be installed in the houses not only offers great advantages for water distribution but, in the production of this kind of electric energy, also avoids the difficulty described by Walker (W/29), that at small-scale wind power plants with low voltage (in regard to battery prices), the power losses can be considerable in the supply lead from the plant to the consumer. They offer the additional advantage that at the first settlement, relatively simple machines with only mechanical transformations, including water distribution systems, are put into action, to which the population will easily become accustomed while the understanding of more subtle technical problems is still lacking.

Use in connexion with electrical networks

For use in connexion with electrical networks which transport large quantities of energy, plants with medium-sized layout output will always be preferred, not only because machines with a larger layout power are specifically cheaper, but also because such plants may have more subtle governing systems in order to fulfil all the operational requirements occurring in the automatic feed-in of electric energy into large networks.

It has been known for years that it is not necessary to govern revolutions or frequency, but that, for instance, precautions must be taken so that the maximum permissible load of the generator is not surpassed, the plant is instantly and automatically stopped at net failure, and, with subduing winds, no energy is taken from the networks.

All plants built for parallel operation with networks during the last decades have been *experimental installations*, some of them ingenious improvisations, the machine and governing components of which were pieced together from elements which had originally been destined for machinery of a totally different kind. But with all the variation of assumptions, the result, from the nature of the matter, was that the governing programmes of all the plants showed fundamental analogies, in spite of the considerable novelty of technical solutions (W/18 and, under agenda item II.B.2, W/9, W/17, W/34 and W/36).

For example, the precautions to avoid too frequent cut-out and cut-in operations at wind speeds which are just sufficient for the delivery of power from the plant, as described by Delafond (W/8), are also described by Juul and Armbrust in similar form (W/17 and W/34, respectively, under agenda item II.B.2).

Two types of vibrations are found to be disturbing at all plants, and they show up mechanically as well as in the form of load oscillation :

(*a*) Oscillations in consequence of the passage of the wing blades past the tower;

(*b*) Those effects of motional unrest which result from the finite number of blades, the addition of wind speed with the altitude, and from the fact that the elastic stiffness of the wheel shaft-support is not axially symmetrical.

Fortunately, both cases deal with stable oscillations, without tendency to resonant rise. Since their causes are known, they can be weakened in their actions in later designs.

Wind power plants being operated parallel to strong networks result in a negative load for the network, as H. Munroe, in his comments on this question, has noted.[2]

These negative loads, mainly in the operation of single wind power plants parallel to strong networks, and not always precisely to be determined, act in the

[2] Meetings of the Electricity Research Association, London, March 1955.

network only as fuel savers. But as the public networks are forced to offer a guaranteed output, the representatives of the electricity corporations maintain that the profit of the fuel-saving is relatively small for the following reasons :

(*a*) The portion of the fuel costs at the gross price of the kilowatt hour is relatively small in all energy-supplying systems;

(*b*) For the provision of each power unit that wind power plants nominally offer, an equally sized power unit must be provided for in case of total lack of wind energy.

These arguments without doubt have a certain justification, but they quietly assume that fuel — oil or coal — is under any circumstances always on hand and, above all, at stable prices. This is not always the case. Figure 5 in W/21 shows that between 1950 and 1960, coal as well as crude oil prices varied plus or minus 50 or 60 per cent from the average price in Denmark. Countries without sufficient resources must even take into account economically or politically caused situations endangering the supply of fuels.

It is by no means true that additional serious difficulties arise for the load distributor of energy-supplying corporations because of the constant oscillation of the power offer from wind power plants, if the share of the wind power of the total net power exceeds 20 to 30 per cent. As shown by Juul (W/21) and Delafond (W/8), an interior power balance takes place at the parallel operation of several, far-spaced wind power plants in such form that the energy offer becomes more uniform. This is due to the fact that wind speed and power oscillations, especially at a larger number of far-spaced wind power plants, are eliminated by local turbulence influences with considerable statistical probability.

The large-scale exchange of air masses and thus the magnitude of the wind speed to be expected can be forecast with some reliability for a period of hours. In the case of a larger portion of the potential wind power in a network, the load distributor ought to be informed continuously of the changing weather situation by existing meteorologic services, enabling him to plan ahead of time the size of the engagement of conventional power plant units.

Since there are basically no unsurpassable difficulties for the feed-in of electric energy from the wind, the fact remains as an essential restriction that the energy price is faced with decidedly stronger competition from the energy delivered by conventional units than from individual uses.

The possibilities of further lowering the energy price from wind power plants as compared with optimum figures so far reached (table 3) consist in the following :

(*a*) Large-scale series production of wind power plants of medium power size, and thus the lowering of the production price. We must bear in mind that, up to now, all larger wind power plants have been single-part productions and that all present energy price calculations are based on the thus raised costs for the erection of the plant. This statement holds true not only for wind power plants in parallel operation with electric networks, but also for commercially produced machines intended for individual use.

(*b*) Systematic further development of the plants in the light of all experience so far gained, with the aim of uncompromising simplification with full consideration of the realizations of modern aerodynamics and governing techniques, as well as unlimited application of the present knowledge of new production techniques and materials.

Topics for discussion

1. How large are the intervals that have been experienced between the necessary maintenance work at wind power plants in comparison with such work at conventional power sets?

2. How large are maintenance and repair costs in relation to the total energy costs of wind power plants for both individual and community use?

3. What damage can occur at wind power plants by lightning and what protective measures are necessary?

4. What influence does icing of the wing blades have on wind power plants? Can damage because of imbalance occur and how is the power of the plant influenced?

5. For certain aims, the operational reliability of wind power plants has advanced so much to the foreground that each constructive simplification of the machine causes an additional simplification of the operational reliability. Such an essential simplification would be the omittance of the wind directional governing. To what extent is the energy output of an installation with fixed direction being reduced in comparison to one with directional governing?

6. Can the power fluctuation, which results from the passing of the wing blades past the tower, be avoided when the wheels do not turn behind the tower in the wind direction, but in front of the tower?

7. How strong are the operational noises of working wind power plants?

8. What is the advantage of the installation, at wind-electric plants, of a three-phase current pump inserted in the well, in comparison with directly driven pumps?

9. During the course of a day, the wind speed, as is well known, shows characteristic maximae and minimae. The energy need curves analogously have a typical trace. Is it possible to modulate the day's energy requirements with the daily fluctuations?

UTILISATION DE L'ÉNERGIE ÉOLIENNE : PROGRÈS RÉCENTS ET AMÉLIORATIONS POSSIBLES

(Traduction du rapport précédent)

Ulrich Hütter *

Vers la fin du XIXe siècle, au moins 30 000 moulins à vent étaient exploités en Angleterre, au Danemark, aux Pays-Bas et dans le nord de l'Allemagne. Leurs ailes avaient de 18 à 24 m de diamètre et la surface qu'elles balayaient était de 250 à 450 m². En prenant comme base les valeurs indiquées par J. Juul dans le mémoire W/20 pour l'énergie spécifique produite par l'aéromoteur expérimental de Gedser, on peut calculer que ces moulins à vent développeraient environ 10 000 000 MWh (10 millions de mégawattheures) par an.

Les données déterminées par J. Juul (mémoires W/20 et W/21, ainsi que le mémoire W/17, présenté plus haut au titre du point II.B.2 de l'ordre du jour) dans trois installations expérimentales (Vester Egesborg, Bogö et Gedser) d'importance variée ne représentent qu'une partie, aussi considérable soit-elle, des connaissances déjà acquises en matière de production et d'exploitation de l'énergie éolienne par les pays qui participent à cette Conférence.

Si l'on considère l'ampleur du problème et la diversité des méthodes essayées et celle des résultats obtenus, les travaux très intéressants qui nous sont présentés ne peuvent donner de tout le problème complexe de l'exploitation de l'énergie éolienne qu'un aperçu en quelque sorte fortuit et limité à certains aspects particuliers.

Il faut ajouter que l'implantation et la construction des installations éoliennes sont si étroitement liées, lorsqu'on passe aux applications, au type et à l'économie de l'exploitation que, pour obtenir une vue d'ensemble de cette section, la discussion ne saurait se limiter aux seuls travaux cités au titre du point II.B.3 de l'ordre du jour.

Les mémoires présentés par Frenkiel (W/6), Jacobs (W/22), Walker (W/29), Stam, Tabak et van Vlaardingen (W/38), par Venkiteshwaran (W/25), traitent de problèmes types de l'utilisation de l'énergie électrique à des fins individuelles, alors que Stam (W/40), Nilakantan, Ramakrishnan et Venkiteshwaran (W/23) ainsi que Havinga (W/32, au titre du point II.B.2), examinent la question de la conception et de l'implantation optimales d'un type d'aéropompe qui puisse être construit même lorsqu'on ne dispose pas d'installations industrielles très évoluées.

Walker (W/18) décrit une installation de la Electrical Research Association, qui présente d'importantes améliorations, tant du point de vue des usagers individuels que de celui des collectivités, en ce qui concerne :

a) L'exploitation totale de l'énergie fournie par l'éolienne;

b) L'utilisation rationnelle de celle-ci selon des critères choisis arbitrairement;

c) Une remarquable amélioration du bilan énergétique et, de ce fait, une revalorisation sensible de l'utilité de l'énergie disponible.

Arnfred (W/1) nous fait part des connaissances qu'il a recueillies au cours d'un demi-siècle d'utilisation d'éoliennes d'importance moyenne accouplées à des groupes thermoélectriques classiques de secours.

Les mémoires présentés par J. Juul (W/20, W/21 et W/17, ce dernier au titre du point II.B.2) et Delafond (W/8 et, au titre du point II.B.2, W/9), judicieusement complétés, au titre du point II.B.2, par ceux de Ledacs-Kiss (W/36) et Armbrust (W/34) sur les aérogénérateurs de courant alternatif reliés à des réseaux de distribution, montrent qu'il est possible de tenir pour résolus les problèmes fondamentaux de la marche en parallèle de ces installations avec des réseaux puissants, dans la mesure où l'on peut prévoir qu'il serait possible, en partant des installations expérimentales actuelles, de réaliser à brève échéance des machines prêtes à fonctionner. Produites en grandes séries, celles-ci pourraient alimenter les réseaux en courant électrique bon marché, tout en permettant d'économiser les combustibles et carburants.

Les réalisations actuelles en matière d'exploitation de l'énergie éolienne

Pour bien comprendre les conditions techniques dans lesquelles se présente le problème et dont il faut tenir compte pour envisager les améliorations qu'il serait possible d'apporter à l'exploitation de l'énergie éolienne, il ne faut pas oublier les considérations suivantes.

a) Dans l'ouest des États-Unis, en Amérique du Sud, dans le bassin méditerranéen, en Australie et en Afrique du Sud, quelques centaines de milliers d'aéropompes classiques à plusieurs pales ont puis-

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samment contribué à la mise en valeur de zones semi-arides, et depuis des dizaines d'années, elles rendent possible la vie dans les fermes de ces régions.

b) Au cours des deux dernières guerres, le Danemark a pu notablement améliorer la situation énergétique de ses zones rurales (mémoire Arnfred, W/1), grâce aux connaissances recueillies par Poul La Cour dans sa station éolienne expérimentale d'Askov, en installant un grand nombre de centrales rurales complétées par des groupes électrogènes diesel de secours, tandis que d'innombrables éoliennes étaient montées dans des fermes.

c) Des années vingt-cinq aux années cinquante-cinq, des milliers et des milliers d'aérogénérateurs ont été livrés, surtout par les États-Unis, installés et exploités pour alimenter des fermes en courant servant à l 'éclairage et au fonctionnement des postes de T.S.F. (mémoire Jacobs, W/22).

d) Depuis environ 1930, des centrales éoliennes expérimentales de 10 à 1 000 kW de puissance nominale, dotées d'hélices tournant à grande vitesse et conçues selon les enseignements de l'aérodynamique moderne, en service parfois depuis des années en URSS, aux États-Unis, au Danemark, en France, en Angleterre et en Allemagne, prouvent que les réseaux publics peuvent être alimentés automatiquement en énergie électrique.

Point n'est besoin d'autres preuves pour démontrer que l'exploitation de l'énergie éolienne est possible dans des conditions qui sont souvent réunies dans les pays peu industrialisés, tant sur le plan technique que sur le plan économique.

Qualité et prix de l'énergie

Pour juger de l'utilité et de l'économie d'une source d'énergie, il faut avant tout tenir compte des facteurs suivants :

a) *Qualité de l'énergie.* C'est le degré d'indépendance à l'égard du temps qu'atteint l'offre d'énergie, et le pouvoir d'adaptation de l'installation productrice d'énergie, qui lui permet de faire face aux demandes de pointe qui peuvent se présenter.

b) *Prix de l'énergie.* C'est la dépense totale consentie par unité d'énergie pour la fourniture de celle-ci.

c) *Sûreté de fonctionnement* de l'installation dans toutes les conditions imaginables qui peuvent se présenter sur une longue période.

Si la question de la qualité prend le pas sur celle du prix, ce n'est pas seulement parce que ce prix est décisivement conditionné par l'appareillage nécessaire à l'amélioration de la qualité, mais aussi parce que, pour décider si l'énergie éolienne peut être rationnellement exploitée dans les conditions discutées dans le cadre de cette Conférence, il faut avant tout résoudre le problème de la qualité (dans le sens de la définition donnée plus haut), et ensuite seulement celui du prix.

L'énergie brute contenue dans le vent varie constamment en raison des fluctuations de la vitesse du vent. L'amplitude de ces fluctuations dépasse souvent la valeur moyenne de la vitesse du vent. Leur fréquence passe de quelques fractions de seconde à plusieurs mois. Toutefois, les fluctuations n'entraînent pas toutes les mêmes conséquences pour la qualité de l'énergie.

a) Les fluctuations brèves (de quelques fractions de seconde à cinq minutes de maximum à maximum), dues à des turbulences, ne créent que des difficultés techniques mineures et n'influent que peu sur la qualité et le prix de l'énergie. Nous pouvons les éliminer, car il suffit d'une capacité d'accumulation extrêmement faible, qui n'entraîne pas d'augmentations sensibles des investissements nécessaires à l'installation, pour les compenser.

b) En revanche, les fluctuations de la vitesse du vent et, par suite, de l'énergie offerte, qui durent d'une demi-heure à une dizaine de jours, créent des difficultés considérables tant par l'importance de l'appareillage technique nécessaire pour les compenser que par les conséquences économiques qu'impliquent alors l'accumulation et la régularisation.

c) A longue échéance, la quantité d'énergie éolienne offerte est extrêmement uniforme — plus même que celle des centrales hydrauliques — et en outre elle montre, ainsi que le signale Juul (W/21), confirmant ainsi les vues exposées en 1932 par H. Honnef dans son livre *Windkraftwerke*, que la quantité d'énergie mensuelle offerte au cours d'une année correspond de façon frappante à l'évolution, exprimée par la charge des grandes centrales, des besoins en énergie d'un pays de l'hémisphère nord, tout au moins à une latitude moyenne. Ainsi que Juul et Honnel l'ont démontré, il y a au contraire disparité entre le régime des grands fleuves de ces régions (et partant la production des centrales hydro-électriques) et la demande d'énergie.

Importance de l'accumulation requise

Il suffit donc, lorsqu'on dresse les plans de centrales éoliennes, de s'occuper des fluctuations de la quantité d'énergie offerte, dues aux variations de la vitesse du vent au cours de périodes de durée moyenne. Si l'on veut donner à l'ensemble d'une centrale éolienne une configuration telle que le prix de l'énergie soit ramené au niveau le plus bas et que l'énergie soit fournie sous une forme optimale, il faut résoudre les problèmes suivants.

a) Comparer le rendement énergétique d'installations diversement conçues avec le rendement théorique postulé en supposant une transformation d'énergie optimale et constante à partir de la répartition de la fréquence des vents telle qu'elle a été observée; il en ressort que le rendement est fonction autant de la vitesse moyenne des vents que du rendement spécifique de la surface balayée (tableau 1).

b) D'un autre côté, les dimensions de l'accumulateur d'énergie nécessaire pour assurer une certaine uniformité du rendement énergétique sont également fonction de la vitesse moyenne du vent pendant une

Tableau 1. Quantité annuelle d'énergie utilisée (en kWh) par rapport à la superficie circulaire balayée par les pales de l'hélice

Vitesse moyenne annuelle du vent	*E-théorique calculé sur la base des mesures du vent*	*E-pratique mesuré aux éoliennes*	*E-théorique calculé sur la base des mesures du vent*	*E-pratique mesuré aux éoliennes*
3 m/sec	180	20 à 120	230	140 à 240
5 m/sec	410	140 à 340	740	410 à 580
7 m/sec	600	240 à 560	1 300	670 à 1 100
9 m/sec	680	380 à 700	1 800	1 200 à 1 640
	Rendement spécifique de la surface balayée: 120 watts/m²		Rendement spécifique de la surface balayée: 340 watts/m²	

$$E \text{ théorique} = \frac{8\,760 \text{ heures/an}}{102 \text{ mkp/kW/sec}} \cdot 0{,}596 \cdot \frac{\delta}{2} \cdot \left[\int_0^{t_{v_1 \max}} V^3\,dt + (1 - t_{v_1 \max}) \cdot v_1^3 \max \right]$$

où δ est en kp sec²/m⁴
t est en heures par an (total : 8 760)
v est en m/sec.

Le rendemennt spécifique de la surface balayée est le quotient de la capacité installée de l'éolienne divisée par la surface circulaire balayée par les pales de l'élice.

longue période et de la puissance spécifique de l'aire balayée (tableau 2). Le quotient de la différence entre la puissance maximum (P_{max}) et la puissance minimum (P_{min}) de l'installation, et la puissance moyenne (P_{moy}), sert d'étalon pour mesurer l'uniformité du rendement. Ces trois valeurs sont données par la courbe de durée de la puissance. Il convient alors de rapporter les dimensions de l'accumulateur nécessaire à l'importance du rendement à prévoir pour la production moyenne journalière d'énergie étalée sur une longue période. L'importance de l'accumulateur s'exprime par le laps de temps pendant lequel il peut alimenter le consommateur en énergie, celle-ci étant fournie à une puissance constante.

c) Le coût total d'une éolienne est déterminé par la somme des dépenses couvrant la machine elle-même, c'est-à-dire l'hélice, les transmissions, l'alternateur, le dispositif d'alignement dans le vent, la tour, les fondations, etc., les frais de montage et d'installation, y compris les appareils de commande et de sélection de la charge (selon Walker, W/18), et des dépenses pour l'accumulateur.

d) La valeur moyenne à long terme de la vitesse du vent, qui ne dépend pas seulement du facteur météorologique dans son ensemble, mais aussi des particularités topographiques locales, est discutée en détail au titre du point II.B.1 de l'ordre du jour.

Contentons-nous de signaler ici que pour une valeur moyenne de la vitesse qui reste en-dessous du facteur météorologique global, les faibles vitesses du vent sont fortement diminuées; le rendement énergétique total diminue, et les exigences en matière d'accumulateur augmentent.

Il est certain qu'entre l'implantation de l'installation, l'importance de l'accumulateur et la vitesse moyenne du vent il y a un rapport qui, eu égard au prix de l'énergie, doit être porté à un niveau optimum pour un projet donné et une uniformité déterminée de l'énergie offerte.

Tableau 2. Capacité d'accumulation nécessaire pour l'implantation d'une installation de 120 W/m²

Équilibre énergétique	*Variations de puissance* $\frac{p_{max} - P_{min}}{P \text{ moyen}}$	*Capacité d'accumulation: volume d'emmagasinage* — *Energie journalière moyenne produite (kWh)*		
Puissance constante.	0	11 jours	20 jours	32 jours
Équilibre excellent .	0,5	3,5	6	20
Utile	1	1,2	2,6	12
Mauvais	2	0	0,8	3,4
Insuffisant . . .	3	0	0	1
Vitesse moyenne du vent.	3	10 m/sec	6 m/sec	3 m/sec

Ce tableau montre qu'aux valeurs plus élevées de vitesse moyenne, et pour des installations identiques, les exigences d'accumulation sont plus faibles qu'aux valeurs moins élevées, par rapport à l'utilisation moyenne d'énergie.

Il y a peu de temps encore, ce niveau optimum dépendait en premier lieu, en ce qui concernait les usages individuels, de l'opinion personnelle, peut-être aussi de l'expérience de techniciens qui concevaient les éoliennes; outre les réalités économiques, des motifs relevant de la psychologie des ventes pouvaient alors jouer un rôle défavorable.

Le niveau optimum de la dépense totale ne dépend pas seulement de l'importance de l'accumulateur nécessaire, mais aussi de son type. E. W. Golding et le rapporteur de cette section ont, en plus d'autres auteurs, signalé très tôt cette circonstance. Ils y ont été amenés par l'idée que l'énergie nécessaire n'est qu'un moyen d'obtenir certains effets et qu'elle ne concerne pas au premier chef la fourniture de produits nécessaires à la vie.

Structure des besoins en énergie : sélection automatique de la charge et exploitation complète de l'énergie offerte

La planification doit donc toujours comprendre non seulement une analyse du *volume des besoins*, mais encore une analyse de leur *structure*, car, dans de nombreux cas, il est plus facile de stocker le produit fini dont la transformation nécessite de l'énergie que cette énergie elle-même.

Il en est particulièrement ainsi de la chaleur et de l'eau. Le rapporteur a eu à sa disposition les résultats d'enquêtes faites sur la structure des besoins d'énergie des exploitations agricoles en Allemagne, entreprises de 1930 à 1938 par la *Deutsche Gesellschaft für Technik in der Landwirtschaft* et de 1946 à 1948 par la *Energieversorgung Schwaben*.

Dans les deux cas, les résultats ont été surprenants, comme l'indiquent les exemples suivants.

a) De 8 à 16 p. 100 seulement de l'énergie totale sont utilisés pour l'éclairage, la radio et le petit appareillage, ainsi que pour les trayeuses et centrifugeuses électriques qui fonctionnent à certains moments de la journée. Ce sont les seuls appareils qui consomment de l'énergie « à la demande », selon Walker (W/18).

b) Les besoins en énergie pour l'entraînement mécanique des scies circulaires à bois, des monte-charge à foin, des petits moulins à céréales, etc., sont du même ordre de grandeur. Les commandes mécaniques de ce genre sont nécessaires pour transformer les produits emmagasinés et pour les stocker de nouveau. Il n'est donc pas absolument nécessaire de faire ces travaux pendant des périodes d'accalmie du vent; on peut au contraire attendre, sans que cela entraîne des conséquences fâcheuses, que la force du vent soit suffisante.

c) De 70 à 80 p. 100 de l'énergie requise sont affectés à des appareils thermiques : chauffage, cuisinières électriques, réfrigérateurs, accumulateurs d'eau chaude, etc. Il est relativement plus facile et nettement moins onéreux d'accumuler de grandes quantités d'énergie pour ces appareils que ce n'est le cas avec l'accumulateur d'énergie électrique dans des batteries plomb-acide.

d) Il en va de même pour le pompage de l'eau. L'eau peut être emmagasinée dans de grands réservoirs, ou pour les installations d'irrigation, dans le sol même, sans grandes dépenses.

Dans le mémoire de Walker (W/18), aussi intéressant que précieux et bien documenté du point de vue des méthodes à appliquer à l'exploitation de l'énergie aérodynamique, il n'est pas seulement question des résultats pratiques obtenus dans une installation en grande partie automatisée qui alimente en énergie éolienne une ferme de moyenne importance, en prenant pour bases les notions qui viennent d'être esquissées; mais encore des conséquences qu'entraînent ses multiples possibilités d'utilisation pour l'exploitation de l'énergie offerte.

Les mesures faites pendant trois ans par Frenkiel (W/6) dans l'installation éolienne d'Eilat, mise au point et décrite par Jacobs (W/22), montrent que, malgré les précautions prises, 2 750 kWh seulement ont pu être effectivement utilisés, alors que 4 200 kWh étaient contenus dans le vent, soit un rendement de 65,5 p.100. Or, le prix de l'énergie étant presque uniquement déterminé par les dépenses d'équipement qu'entraîne l'installation de l'éolienne, il s'ensuit que l'exploitation partielle d'un aéromoteur du type décrit par Frenkiel provoque une augmentation de 50 p. 100 environ du prix de l'énergie.

Le procédé de l'E.R.A. (Electrical Research Association) décrit par Walker prévoit un système automatique de commande de toute l'installation, conçu pour être utilisé par un usager non technicien tout en permettant à celui-ci de choisir à son gré l'ordre de priorité des diverses charges.

Le dispositif de répartition de la charge, commandé par les variations de tension de l'alternateur entraîné par le vent, se compose essentiellement d'un relai à solénoïde mobile alimenté, par l'intermédiaire d'un redresseur, par l'alternateur. Les chutes ou les hausses de tension dans l'alternateur excitent le contact mobile du relai, qui fait démarrer un moteur de faible puissance, celui-ci entraînant à son tour, par l'intermédiaire d'un engrenage, 28 cames disposées de façon qu'à chaque rotation de 6 degrés de l'arbre corresponde la fermeture d'un microrupteur. Le courant dérivé d'un pôle unique, prélevé sur les trois barres omnibus, alimente une rangée verticale de 28 douilles après être passé dans les microrupteurs.

Le nombre des cames, microrupteurs, douilles, etc. dépend entièrement du nombre des charges installées. Les douilles sont groupées de telle sorte que toute augmentation de la tension de débit, et par conséquent de la puissance de l'éolienne, provoque leur excitation dans un ordre ascendant, tandis qu'une baisse de la tension de débit les désamorce dans l'ordre inverse.

L'utilisateur peut choisir à volonté, en enfonçant les fiches dans la rangée verticale de douilles, l'ordre dans lequel les charges doivent se trouver par

rapport à l'alimentation, au fur et à mesure que l'énergie devient disponible.

La conception fondamentale du système à sélecteur de charge peut être appliquée à n'importe quel type de machine ayant jusqu'à, disons, 50 kW de puissance, à condition que la puissance et le nombre des contacts de charge soient adaptés à tous les besoins prévus.

Groupes thermo-électriques de secours classiques

Dans les cas d'éoliennes suffisamment grandes pour alimenter largement en énergie des fermes d'importance moyenne ou de petites collectivités, le fait de disposer d'un groupe de secours permet de créer des conditions extrêmement favorables en ce qui concerne la sûreté de fonctionnement et l'économie de toute l'installation (voir mémoires W/1 et W/18).

Ces groupes thermo-électriques présentent les avantages suivants.

a) Fourniture de courant de secours en cas de périodes d'accalmie extrêmement longues. Les accalmies moyennes, d'une à 48 heures, sont très nombreuses, tandis que les accalmies de plus de deux jours, par suite de conditions météorologiques stables, sont très rares. Il serait peu économique et peu rationnel de prévoir une installation d'accumulation de l'énergie qui ne servirait que deux ou trois fois par an. Il serait plus rationnel d'utiliser dans ce cas un groupe de secours.

b) Le groupe de secours alimente entièrement le consommateur en énergie lorsqu'il s'avère nécessaire de procéder à l'entretien ou à la réparation de l'éolienne.

c) Pendant les pointes de consommation saisonnières, importantes et de courte durée (battage du blé, par exemple), le groupe de secours, l'accumulateur et l'éolienne peuvent alimenter ensemble le réseau et faire face ainsi aux pointes de charge rares et importantes.

L'installation expérimentale construite par l'E.R.A. en Écosse ainsi que l'éolienne exploitée par le *Wasser- und Schiffahrtsamt* de Kiel sur l'île Schleimünde pour l'alimentation du phare et de quelques maisons d'habitation (voir la référence 4 du mémoire W/6) étaient équipées de groupes de secours diesel, qui prenaient le relais d'une éolienne Allgaier équipée d'une hélice de 10 m de diamètre et développant l'un 6 kW, l'autre 7,5 kW de puissance nominale. Dans les deux cas, il s'est avéré au cours de plusieurs mois d'exploitation que les groupes diesel n'étaient que rarement utilisés. A Schleimünde, l'éolienne produit 94,5 p. 100 de l'énergie nécessaire; ce pourcentage est de 98,6 p. 100 à l'installation E.R.A. bien que la vitesse moyenne annuelle du vent n'ait été que de 3,8 m/s.

Du fait de cette faible participation du groupe de secours à la fourniture de l'énergie totale, Walker estime qu'il suffirait de disposer d'un groupe électrogène portatif à essence dont la capacité équivaudrait à 12 ou 20 p. 100 de la puissance calculée de l'éolienne.

Prix de l'énergie comparé à celui des groupes électrogènes classiques

Lorsque l'on compare les prix de l'énergie destinée aux usagers individuels et aux collectivités, il faut se rappeler que dans tous les cas où l'on envisage d'utiliser le vent (ou l'énergie solaire), le prix de l'énergie ne concurrence pas celui de l'énergie fournie par les réseaux de distribution publics des pays très industrialisés, mais celui des centrales thermiques locales. Le tableau 3 donne un aperçu des frais de production de l'énergie tels qu'ils figurent dans les mémoires de cette section et les compare aux données fournies par Golding.[1]

Il faut se rappeler à ce propos que les données reprises dans le mémoire W/21 s'appliquent à des installations exploitées en parallèle avec des réseaux de distribution publics. Il est possible que les valeurs

[1] Golding, E. W., La production d'énergie à partir des ressources locales, *Actes officiels de la Conférence des Nations Unies sur les sources nouvelles d'énergie, 1961*, vol. 1 point II.D.1 de l'ordre du jour, mémoire GEN/5.

Tableau 3. Comparaison des prix de l'énergie calculés sur la base d'un amortissement décennal et de la vente de toute l'énergie produite

Auteur	*Mémoire*	*Puissance nominale*	*Diamètre de l'hélice*	*Dollar des États-Unis par kWh*
Juul	W/21	200 kW	24 m	0,00105
Arnfred	W/1	30 kW	18 m	0,00073
Walker	W/18	7,5 kW	10 m	0,041
Jacobs	W/22	3 kW	4,5 m	0,028 [a]
Frenkiel	W/6	3 kW	4,5 m	0,1 [b]
Frenkiel	W/6	3 kW	Groupes électrogènes diesel	0,18
Golding	GEN/5	50 kW		0,073
Golding	GEN/5	100 kW		0,051
Golding	GEN/5	200 kW		0,042

[a] Prix de l'éolienne à l'usine.
[b] Prix de l'éolienne livrée.

trouvées dans le mémoire W/1 reposent sur les prix d'achat d'éoliennes tellement anciens qu'ils n'ont plus cours à l'heure actuelle. Cependant, si l'on admet des conditions tellement variées, on ne peut manquer de remarquer combien est vaste l'éventail des données concernant le prix de l'énergie.

Ces différences dénotent un manque de certitude quant au calcul des prix de l'énergie. Elles sont encore plus frappantes lorsqu'on pense qu'aux valeurs moyennes divergentes de la vitesse du vent qui ont servi de bases au calcul des dépenses, telles qu'elles figurent aux mémoires W/1, W/21, W/18, W/22 et W/6, s'ajoutent encore les facteurs d'incertitude dont Stam dit (W/40) : « les produits qui n'empruntent pas les voies normales du commerce mondial voient leurs prix multipliés... »

Les éoliennes décrites dans les mémoires W/22 et W/6 sont de type identique et construites par les mêmes fabricants. Bien que les vitesses moyennes des vents retenues dans les deux cas pour calculer le prix de l'énergie aient été analogues, les deux prix varient entre eux dans une proportion de 1 à 3.

Le pompage de l'eau par des éoliennes

Il n'y a malheureusement que deux mémoires (W/40 et W/23) consacrés au pompage de l'eau par des moyens mécaniques. Il y est question des efforts déployés pour établir, en faisant appel à des solutions de conception particulièrement simple, les prémisses nécessaires à la fabrication de telles installations dans les pays qui ne disposent pas encore d'une industrie très évoluée.

Il est indispensable, si l'on veut planifier rationnellement de vastes projets d'irrigation dans le cadre de programmes de colonisation des terres ou de programmes visant à améliorer le rendement du sol dans des régions déjà peuplées, de réunir les données suivantes au moyen d'observations météorologiques et de forages :

a) La valeur moyenne hebdomadaire ou mensuelle de la vitesse du vent au cours de plusieurs années;

b) La valeur moyenne hebdomadaire des précipitations;

c) Le niveau des eaux souterraines;

d) Le débit maximum des puits forés.

Il semble que le débit moyen des puits (jusqu'à leur assèchement) et la profondeur moyenne des nappes d'eau souterraines, dans les régions semi-arides où les éoliennes de pompage sont couramment utilisées, aient joué un rôle déterminant pour les dimensions du châssis multipale dont sont dotées les éoliennes les plus répandues.

D'un autre côté, le niveau des nappes d'eau souterraines et le débit possible des puits varient tellement d'une région à l'autre qu'il vaut la peine, lors de la mise en valeur d'un nouveau territoire, de procéder à des enquêtes climatologiques et hydrologiques dans le cadre de la planification et, ensuite seulement, de définir l'importance et l'implantation de l'installation ainsi que le système d'irrigation optimum.

Les éoliennes de pompage, comme les pompes à gouttière ouverte dont parle Stam (W/40) ou les moulins à vent à faible écoulement auxquels se réfère Havinga (II.B.2, W/32), dans lesquels la hauteur de refoulement est minime alors que la quantité d'eau à débiter est forte, représentent un cas spécial. Des aéropompes de ce genre ont déjà été utilisées aux Pays-Bas et dans le nord de l'Allemagne pour assécher des terrains bas endigués, en Camargue pour reconquérir des terrains défrichables en faisant déposer les boues, et dans les deltas des grands fleuves à des fins d'irrigation ou d'assèchement; elles y remplissent des tâches caractéristiques qui leur sont propres.

Les groupes hydro-électriques dans les systèmes de distribution d'eau

Souvent, la première tâche à remplir lors de la mise en valeur des terres de colonisation à l'aide de l'énergie éolienne consiste à rendre disponible l'eau nécessaire à la vie. L'emmagasinage de l'eau dans des réservoirs en tôle ou dans des cuves souterraines offre la possibilité, mise en avant par Walker (W/18), Stam (W/40) et par le rapporteur (conférence faite en janvier 1961 en Inde, à Bangalore), d'installer de petits groupes hydro-électriques sur les conduites amenant l'eau du réservoir au consommateur (W/18) ou ramenant l'eau en surplus vers le puits, et de produire ainsi du courant qui assure l'éclairage ainsi que le fonctionnement des postes de T.S.F. et des petits appareils ménagers.

L'installation d'un réseau de distribution d'eau composé de conduites souterraines en plastique et celle de groupes électrogènes dans les maisons alimentées en eau offrent de grands avantages pour la distribution de ce liquide. Elles permettent aussi de surmonter, grâce à cette façon de produire l'électricité, la difficulté dont parle Walker (W/29) : les pertes de puissance dans les lignes d'amenée au consommateur, qui peuvent être considérables dans le cas des petits aérogénérateurs où, vu le prix des batteries, la tension est faible. Il y a un autre avantage encore pour la mise en valeur des terres nouvelles, le fait qu'il ne soit d'abord fait appel qu'à des machines et à des systèmes de distribution d'eau relativement simples, à transformation uniquement mécanique, avec lesquels la population peut aisément se familiariser, alors qu'elle ne saurait encore s'attaquer à des problèmes techniques plus subtils.

Utilisation en liaison avec des réseaux électriques

Lorsque les installations doivent être utilisées en parallèle avec des réseaux transportant de grandes quantités d'énergie, on les choisit de préférence de puissance et de grandeur moyennes, non seulement parce que les machines de grande puissance sont moins chères, mais encore parce que ces installations

peuvent être équipées de systèmes de réglage plus sensibles et capables de répondre à toutes les exigences posées par l'alimentation automatique de grands réseaux en énergie électrique.

On sait depuis longtemps qu'il n'est pas nécessaire de régler la vitesse de rotation ou la fréquence d'une telle installation; il faut cependant prendre des précautions pour que, par exemple, la charge maximum admissible de l'alternateur ne soit pas dépassée, que l'installation soit arrêtée automatiquement en cas de panne de secteur et qu'aucune énergie ne soit prélevée sur le réseau quand le vent mollit.

Toutes les éoliennes construites ces dernières années et destinées à être montées en parallèle avec des réseaux étaient des appareils *expérimentaux*. Certains d'entre eux étaient des improvisations géniales dont les éléments et le système de réglage avaient été « bricolés » avec des pièces destinées à l'origine à des machines d'un tout autre genre. Malgré la diversité des postulats et bien que les solutions trouvées soient très différentes, il résulte de la nature des choses que les programmes de commande et de régulation de toutes les installations présentent des analogies fondamentales (voir mémoires W/18, W/9, W/17, W 34 et W/36, ces quatre derniers au titre du point II.B.2).

C'est ainsi que Juul et Armbrust (mémoires W/17 et W 34, respectivement, au titre du point II.B.2 de l'ordre du jour) décrivent d'une manière analogue à celle de Delafond (W/8) les mesures à prendre pour éviter les couplages et découplages trop fréquents lorsque la vitesse du vent suffit tout juste à faire produire de l'énergie à l'aérogénérateur.

Il y a deux sortes d'oscillations, les oscillations mécaniques et les variations de charge, qui troublent le fonctionnement de toutes les éoliennes :

a) Celles que provoque le passage des pales de l'hélice devant la tour;

b) L'effet de « pompage » provoqué par le nombre fini de pales, par l'augmentation de la vitesse du vent avec l'altitude et par le fait que la rigidité de l'appui sur lequel repose l'arbre de l'hélice n'est pas symétrique à son axe de rotation.

Il est heureux que dans les deux cas il s'agisse d'oscillations stables qui n'ont pas tendance à se transformer en vibrations. Leur origine étant connue, il sera possible d'y remédier en grande partie dans les modèles ultérieurs.

Les aérogénérateurs exploités en parallèle avec des réseaux puissants constituent une charge négative pour ces réseaux, ainsi que l'a noté Munroe, dans les commentaires formulés par lui à ce sujet (réunions de l'Electricity Research Association, Londres, mars 1955).

Ces charges négatives, qu'il n'est pas toujours possible de prévoir à l'avance, surtout lorsque des aérogénérateurs isolés sont exploités en parallèle avec des réseaux puissants, ont pour effet d'économiser le combustible ou le carburant. Toutefois, les réseaux publics doivent avoir une puissance garantie; c'est pourquoi les représentants des entreprises distributrices de courant électrique soutiennent que l'économie ainsi réalisée est relativement faible pour les raisons suivantes :

a) La part revenant au combustible dans le prix de revient brut du kWh est relativement minime, quel que soit le système d'alimentation en énergie;

b) Pour chaque unité de puissance nominalement produite par un aérogénérateur et fournie à l'usager, il doit y avoir une unité de puissance égale d'origine classique utilisable en cas d'accalmie complète du vent.

Bien que ces arguments soient fondés en un certain sens, il n'en reste pas moins qu'ils postulent que le combustible ou le carburant (charbon ou mazout) sera disponible en toute circonstance à des prix stables. Or, tel n'est pas le cas. Il ressort de la figure 5 du mémoire W/21 que, de 1950 à 1960, le prix du charbon et du pétrole a varié au Danemark de plus ou moins 50 à 60 p. 100 par rapport au prix moyen. Les pays qui ne disposent pas de ressources suffisantes en ce domaine doivent même s'attendre de temps en temps à des situations économiques ou politiques qui mettent en danger leur approvisionnement.

Il n'est pas toujours vrai non plus que le répartiteur de charge des entreprises de distribution de courant pourrait éprouver de grandes difficultés par suite des oscillations constantes de la puissance offerte par les aérogénérateurs lorsque la part de l'énergie éolienne dans la puissance totale du réseau dépasse 20 à 30 p. 100. Comme le démontre Juul (W/21) et comme le signale Delafond (W/8), il s'établit un équilibre énergétique interne dans l'exploitation en parallèle de plusieurs aérogénérateurs largement espacés, la quantité d'énergie offerte étant alors plus uniforme. Ainsi qu'il ressort des probabilités statistiques, cela s'explique par le fait que les variations de la vitesse du vent dues aux turbulences locales de même que les oscillations de puissance sont ainsi supprimées, surtout si les aérogénérateurs sont nombreux et largement disséminés.

Les échanges de masses d'air importantes et, de ce fait, l'ordre de grandeur de la vitesse prévisible du vent peuvent être prédits quelques heures à l'avance avec une assez grande certitude. Lorsque l'énergie éolienne potentielle représente une part assez grande du réseau, le répartiteur de charge doit être constamment renseigné par les services météorologiques sur les changements de la situation météorologique, afin qu'il puisse programmer son recours aux groupes électrogènes classiques.

Aucune difficulté fondamentale et insurmontable ne s'oppose donc à l'alimentation d'un réseau en énergie d'origine aérodynamique. Il ne reste alors qu'une seule restriction, le fait que cette énergie est mal placée, en ce qui concerne les prix, pour soutenir la concurrence de l'énergie d'origine classique, surtout lorsqu'elle est utilisée par des usagers privés.

Il serait pourtant possible de baisser encore son prix de revient par rapport aux valeurs indiquées dans le tableau 3. Pour cela, il faudrait :

a) Produire en grandes séries des aérogénérateurs de puissance moyenne et abaisser ainsi les prix du fabricant. Il faut se rappeler que, jusqu'à présent, tous les grands aérogénérateurs étaient des modèles uniques et que tous les prix de revient de l'énergie étaient fondés sur les frais plus élevés qui en découlaient. Il en est ainsi non seulement pour les aérogénérateurs exploités en parallèle avec des réseaux de distribution, mais encore (sous réserve de certaines restrictions) pour les machines fabriquées industriellement et destinées à être vendues à des usagers privés;

b) Perfectionner systématiquement les installations sur la base des connaissances déjà acquises, en vue de simplifier au maximum, en tenant pleinement compte des données de l'aérodynamique moderne et de la technique de la régulation, ainsi qu'en mettant en pratique nos connaissances dans le domaine des matériaux nouveaux et dans celui des procédés de fabrication les plus récents.

Thèmes de discussion proposés

1. De quelle durée doivent être, en comparaison des groupes électrogènes classiques, les intervalles séparant les travaux d'entretien et de réparation effectués sur les éoliennes?

2. Quelle est l'importance des frais d'entretien et de réparation par rapport au prix de revient total de l'énergie éolienne destinée à des usagers privés ou à des collectivités?

3. Quels dommages la foudre peut-elle causer aux éoliennes, et quelles précautions faut-il prendre à ce sujet?

4. Quelle influence le givrage des pales d'hélice exerce-t-il sur les éoliennes? Des balourds peuvent-ils les endommager, et de quelle façon le débit de l'installation en est-il affecté?

5. La sûreté de fonctionnement des éoliennes revêt une telle importance dans certains domaines que toute simplification de leur construction entraîne une simplification supplémentaire du fonctionnement. La suppression du système d'alignement dans le vent constituerait une telle simplification. Dans quelle mesure le débit d'une éolienne fixe diminuerait-il par rapport à celui d'une installation à commande d'alignement?

6. Est-il possible d'éviter les oscillations de puissance provoquées par le passage des pales devant la tour en faisant tourner l'hélice devant celle-ci et non pas derrière elle, dans le sens du vent?

7. De quel ordre de grandeur sont les bruits provoqués par les éoliennes en marche?

8. Quels avantages présentent, par rapport aux pompes à entraînement mécanique direct, les installations de pompage dans lesquelles des aérogénérateurs alimentent en courant triphasé des pompes plongeantes montées sur un puits?

9. On sait que, au cours de la journée, la vitesse du vent accuse des valeurs maxima et minima caractéristiques. Les courbes de demande d'énergie présentent elles aussi un aspect caractéristique. Est-il possible de faire suivre à la demande d'énergie les fluctuations journalières de la vitesse du vent?

RECENT DEVELOPMENTS AND POTENTIAL IMPROVEMENTS IN WIND POWER UTILIZATION

Rapporteur's summation

The main points which emerged from the discussion concerning agenda item II.B.3 are here summarized.

Apart from the potentiality of solar energy, the only presently available energy source for individual use, as well as for small isolated communities, is the thermo-electric unit of conventional type. If the local average wind velocity at the selected site, measured over a long period, exceeds 4 m/sec or 9 mph, integrated wind power installations of present day design can easily compete with conventional thermo-electric sets, both economically and from the point of view of maintenance.

The relation between the price of a kilowatt produced by a wind electric installation and that produced by conventional thermo-electric sets is much better for a unit producing more than about 20 000 kW per annum than for smaller ones.

If there exists, at the site provided for the erection of a wind power plant, a measured long-time average wind velocity value, then the quantity of energy which a certain wind power plant at this site will produce can be predicted exactly.

If, for at least a year, the daily average of wind velocity at the site has been measured, the necessary capacity of the energy-storing device (which has a considerable influence on the economy of the installation) can be exactly calculated on the basis of the power availability diagram which the the user of the plant has.

A small conventional thermo-electric stand-by unit is certainly of some help, but it will contribute only 1 to 3 per cent to the total energy supply.

As the required energy is only a means for providing certain products necessary for life and therefore not of primary interest, not only the size but also the kind of the required accumulator has a marked influence on the economy of an integrated plant.

By correct choice of the characteristic outlay data, the economy of a wind power plant can be optimized. The influencing data are the rated power per unit of area swept by the wings and the capacity of the energy storage device expressed in days of independent energy storage. It is remarkable that the necessity of energy storage makes it more reasonable to choose a smaller specific power than that which seems to be the optimum if no storage is considered.

The optimum size of wind power plants depends on the average wind velocity and the design concept. Plants of this optimum size exist in Grand Vent, Algeria; Gjedser, Denmark; Nogent le Roi, France; and Stötten, Germany.

This size, about 24 to 34 metres in diameter, can easily be produced in quantities so that the selling price will fall to a reasonable level; the wind power plants will be able to serve as power sources for communities, producing 100 to 500 megawatt hours per unit per annum at only 10 mph average wind velocity.

For water pumping, it has for many years frequently been proposed that wind electric units of some size be installed on hill-tops to feed electrically driven water pumps at deep points in the valleys where sub-surface water exists. This would not only divide the problem into a more or less new one — wind electricity — and an old one — pumping water by electric driven pumps — but would also take advantage of the higher energy gain on the hill-tops.

Where flat country prevails, even mechanically driven pumps with variable stroke, following the ideas of patents more than thirty years old, may pump water in quantities using wheels with high specific speed.

To obtain water from moisture in the air, direct, mechanically, driven compressors of refrigerator systems may be of considerable value.

As many parts of wind power plants, such as wings and tower, are bulky for transport, on the one hand, and comparatively easy to make, on the other hand, if the preparatory engineering is on a high level — taking into account even the much bigger tolerances, which have to be conceded — these could easily be made by local labour. This not only decreases the necessary capital investment but also has the psychological effect of giving local labour the feeling of ability to make such a plant as well as the responsibility for the installation.

The facts concerned with parallel operation of wind power plants are well known. Years of satisfactory and completely automatic operation have proved it.

In summarizing these points and in considering what could be done now, we are confronted with the following situation.

A comparatively small group of enthusiastic engineers and scientists have already developed all

the techniques to use wind power on a large scale. The difficulty, however, lies in the fact that, on the one hand, industrialized countries are expected to undertake the considerable investment necessary for mass production of units, while on the other hand, developing countries are expected to place orders in such quantity that the efforts to organize a planning, selling and servicing system, which is essential to bring wind power utilization to a success, can be considered economically reasonable. It is to be hoped that this Conference may help to resolve this difficulty.

UTILISATION DE L'ÉNERGIE ÉOLIENNE : PROGRÈS RÉCENTS ET AMÉLIORATIONS POSSIBLES

Résumé du rapporteur

On trouvera ci-après un résumé des principales idées émises au cours de l'examen du point II.B.3 de l'ordre du jour.

Abstraction faite des utilisations possibles de l'énergie solaire, la seule source d'énergie actuellement à la disposition des particuliers et des petites collectivités isolées est le groupe thermo-électrique de type classique. Si, à l'emplacement choisi, la vitesse moyenne du vent, mesurée pendant une période de longue durée, dépasse 4 m/s, soit 9 milles par heure, l'installation éolienne intégrée de type courant peut facilement rivaliser, tant sur le plan économique que du point de vue de son entretien, avec la centrale thermo-électrique classique.

Le rapport du prix du kilowattheure produit dans une centrale éolienne à celui du kilowattheure produit dans une centrale thermo-électrique de type classique est beaucoup plus favorable s'il s'agit d'une installation produisant plus de 20 000 kilowattheures par an que d'une installation plus faible.

Si l'on a mesuré la vitesse moyenne du vent pendant une longue période à l'emplacement choisi pour la construction d'une centrale éolienne, on peut prévoir avec exactitude la quantité d'énergie que produira cette centrale.

Si l'on a établi, pendant une année au moins, la moyenne quotidienne de la vitesse du vent à l'emplacement donné, on peut calculer avec exactitude la capacité nécessaire du dispositif d'accumulation d'énergie (qui influe considérablement sur la rentabilité de l'installation) d'après la courbe de la puissance disponible que possède l'utilisateur de l'installation.

Un petit groupe thermo-électrique classique de réserve n'est certes pas inutile, mais il ne peut fournir que 3 p. 100 de la quantité totale d'énergie.

Comme l'énergie requise ne représente qu'un moyen de se procurer certains produits nécessaires à la vie et, par conséquent, ne revêt qu'un intérêt secondaire, la rentabilité d'une installation intégrée dépend dans une large mesure non seulement de la dimension de l'accumulateur utilisé, mais aussi du type auquel il appartient.

On peut assurer la rentabilité optimale d'une centrale éolienne en choisissant correctement les caractéristiques de l'installation. Les facteurs essentiels sont la puissance de régime par unité de surface balayée par les ailes et la capacité de l'accumulateur d'énergie exprimée en journées d'accumulation indépendante d'énergie. Il y a lieu de noter que, vu la nécessité d'accumuler l'énergie, il est plus avantageux de choisir une puissance spécifique plus faible que celle qui semble optimale lorsqu'on n'envisage pas la question de l'accumulation de l'énergie.

La dimension idéale des centrales éoliennes dépend de la vitesse moyenne du vent et du modèle choisi. On trouve des centrales ayant cette dimension optimum à Grand Vent (Algérie), Gjedser (Danemark), Nogent-le-Roi (France) et Stötten (Allemagne).

Des installations de cette dimension — c'est-à-dire ayant de 24 à 34 mètres de diamètre — peuvent être aisément fabriquées en grandes quantités de manière que le prix de vente en soit raisonnable; ces centrales, qui peuvent produire de 100 à 500 mégawattheures par groupe et par an pour une vitesse moyenne du vent de 10 milles par heure seulement, permettront d'alimenter des collectivités en énergie.

Pour le pompage de l'eau, on propose depuis plusieurs années d'installer sur les hauteurs des centrales éoliennes de dimension assez importante afin d'alimenter des pompes à eau électriques situées au fond des vallées, où se trouve de l'eau à faible profondeur. Le problème se subdiviserait ainsi en deux, dont l'un — la production d'électricité au moyen de l'énergie éolienne — est plus ou moins nouveau et l'autre — le pompage de l'eau par des pompes actionnées électriquement — est ancien; en outre, on pourrait tirer parti du gain d'énergie plus élevé, existant sur les hauteurs.

En terrain plat, même des pompes mécaniques à course variable construites d'après des brevets datant de plus de 30 ans peuvent pomper de grandes quantités d'eau grâce à des roues à grande vitesse spécifique.

Lorsqu'il s'agit d'obtenir de l'eau à partir de l'humidité contenue dans l'air, les compresseurs mécaniques directs utilisés dans les installations frigorifiques peuvent présenter un intérêt considérable.

Comme un grand nombre des éléments des centrales éoliennes, notamment les ailes et la tour sont, d'une part, difficiles à transporter en raison de leur volume et, d'autre part, de fabrication assez simple si celle-ci est mise au point avec soin — même en tenant compte des tolérances plus élevées à observer — ces éléments pourraient être aisément fabriqués par la main-d'œuvre locale. On pourrait ainsi réduire le montant des investissements nécessaires; en outre, on donnerait aux travailleurs locaux le sentiment qu'ils sont capables de construire une installation

de ce genre et on pourrait leur confier la responsabilité de l'installation.

Tout ce qui concerne l'exploitation parallèle des centrales éoliennes est bien connu, comme l'attestent des années de fonctionnement satisfaisant et entièrement automatique.

Compte tenu de l'exposé ci-dessus et des possibilités qui s'offrent actuellement, la situation se présente de la manière ci-après.

Un groupe assez restreint d'ingénieurs et de savants enthousiastes ont déjà effectivement mis au point toutes les méthodes d'utilisation de l'énergie éolienne à grande échelle. Cependant, une difficulté demeure car, d'une part, on compte sur les pays industrialisés pour effectuer les investissements considérables qui permettront de produire les machines en grande quantité et, d'autre part, on espère que les pays en voie de développement feront assez de commandes pour que puissent être considérés comme économiquement rentables les efforts déployés en vue d'organiser un système de planification, de vente et d'entretien sans lequel l'utilisation de l'énergie éolienne ne peut donner des résultats satisfaisants. Il faut espérer que les travaux de la Conférence permettront de surmonter cette difficulté.

Agenda item II.B.3 (*a*)

WIND POWER PLANT IN EILAT

J. Frenkiel *

Eilat, the southernmost settlement in Israel (29° 33′ N, 54° 57′ E), lying on the arid north-eastern extremity of the Red Sea shore, is an excellent example of a new locality in a completely undeveloped area. When first established in 1949, it was almost 250 km distant from the nearest inhabited place in Israel, and all supplies had to be brought either by road, most of it dirt track, over a distance of some 400 km, or by air. Since then conditions have greatly improved: there is now a hard-surfaced road all the way with a chain of settlements along it, and some supplies are brought by sea as well. Even now, however, because of the considerable distance of Eilat from the centers of supply, the price of bulky goods is appreciably higher there than elsewhere in Israel. Obviously, this price differential was much more pronounced before the road was built.

One of the first and most pressing needs of the new settlement was power generation, and this was first supplied by a relatively small (30 kW) Diesel generator, working on a 15-hour a day schedule. The electricity so produced was very expensive, and its supply was not continuous.

For some purposes it was essential to have a continuous supply of electricity, and wind power was among the alternatives considered. The Eilat area had been known since antiquity as a place where strong and steady winds prevail; its winds were said to have helped in smelting copper in the fabled King Solomon's mines.

Since 1945, regular wind measurements have been made there (at that time, the locality consisted of a lonely police outpost known as Um-Rash-Rash only), and these have confirmed its biblical reputation.

Consequently, it was decided to set up a small wind power plant, to cater for a connected load of about 3 kW. The plant chosen was the largest available commercially at the time (1952), a 3 kW, 110 V D.C. Jacobs unit. It was set up on a small ridge athwart the prevailing wind direction, at a distance of about 30 m from a wind-recording instrument and at the same height. The load was provided by two near-by cottages housing Government offices with attached living quarters.

The plant was in continuous operation for more than three years. During this time, wind velocity and direction were recorded and daily readings were taken of the output of the plant and the effective electricity consumption. The following sections deal with wind régime in Eilat; the installation; performance data; and economic aspects.

Wind régime in Eilat

As stated above regular wind observations were started in Eilat in 1945. Monthly means of wind force and frequency of direction at 08, 14 and 20 hours local time are given in tables 1 and 2 which are derived from *Climatalogical Normals, 1956* (1) and are based on six years of observation (1945-1947 and 1950-1952) prior to the installation of the wind power plant in Eilat.

Tables 1 and 2 show some salient features of the wind régime in Eilat. These are : (a) a pronounced seasonal variation with a flat winter minimum and a broad summer maximum with a trough in the middle of it; (b) a comparatively strong diurnal variation; (c) a year-round strongly prevailing wind direction.

In the spring of 1953, a Dines wind-speed and direction recorder was set up on a small 20-m high east-westerly ridge some 30 m from the wind power plant (see figure 1). The pressure tube was placed on a self-supporting tower about 12 m above ground with the recorder on the ground directly below it. At a later date, a cup-counter anemometer was

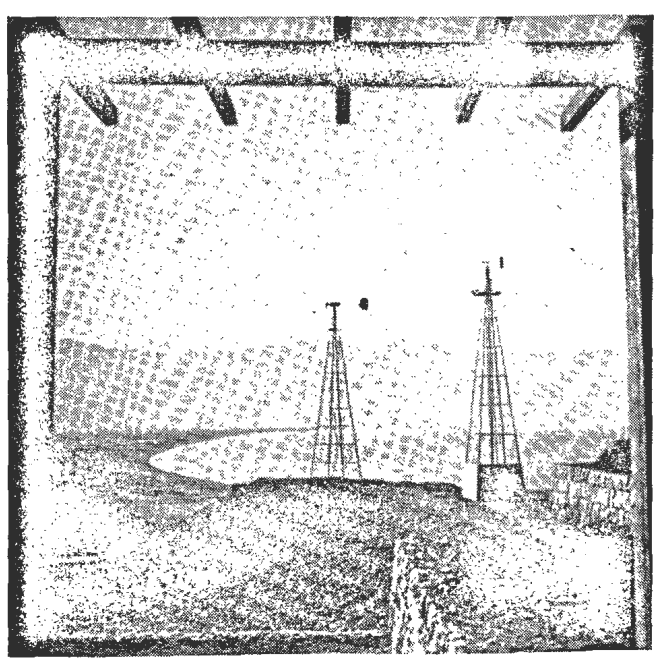

Figure 1. Wind power plant and wind measuring instruments in Eilat

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Table 1. Weighted means of wind force in Eilat (in Beaufort)

Time (G.M.T. + 2)	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Yearly mean*
08.	2.9	3.0	3.4	3.9	3.9	4.0	3.5	3.6	4.3	3.8	3.4	2.6	3.53
14.	3.6	3.4	3.6	3.9	3.9	4.6	4.0	4.3	4.6	3.9	3.8	3.0	3.88
20.	2.8	2.8	3.1	3.3	3.6	4.0	2.9	3.6	3.8	3.0	2.9	2.2	3.17
Mean (Beauf.)	3.1	3.1	3.4	3.7	3.8	4.2	3.5	3.8	4.2	3.6	3.4	2.6	3.53
(Conv.) (km/hr) . . .	16.4	16.4	18.8	21.3	22.2	25.8	19.7	22.2	25.8	20.5	28.8	12.6	19.8

Table 2. Frequency of wind directions (in per mille) in Eilat

Month	*Time (GMT + 2)*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*Calm*
Jan.	08	545	286	11		20	3	14	24	97
	14	425	255	62	28	119	37	3	30	43
	20	527	201	6	13	32	17	38	59	107
Feb.	08	549	278	9	6	9	24	30	30	65
	14	364	226	57	12	128	111	42	48	12
	20	529	190	3	6	30	27	36	84	95
Mar.	08	537	306	16		22	16		17	86
	14	318	206	41	16	235	108	38	11	27
	20	522	134		3	74	76	24	87	80
Apr.	08	567	318	9	9	29		18	17	33
	14	361	214	20	37	226	84	15	32	11
	20	461	136	9	6	70	35	69	135	81
May	08	600	302	6		41	22	8	5	16
	14	440	214	24	13	186	78	13	16	16
	20	492	175	3	3	85	60	31	113	38
June	08	664	304				3	3	15	11
	14	556	272	6	25	97	23	3	18	
	20	561	73			34	12	17	292	11
July	08	582	370	9	3		8	3	3	22
	14	425	229	12	28	203	76	3	19	5
	20	538	33			33	60	19	195	122
Aug.	08	688	288	3				3	13	5
	14	561	227	3		102	67	11	24	5
	20	623	70			40	33	27	180	27
Sept.	08	689	293						18	18
	14	645	294	9	3	23	20		6	12
	20	669	110			12	17	3	178	11
Oct.	08	680	264			5			8	43
	14	557	233	3	22	65	40	3	39	38
	20	633	168			18	17	14	107	43
Nov.	08	728	200	14		6	15	6	14	17
	14	611	179	9	3	87	38	9	25	39
	20	660	136	9		31	18	18	56	72
Dec.	08	593	188	3		16	3	3	33	161
	14	498	162	16	62	85	55	5	27	90
	20	548	160	3		27	16	13	35	198
Yearly mean	08	617	283	7	2	12	8	8	17	46
	08	480	226	22	21	129	61	12	25	24
	20	564	132	3	3	40	32	26	126	74

installed at the same height, and regular daily readings of this instrument were taken at the time of changing the Dines chart. The two wind measuring instruments were in continuous operation for the next four years, Dines chart evaluation having been made for three years. The results of the previous measurements were fully confirmed (see figure 2) with an important addition: constancy of yearly wind regime, as shown in table 3.

Table 3. Yearly mean wind speeds and energy in the wind in Eilat

Period	*Mean wind speed (km/hr)*	*Energy in the wind (kWh p.a./sq.m.)*
1 April 1953-1 April 1954	18.5	1 250
1954	19.0	1 220
1955	19.4	1 300

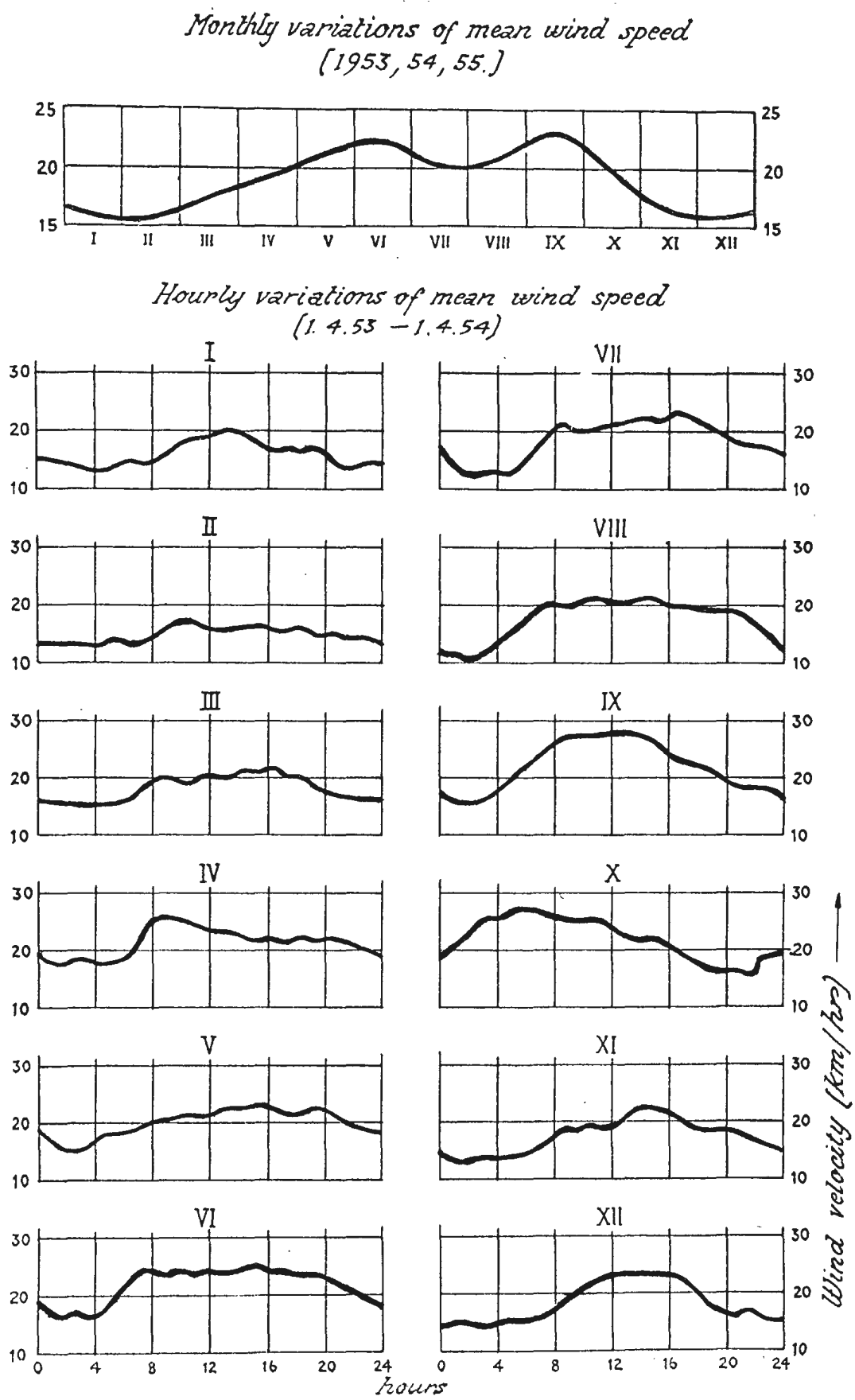

Figure 2. Wind velocity survey, Eilat (25 m above sea level; 12 m above ground)

Description of the installation

The wind power unit chosen was a Jacobs wind electric plant, model 60 BX, 110 volt rated at 3 kW. It had a 14 ft-diameter, 3-blade variable pitch propeller steered by a vane to face the wind and driving directly a slow-speed (150 to 250 rpm) shunt generator. It was linked to a 150 Ah. heavy duty battery through a control cabinet consisting of a reverse current relay, a charge control unit and a voltage control unit. In view of the capacity of the battery, the charge limit was set at 18 amp, and the voltage limit at 138 V, resulting in the effective maximum power of the plant of 2.5 kW, or 175 watts per square meter of the swept area of the propeller.

The plant was set on a 12-m high self-supporting tower at the eastern extremity of a small ridge. overlooking the settlement and Eilat Bay (figure 1). The battery was stored on the rear porch of a cottage built at the other extremity of the ridge some 60 m from the plant, and in one of the rooms the instrument panel was set up (figure 3). The latter contained a voltmeter, an amperemeter in the generator circuit and an amperemeter to measure the net current to the battery; an amperehourmeter indicator giving the state of charge of the battery; a watthourmeter in the generator circuit, and an amperehourmeter in the load circuit.

The load was provided by two cottages of about 120 sq.m. floor area each : one of these, which housed the instrument panel and a battery, served as living quarters for the Government's representative in Eilat; the other housed his offices and a small maritime museum. The total connected load was about 3 kW.

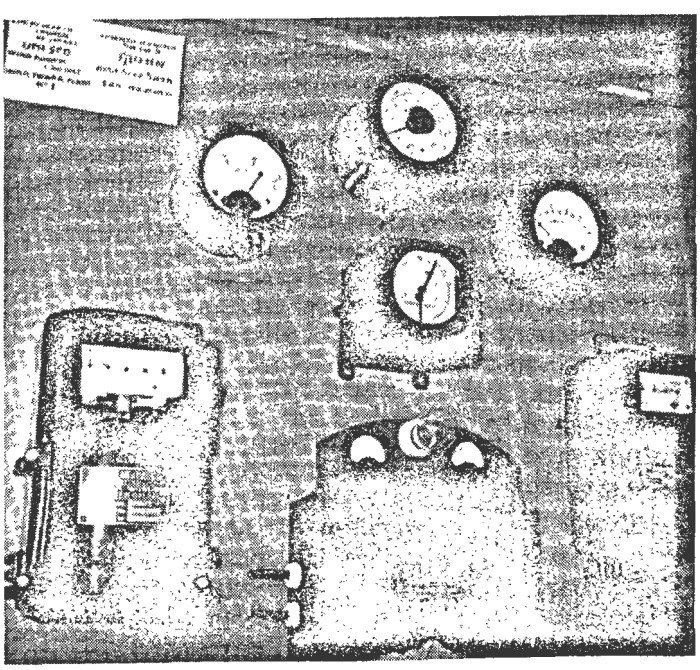

Figure 3. Instrument panel

Performance data

The wind power plant was put into operation in the middle of June 1953, some three months after the beginning of wind measurements with the Dines recorder, and remained in operation practically without interruption until September 1956. During this first year (1 July 1953-1 July 1954), daily readings were taken of the consumption of wind-produced electricity, and subsequently both the output (kWh) and the consumption (in amp/h), together with the state of charge of the battery, were recorded daily. These data are summarized for 3 months' periods in table 4.

From table 4 it may be seen that the average yearly output — with charge limiting device operating — was 4 200 kWh, equivalent to 1 680 kWh per kW installed, or 294 kWh per square meter of the swept area of the propeller.

The figure of 1 680 kWh per annum per kW installed and the corresponding figures for shorter periods may be compared with the specific output of an "ideal wind machine" obeying the following relationship :

$$P = k\lambda(v)v^3 \quad \lambda(v) = \begin{cases} = 0 \text{ when } v < v_s \\ = \lambda(v_r) = \text{const. when } v_s \leqslant v \leqslant v_r \\ = \lambda(v_r)\,(v_r/v)^3 \text{ when } v_r \leqslant v \end{cases}$$

where P — effective power of the windmill
k — constant for given atmospheric conditions
v_s — cut in wind speed = 16 km/hr
v_r — rated wind speed = 32 km/hr.

In the wind régime of Eilat, the specific output has been found to be a precise linear function of the mean wind speed relating to 3-monthly period according to the regression equation (2) :

$$T_s/T_o = a + b\bar{v}$$

T_s = specific output (related to one year); T_o = 8 760 (hours)
$\bar{v}$ = quarterly (i.e. 3-monthly) mean wind speed
a = —0.398 ± 0.014; b = 0.0360 ± 0.0007

variance about the regression line 0.00003.

Now, the characteristic of the Eilat plant was not very different from the above characteristic of an "ideal wind machine". It started generating at a wind speed of about 15 km/hr, and achieved its rated (2.5 kW) power at about 32 km/hr, when its over-all efficiency was 41 per cent (when related to power in the wind) or 68.5 per cent (when related to available power in the wind). With wind velocity rising above 32 km/hr, the flyball governor reduced the pitch of the blades, resulting in an approximately constant rotational speed of 250 rpm, and a progressively diminishing over-all efficiency.

A comparison of the maximum possible output (i.e., if all the energy available could be utilized) with the effective output is given in table 5.

The very high ratio of the effective output to maximum possible output in the period January-

Table 4. Performance data of wind power plant in Eilat (1 July 1953-1 July 1956), three-monthly periods

Period	*Output (kWh)*	*Consumption (amph/)*	*Days of battery fully charged (number)*	*Mean wind speed (km/hr)*
July-Sept. 1953		6 947		19.5
Oct.-Dec. 1953		3 252		17.1
Jan.-Mar. 1954		4 743		16.0
Apr.-June 1954		7 424		21.2
1 July 1953 - 1 July 1954		22 366		18.5
July-Sept. 1954	1 146	6 422	28	21.9
Oct.-Dec. 1954	874	4 710	34	16.9
Jan.-Mar. 1955	959	3 226	41	16.9
Apr.-June 1955	1 216	6 965	40	21.0
1 July 1954-1 July 1955	4 195	21 323	143	19.2
July-Sept. 1955	1 152	6 974	54	23.3
Oct.-Dec. 1955	848	4 780	24	16.3
Jan.-Mar. 1956[a]	1 200	6 007	31	16.5
Apr.-June 1956[a]	1 702	6 860		21.6
1 July 1955-1 July 1956	4 902	24 621		19.4

[a] Beginning with January 1956, the charge limiting device did not operate; this explains the high output figures for this period.

March 1956 is apparent only. This will be explained when analysing the performance on a monthly basis.

The figure of 294 kWh per annum/sq.m. may be compared with the specific output from 76.5 to 251 kWh per annum/sq.m. for Lykkegard wind power plants, and from 107 to 304 kWh per annum/sq.m. for Smidth aerogenerators in Denmark in the years 1941-1944 (3). It is noteworthy that the highest figure was achieved by the 17.5 m diameter, 50 kW units in parallel operation with local networks in a wind régime characterized by a mean wind speed of 6 m/sec (as against mean wind speed of 5.3 m/sec in Eilat). When the charge limiting device of the Eilat plant did not operate, the output figures rose by 30 per cent giving an extrapolated specific yearly output of 380 kWh per sq.m. (see also table 6).

Table 5. Comparison of the effective output of the Eilat plant with the maximum possible output

Period	*Maximum possible output (kWh/kW)*	*Effective output (before battery)*	
		kWh/kW	*Per cent of maximum possible output*
July-Sept. 1954	889[a]	458	52.6
Oct.-Dec. 1954	476[a]	349	73.4
Jan.-Mar. 1955	456[a]	383	84.0
Apr.-June 1955	773[a]	486	62.8
July-Sept. 1955	963[a]	461	47.9
Oct.-Dec. 1955	393[a]	339	86.2
Jan.-Mar. 1956	417[b]	400	95.9
Apr.-June 1956	850[b]	567	66.7

[a] Computed from power duration curves.
[b] Computed from the regression equation.

Another comparison may be drawn with an Allgaier 6 kW aerogenerator operating navigation lights on Schleimuende Island (4), in a wind régime characterized by the same mean wind speed as in Eilat. There, during the period August 1953-October 1954, 5 546 kWh were produced, equivalent to 57 kWh per annum/sq.m. This low figure is explained by low demand, and it is stated that if full available energy could have been utilized, the output would have trebled, reaching about 170 kWh per annum/sq.m. Even so, it would have been much below the figure obtained with the Eilat plant.

However, of the 4 200 kW produced yearly by the latter, only 2 750 kWh (22 000 amph at an average voltage of 125 V) or 65.5 per cent were actually consumed, whereas the remainder of 1 450 kWh, or 34.5 per cent, must be regarded as loss incurred during battery charging.

A more detailed picture of the performance of the Eilat plant (on a monthly basis) for a two-year period is given in table 6. It is seen that the monthly output varied from 184 kWh to 524 kWh (with charge limiting device operating) and 650 kWh (with charge limited only by the battery voltage). The lowest monthly value of output was achieved, not surprisingly, in the least windy month, December 1955. When this output is compared to that of January 1956, the ratio is found to be 1 : 2, which is identical to the ratio of specific outputs as computed from the regression equation when substituting the respective mean wind velocities (13.5 km/hr and 15.9 km/hr). In both cases, the actual output is some 12 per cent higher than the possible maximum output as computed from the equation. There are several explanations for this apparent incompatibility:

(*a*) Departure of the actual performance of the Eilat wind machine from ideal windmill; (*b*) un-

Table 6. Performance data of wind power plant in Eilat (1 July 1954-1 July 1956), monthly periods

Month	*Output (kWh)*	*Consumption (amp/h)*	*Days of battery fully charged (number)*	*Mean wind speed (km/hr)*
1954				
July	524	2 786	6	21.9
Aug.	416	1 934	12	21.1
Sept.	305	1 702	10	22.8
Oct.	344	2 374	9	19.0
Nov.	224	1 140	15	15.6
Dec.	306	1 195	10	16.0
1955				
Jan.	275	922	19	17.1
Feb.	281	1 071	10	15.7
Mar.	403	1 233	12	17.9
Apr.	415	2 522	8	18.5
May	393	2 188	14	21.2
June	405	2 255	18	23.4
July	364	2 098	12	20.9
Aug.	370	2 118	22	23.6
Sept.	418	2 756	20	25.4
Oct.	314	1 924	14	19.1
Nov.	360	1 821	6	16.3
Dec.	184	1 035	4	13.5
1956[a]				
Jan.	374	1 852	11	15.9
Feb.	402	1 928	11	16.6
Mar.	424	2 227	9	16.9
Apr.	458	2 779	(b)	18.6
May	594	2 439	(b)	23.4
June	650	1 642	(b)	22.7

[a] Beginning with January 1956, the charge limiting device did not operate; this explains the high output figures for this period.

[b] No data recorded.

Table 7. Some daily maxima of output of the wind power plant in Eilat and corresponding wind runs

Date (day ending on the morning of)	*Max. daily output (kWh)*	*State of battery*	*Corresponding wind run (km)*	*Corresponding consumption (amp/h)*
1954				
20 June	25.4	almost full	646	116
8 July	24.4	almost full	554	66
20 Aug.	25.7	full	657	118
29 Sept.	28.8	full	641	112
10 Oct.	26.4	half-full	497	114
10 Nov.	21.4	full	663	98
17 Dec.	23.8	half-full	402	92
1955				
24 Feb.	47.6[a]	almost full	762	65
20 May	34.9	full	701	177
26 June	26.6	full	778	91
22 Aug.	24.4	full	680	85
10 Sept.	38.1	half-full	717	157
21 Dec.	30.2	almost full	495	24
1956				
24 Jan.	29.5	half-full	500	229
24 Mar.	29.3	almost full	502	66
13 May	36.6		639	

[a] 27 hours.

Table 8. Some minima of daily wind run and corresponding output

Date (ending on the morning of)	*Wind run (km)*	*Output (kWh)*	*State of battery*
1954			
31 July	212	0.7	empty
23 October . . .	198	3.9	empty
2 November . . .	249	1.7	empty
1 December . . .	212	0.8	half empty
1955			
4 February . . .	251	2.5	half empty
12 February . . .	172	1.1	almost full
1 March	187	1.2	almost full
28 March	193	1.4	half empty
4 April	168	6.3	empty
27 October . . .	203	3.5	half empty
7 November . . .	117	1.3	empty
15 December . .	171	1.0	empty

certainty of the regression equation for monthly mean values, especially for low mean wind speeds; (*c*) energy pattern factor (i.e., the ratio of the actual energy in the wind to the energy which would obtain if the wind speed was constant during the hour); (*b*) and (*c*) each could account for too low assessment of the maximum possible output by as much as 15 per cent.

In view of the above, it seems necessary to revise the maximum possible output as given in the second column of table 5 by at least 15 per cent. This will result in a corresponding reduction of the ratio of effective output to maximum output (fourth column), and take care of an unduly high ratio of effective output to maximum possible output as in the period January-March 1956.

To proceed one step further with the performance analysis, daily maxima of output will be given for most single months of the two-year period June 1954-May 1956 (Table 7).

From the table, the close dependence of the output on the state of battery is clearly seen. Some daily minima of wind run were also sought and corresponding output noted. These are given in table 8.

The interesting feature of the figures in table 8 is that even on the least windy days some output was registered.

Economic analysis

As stated previously, the average yearly output of the Eilat plant was 4 200 kWh. The plant with the tower cost $990 f.o.b. New York. Its approximate price in Eilat was $1 100. The battery, made locally, cost another $1 100, according to the official rate of exchange ($1 = I£1.80). The erection of the plant cost about $300. Altogether, its price was about $2 500, or $1 000 per kilowatt installed.

The cost of wind generated electricity is equal to the annual charges on the investment, together with the maintenance cost, divided by the yearly output.

The effective lifetime of a wind power plant can be taken as 15 years, and that of a battery as 5 years. With an 8 per cent interest rate, this would be:

	$
8 per cent interest on $2 500.	200.00
Depreciation over 15 years with 8 per cent interest on $1 400.	51.50
Depreciation over 5 years with 8 per cent interest	438.50
on $1 100.	187.00
	438.50

i.e., about $0.10 per kWh produced (without maintenance costs, which are not included for the sake of comparison with comparable Diesel plants), or $0.15 per kW consumed.

As against this, a 2.5-kW Diesel set would have cost, with installation, about $800. It would have to be fully depreciated in 12 000 hours of operation or about 3 years of operation if no battery was provided; the fuel consumption, which would have been about 400 g per kWh when operating at full capacity, would go up to 600 g per kWh at the average (0.3) load factor.

Thus, the cost of Diesel-generated electricity would have been:

	$
8 per cent interest on $800	64.00
Depreciation over 3 years with 8 per cent interest	260.00
Fuel component 1.65 ton at $100 a ton	165.00
	489.00

i.e., $0.18 per kWh consumed, as against $0.15 per kWh consumed of wind-generated electricity.

In this comparison, no account was taken of maintenance costs, which weigh heavily against the Diesel units, making wind power even more attractive.

To validate the above comparison for present conditions in Eilat, it is only necessary to lower somewhat the price of fuel (to $87 a ton), thereby lowering the over-all cost of Diesel-generated electricity, without maintenance, to $467.50, i.e., to $0.17 per kWh consumed.

Conclusion

On the basis of the above analysis, it may be stated with some degree of confidence that in any undeveloped area where mean wind speeds of 5 m/sec (18 km/hr) prevail, there is every advantage in installing wind power units to supply needs in electrical energy of up to about 10 000 kWh yearly. If the wind régime of the area is characterized by a strong diurnal cycle, even lower mean wind speeds (down to 4 m/sec) may be enough to confer economic advantage on wind-produced electricity.

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Summary

Eilat, the southernmost settlement in Israel, lying on the Red Sea shore, is an excellent example of a new locality in an undeveloped area. When first established in 1949, it was almost 250 km distant from the nearest inhabited place in Israel, and all supplies had to be brought either by a dirt track or by air.

Power generation presented one of the more pressing needs, and this was first supplied by a relatively small Diesel generator. The electricity so produced was very expensive, owing primarily to the exorbitant cost of fuel, and its supply was not continuous. For some purposes it was essential to have a continuous supply of electricity, and wind power was among the alternatives considered. Winds are comparatively strong and steady in Eilat, and it was decided to set up a small wind power plant there.

The plant chosen was the largest available commercially at the time (1952), a 14-ft diameter, 3-kW nominal power 110 V D.C. Jacobs unit. The plant was set up on a 12-m high tower erected on a small ridge athwart the prevailing wind direction, at a distance of about 30 m from a wind-recording instrument and at the same height. It was equipped with a 150-amph battery and electrical measuring instruments. In view of the capacity of the battery, the charge limit was set at 18 amp, and the voltage limit at 138 volts. The load was provided by two near-by cottages housing government offices with attached living quarters.

The plant was in continuous operation for more than three years. During this time, wind velocity and direction were recorded, and daily readings were taken of the output of the plant and the effective electricity consumption.

Wind régime in Eilat

The wind regime in Eilat is characterized by the following:

(a) *A pronounced seasonal variation*, as shown in the following monthly mean wind speeds (1954-1957), in km/hr:

Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
15.5	15.7	16.3	17.9	21.3	21.9	20.7	22.1	23.5	19.3	16.2	15.9

It is seen that there is a flat minimum in winter, and a broad maximum in summer with a slight trough in the middle of it.

(b) *A strong diurnal variation*, especially in summer: ratio of the difference of mean maximum and minimum hourly wind speed to mean monthly speed is as follows:

Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
0.45	0.33	0.38	0.40	0.43	0.43	0.60	0.60	0.57	0.53	0.55	0.50

(c) *A year-round strongly prevailing wind direction*: frequency (in per mille) of yearly mean wind direction is as follows:

Time (G.M.T. + 2)	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*Calm*
8 a.m.	617	283	7	2	12	8	8	17	46
2 p.m.	480	226	22	21	129	61	12	25	24
8 p.m.	504	132	3	3	40	32	26	126	74

(d) *A constancy of yearly wind régime :* yearly wind speed and energy in the wind in Eilat are as follows :

Period	*Mean wind speed (km/hr)*	*Energy in the wind (kWh per annum/sq. m)*
1 April 1953-1 April 1954 .	18.5	1 250
1954	19.0	1 220
1955	19.4	1 300
1956	19.2	(not computed)
1957	18.1	(not computed)

Performance data

The performance data of the plant relate to the period July 1953-June 1956. During this time, the average yearly output — with charge and voltage limiting devices operating — was 4 200 kWh, equivalent to 1 680 kWh per kW installed, or 294 kWh per square meter of the swept area of the propeller. The latter figure approaches that achieved by the 17.5-m diameter, 50 kW Smidth aerogenerators during the years 1941-1944 when working in parallel with local D.C. Danish grids in wind régimes characterized by the mean wind speed of 6 m/sec (as against mean wind speed of 5.3 m/sec in Eilat), and is far superior to any known published performances of D.C. wind units operating individually. However, of the 4 200 kWh produced yearly, only 2 750 kWh (or 65.5 per cent) were actually consumed; the remainder of 1 450 kWh (or 34.5 per cent) must be regarded as loss incurred during battery charging.

Monthly outputs varied from 184 to 524 kWh (with charge limiting device operating) and 650 kWh (with charge limited only by the battery voltage), while the maximum daily output was 47.6 kWh (for 27 hours).

Whereas during calm winter months the output was near the plant capacity, during windy summer months it was 50 per cent of the capacity, limited as it was by insufficient consumption. Not surprisingly, the highest daily output was achieved on a windy winter day, the battery almost discharged. It is noteworthy that there was not a single day during the operation of the plant in which at least some output was not registered.

Economic analysis

The price of the Eilat plant, including the batteries, was about $2 500, or $1 000 per kW installed. Assuming an 8 per cent interest rate, a 15-year lifetime of the plant, excluding the battery, and a 5-year lifetime of the battery, it is found that the price of 1 kWh produced was about $0.10 and that of 1 kWh consumed about $0.15. As against this, a 2.5-kW Diesel set would have cost about $800. To give service equivalent to that of the wind power plant at Eilat, it would have to be in operation (mostly partial) at least for 4 000 hours yearly, and consequently would have to be fully depreciated in three years. With the high prices of fuel prevailing in Eilat at the time of the operation of the wind power plant, the price of electricity so produced (and consumed) would have amounted to $0.18 per kWh. With the present lower prices of fuel, it would still amount to $0.17. The prices of wind- and Diesel-generated electricity do not take into consideration the maintenance costs which tip the balance even further in favour of wind power plants.

Conclusion

In any undeveloped area, whenever small quantities of electricity (of the order of 10 000 kWh yearly or less) are required and the mean wind speed is about 5 m/sec (18 km/hr) or more, there is a definite advantage in using wind power units rather than diesel generators.

LA CENTRALE ÉOLIENNE D'EILAT

Résumé

Eilat, qui est le centre le plus méridional d'Israël, en ce sens qu'il se trouve sur la côte de la Mer Rouge, offre un excellent exemple d'un nouvel établissement situé dans une région dont le développement est à poursuivre. Quand la ville fut fondée, en 1949, elle se trouvait à près de 250 km du plus proche autre centre de population d'Israël, et toutes les fournitures devaient y être amenées, soit par un chemin de terre, soit par avion.

La force motrice était l'un de ses besoins les plus pressants et la fourniture en fut assurée, au début, par un groupe électrogène à moteur diesel relativement petit. L'électricité ainsi produite était très coûteuse en raison, au premier chef, du prix exorbitant du combustible, et elle n'était pas fournie de façon continue. Or, il était essentiel de disposer d'une source continue d'électricité et l'énergie éolienne était une des solutions envisagées pour ce problème. Les vents sont relativement forts et soutenus à Eilat, et on décida d'y organiser une petite centrale à énergie éolienne.

Le groupe était le plus puissant en production commerciale à l'époque (1952) étant constitué par un appareil de Jacobs de 14 pieds de diamètre (4,20 m), débitant 3 kW de puissance nominale sous 110 V en courant continu. On l'installa sur une tour de 12 mètres de haut érigée sur une petite crête, à angle droit avec la direction des vents dominants et à une distance de 30 mètres d'un anémographe ayant même cote. Il fut doté d'une batterie d'accu-

mulateurs de 150 ampères/heure et d'instruments électriques de mesure. Eu égard à la capacité de la batterie, on fixa la limite de charge à 18 ampères et celle de la tension à 138 V. La charge était constituée par deux petites maisons situées non loin de la centrale, qui abritaient les bureaux du gouvernement, avec les locaux d'habitation y afférents.

Le groupe électrogène fonctionna de manière continue pendant plus de trois ans. Au cours de ce temps, on enregistra la vitesse et la direction du vent et on procéda à des lectures quotidiennes du débit de courant de la centrale et de la consommation effective d'électricité.

Le régime des vents à Eilat se caractérise par :

a) Une variation saisonnière marquée, ainsi que l'indique le tableau suivant, donnant les vitesses-moyennes mensuelles du vent en km/h (1954-1957) :

Janv.	*Fév.*	*Mars*	*Avr.*	*Mai*	*Juin*	*Juil.*	*Août*	*Sept.*	*Oct.*	*Nov.*	*Déc.*
15,5	15,7	16,3	17,9	21,3	21,9	20,7	22,1	23,5	19,3	16,2	15,9

On observera qu'il y a un minimum en plateau pendant l'hiver et un maximum en plage étalée en été, avec une légère dépression en son milieu;

b) Une variation diurne sensible, particulièrement pendant l'été; le rapport entre l'écart du maximum et du minimum horaire moyen de la vitesse du vent sur la moyenne mensuelle se présente ainsi :

Janv.	*Févr.*	*Mars*	*Avr.*	*Mai*	*Juin*	*Juil.*	*Août*	*Sept.*	*Oct.*	*Nov.*	*Déc.*
0,45	0,33	0,38	0,40	0,43	0,43	0,60	0,60	0,57	0,53	0,55	0,50

c) Une direction nettement préférée par les vents, sur toute l'année. La fréquence (en parties par mille), de la direction moyenne annuelle du vent se présente comme suit :

Heure (G.M.T. + 2)	*N*	*NE*	*E*	*SE*	*S*	*SO*	*O*	*NO*	*Calme*
08	617	283	7	2	12	8	8	17	46
14	480	226	22	21	129	61	12	25	24
20	504	132	3	3	40	32	26	126	74

d) Une constance du régime annuel des vents. La vitesse annuelle du vent et l'énergie éolienne à Eilat se présentent ainsi :

Période	*Vitesse moyenne du vent (km/h)*	*Énergie du vent (kWh. p.a. m²)*
1 avril 1953-1 avril 1954. .	18,5	1.250
1954	19,0	1.220
1955	19,4	1.300
1956	19,2	(non calculée)
1957	18,1	(non calculée)

Données sur l'exploitation

Elles s'appliquent à la période allant de juillet 1953 à juin 1959. Pendant cette période, le débit annuel, les limiteurs de charge et de tension étant en service, s'est établi à 4 200 kWh, soit 1 680 kWh par kilowatt installé, ou 294 kWh par m² de surface balayée par les pales de l'éolienne. Ce dernier chiffre est voisin de celui qui a été réalisé par les aéromoteurs de 17,5 mètres de diamètre et de 50 kW du modèle Smidth durant les années 1941-1944 lorsqu'ils fonctionnaient en parallèle avec les réseaux de distribution danois en courant continu, par des régimes de vent caractérisés par une vitesse moyenne de 6 m/sec (contre 5,3 m/sec à Eilat) valeur très supérieure à tout autre résultat publié pour des aéromoteurs à courant continu fonctionnant individuellement. Néanmoins, des 4 200k Wh produits annuellement, on ne consomma en réalité que 2 750 kWh, soit 65,5 p. 100; le reste, soit 1 450 kWh (34,5 p. 100), doit être considéré comme une perte subie pendant le chargement de la batterie.

Les débits mensuels ont varié entre 184 kWh et 524 kWh (avec un dispositif limiteur de charge en fonctionnement) ou 650 kWh (la charge n'étant limitée que par la tension de la batterie), tandis que le débit maximum quotidien s'établissait à 47,6 kWh pour 27 heures.

Alors que pendant les mois calmes d'hiver le débit était voisin de la capacité de la centrale, il ne dépassa pas 50 p. 100 de cette dernière pendant les mois d'été, où les vents soufflent beaucoup, en raison des limites imposées par l'insuffisance de la demande. Chose peu surprenante, le débit quotidien maximum fut réalisé un jour d'hiver où le vent soufflait fort, la batterie étant alors presque déchargée. Il est à observer qu'il n'y eut aucun jour, pendant la période de fonctionnement de l'usine, pendant lequel on n'enregistrât pas au moins un certain débit.

Analyse économique

Le coût d'installation de la centrale d'Eilat, y compris celui des batteries, était de l'ordre de 2 500 dollars ou 1 000 dollars par kW installé. Si on prend un taux d'intérêt d'environ 8 p. 100 et une durée de service de quinze ans pour la centrale, à l'exclusion de la batterie, dont la vie utile peut être prise comme devant être de cinq ans, on calcule que le prix du kWh produit ressort à environ 10 cents et celui du kWh consommé à 15 cents. Un groupe électrogène à moteur diesel de l'ordre de 2,5 kW aurait coûté environ 800 dollars. Pour rendre les mêmes services que ceux de la centrale éolienne d'Eilat, il aurait fallu qu'il fonctionne (partiellement en général) 4 000 heures par an au minimum et, en conséquence, on aurait dû l'amortir complètement en trois ans. Compte tenu du prix élevé du combustible à Eilat au moment où fonctionnait la centrale éolienne, le prix de l'électricité ainsi produite (et consommée) se serait élevé à 18 cents par kWh. Avec la réduction des prix du combustible dont on bénéficie actuellement, il serait encore de 17 cents. Ni le prix de revient de l'électricité produite par la centrale éolienne, ni celui du courant fourni par le groupe électrogène à diesel ne tiennent compte des frais d'entretien qui font pencher la balance encore davantage vers les centrales éoliennes.

Conclusions

Dans toute région à développer, chaque fois qu'il est besoin de petites quantités d'électricité (de l'ordre de 10 000 kWh par an ou moins) et que la vitesse moyenne du vent est de 5 m/sec à peu près (18 km/h) ou davantage, il est nettement avantageux de faire usage de centrales éoliennes plutôt que de groupes électrogènes à moteur diesel.

EXPERIENCE WITH JACOBS WIND-DRIVEN ELECTRIC GENERATING PLANT, 1931-1957

Marcellus L. Jacobs *

This report outlines the engineering, construction, performance, electric output, and different uses of the Jacobs wind electric 2 500 to 3 000 watt plant, thousands of which were installed in many parts of the world between 1931 and 1957.

Early engineering started on this wind-operated electric generating plant in 1925. After several years of testing different types of windmills, the three-blade aeroplane type of propeller was found to be far superior in power output. By means of a flyball-governor-operated, variable pitch speed control, the maximum speed of the propeller was accurately and easily controlled, to prevent excessive speeds in high winds and storms. The three-blade propeller was found to be necessary (as compared to the two-blade type) to prevent excessive vibration whenever the shift of the wind direction required the plant to change its facing direction on the tower.

The periods of vibration which occurred, on the two-blade propeller, every time the tail vane shifted, to follow the changes in wind direction, were found to be caused by the fact that the two-blade propeller, when in a vertical position, offers no centrifugal force resistance to the horizontal movement of the tail vane in following changes in wind direction. However, when the two-blade propeller is in the horizontal position, its maximum centrifugal force is applied to resist horizontal movement of the tail vane; thus the tail vane is forced to follow wind direction changes by a series of jerks, causing considerable serious vibration to the plant.

The three-blade propeller was developed by us in 1927 to correct this condition. When in operation, the three-blade propeller creates a steady centrifugal force resistance, against which the tail vane reacts with a constant pressure and produces a smooth shifting horizontal movement of the plant facing direction. The centrigufal force generated by the very light aeroplane spruce-wood blades, when operating at 225 rpm is 550 pounds each, making a force of over 1 600 pounds of gyroscopic resistance force to the horizontal vane movement for the three blades, but this resistance is in the form of an even pressure or resistance to horizontal movement, whereas the 1 100 pounds of gyroscopic resistance force of the two-blade propeller to the vane movement is applied and then eliminated twice during each revolution.

A propeller diameter of 15 feet was found to produce ample power for electric generator operation to develop 400 to 500 kWh per month, based on the available winds in most areas of the states in the western half of the United States. This required 10 to 20 mph winds for two or three days per week. A specially designed 6 pole battery charging type shunt generator was developed to operate at a speed range from 125 to 225 rpm for direct connexion to the governor hue of the propeller. It was designed so that its load factor would exactly parallel the power output curve of the wind-driven propeller when operating in the 7 to 20 mph range that it was felt produced the most hours of wind per month. Wind plants that require higher than 20 mph winds to deliver their rated output will find too many areas where there are too many days with winds below that speed each month and thus their effective average monthly output in many areas is below expectations. The generator weighs 440 pounds with a 9-inch diameter armature with a 9-inch core length. The 60 pounds of wire on the field poles gave maximum efficiency with a drain of less than 100 watts for field coil operation. The generator output is 2 500 watts at 32 volts, and for the 110-volt generator, it is rated at 3 000 watts.

Our experience with plants installed in many parts of Alaska, Canada, Finland, northwestern United States and a number of special installations such as the plant we have installed for the joint operated United States and United Kingdom weather station at Eureka, in the Arctic Circle, and with the Byrd expedition at Little America has shown that aluminum painted (copper edged) spruce-wood propellers have considerably less trouble with frost and ice formation than when they are varnished or when other type coatings are used.

Generators located on high steel towers are subject to considerable static discharge from the armature through the ball or roller bearings, and excessive charges from nearby lightning will often arc through a bearing and weld spots on the balls and race, causing it to brake up soon. We found the revolving propellers collected discharges into the direct connected armature and the lightning pick-up effect of the propellers was frequent and of considerable intensity. To correct this, we installed dual sets of heavy grounding brushes on the armature shaft which completely eliminated any trouble from this cause. With the additional use of a large capacity oil-filled condenser connected across the generator

* Jacobs Wind Electric Company, Inc., Fort Myers, Florida.

brushes and frame, we practically eliminated any damage to the generators from lightning, so much so that, with high grade ample insulation used throughout the generator and the grounding brushes and condensers, we gave an unconditional five-year guarantee with every generator against burn-out from any cause and have built many thousands during the past twenty years using this construction without any replacements ever being required because of lightning damage or burn-out from any cause.

The price received at the factory for our 2 500-watt, 32-volt plant was $490, less the cost of a suitable tower and batteries, which could often be secured in the country or area to which the plant was shipped. We supplied a 21 000 watt hour glass cell lead-acid type of storage battery with a ten-year guarantee, for which we received $365. A fifty-foot self-supporting steel tower was supplied for $175, making a total cost for the plant of $1 025. This is about $400 per kilowatt as the manufacturing cost of the plant. Shipping and installation costs are additional. Installation cost requires only the labour of two men for two days and a small amount of cement to put into the anchor holes when the tower is built. No special equipment or training is necessary. We have shipped hundreds of plants to most countries with not a single request for additional information to enable them to erect the plant. Regular installation and operating instructions are prepared and sent with each plant.

Operating and maintenance costs of this plant are largely limited to the replacement of the storage battery which, on a ten-year basis, is about $36 per year; from records kept of more than 1 000 plants over a ten-year period, the maintenance cost of repairs was less than $5 per year. Some of the owners of our plants bought the Edison type battery and after twenty years are still using the same battery. New batteries of this type are quite expensive, but these owners bought second-hand batteries which still gave them twenty years of service.

Special generators designed for the cathodic protection of underground steel pipelines were developed by us in 1936. These generators were wound for an external circuit resistance of 1/10 ohm or higher. The generators produced 10 volts at 100 amperes and were straight shunt wound. When connected to the pipelines in any normal wind, they maintained a pipe-to-soil potential of 3/10 of a volt pipe negative. Due to the action of the current, the pipe maintained a fair degree of protection through calm wind periods. Hundreds of our plants are protecting many miles of pipelines in North and South America and in Arabia. Some of these plants have been in service since 1937.

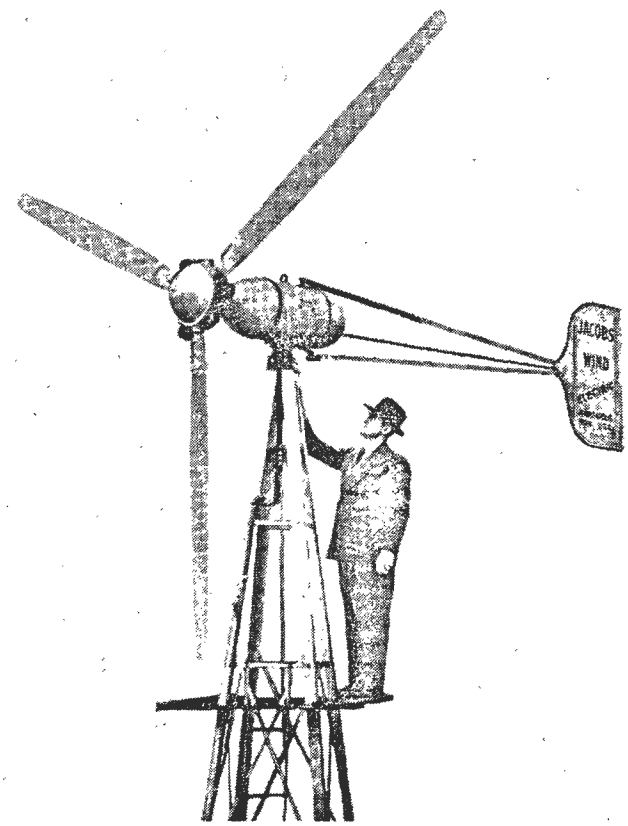

Figure 1

Summary

After several years of testing d fferent types of windmills, a three-blade aeroplane-type propeller, developed in 1927, was found to be far superior both in power output and in minimizing vibration. A propeller diameter of 15 feet was found to produce ample power, developing 400 to 500 kWh per month in most areas of the western United States with wind speeds ranging from 10 to 20 miles per hour for two to three days per week.

Dual sets of heavy grounding brushes were installed on the armature shaft and a large capacity oil-filled condenser was connected across the generator brushes and frame to eliminate the otherwise considerable static discharge and damage from lightning, while aluminum painted (copper edged) sprucewood propellers reduced trouble with frost and ice formation.

The total factory cost of the plant of $1 025, or about $400 per kilowatt, included $490 for a 2 500-watt, 32-volt plant, as well as, optionally, $360 for a 21 000 watt storage battery with a ten-year guarantee and $175 for a self-supporting steel tower. Operating and maintenance costs of the plant are largely limited to the replacement of the storage

battery, while according to records kept for more than 1 000 plants over a ten-year period, the repair costs have been less than $5 per year.

Hundreds of these plants, with specially designed generators, are used for the cathodic protection of underground steel pipelines in several countries.

EXPÉRIENCE ACQUISE AVEC UNE CENTRALE ÉLECTRIQUE ÉOLIENNE JACOBS ENTRE 1931 ET 1957

Résumé

Après plusieurs années d'essais de divers types d'éoliennes, on a établi qu'une hélice du genre avion, mise au point en 1927, était nettement supérieure aux autres dispositifs, tant quant à leur débit d'énergie qu'en ce qui concerne la réduction des vibrations. On a découvert qu'un diamètre d'hélice de 15 pieds (soit 4,57 m) fournissait une abondance d'énergie (de 400 à 500 kWh par mois) dans la plupart des régions de l'ouest des États-Unis, avec des vitesses de vent s'échelonnant entre 10 et 20 milles (16 et 32 km) à l'heure, pendant deux ou trois jours par semaine.

On a prévu des jeux doubles de gros balais de mise à la terre sur l'arbre de l'induit ainsi qu'un condensateur à bain d'huile de grande capacité, monté en parallèle entre les balais de la génératrice et le châssis, de manière à éliminer les fortes décharges d'électricité statique qui se produisaient autrement, ainsi que pour protéger l'ensemble contre la foudre. On a observé également que l'emploi d'hélices en bois peintes à l'aluminium (à bords revêtus de cuivre) réduisait les ennuis dus à la gelée et au givrage.

Le prix total de la centrale, f.o.b. usine, soit 1 025 dollars ou environ 400 dollars par kilowatt, comportait 490 dollars pour une installation de 2 500 watts sous 32 volts et, facultativement, 365 dollars au titre d'une batterie d'accumulateurs de 21 000 watts avec garantie de dix ans et 175 dollars pour une tour en acier autonome. Les frais d'exploitation et d'entretien de la centrale se limitent essentiellement au remplacement de la batterie tandis que, d'après les archives tenues pour plus de 1 000 usines pendant une période de dix ans, les frais de réparation ont été inférieurs à 5 dollars par an.

Des centaines de ces installations, avec génératrices spéciales, s'utilisent pour la protection cathodique de pipelines souterrains en acier dans nombre de pays.

SMALL RADIO, POWERED BY A WIND-DRIVEN BICYCLE DYNAMO

H. Stam, H. Tabak and C. J. van Vlaardingen *

The essential conditions to be fulfilled in the successful production of radio receivers in the less-industrialized countries were set out in "Low cost radio reception" by M. Claude Mercier.[1]

The keen interest in listening to broadcasting amongst the populations of Africa and the Middle and Far East, the rapidly growing skills in the repair and assembling of sets, the introduction of transistors that consume less power, and so require fewer dry batteries, all favour the fabrication, locally, of cheap sets even in rural districts of the less-industrialized areas.

Still the demand seemed greater than the supply. Organizations concerned with refugees and orphanages requested our foundation to design a small receiver which would (*a*) be adapted to assembling by nearly unskilled people, but under the guidance of instructors; and (*b*) avoid consumption of dry batteries, their major disadvantage being not their cost but the difficulty of procurement in the remote regions concerned.

Thermo-electricity by solar heat or by a wind-driven dynamo can act as a substitute for batteries if only sufficient storage is provided to tide over the hours of dark or calm, respectively. Such a thermo-element for a radio is mentioned in our contribution on solar kitchens using accumulated heat, but in general, a wind-driven (bicycle) dynamo offers the cheapest solution for a radio alone. Moreover, the dynamo can supply some light during the night if there is sufficient wind during those hours. We therefore tried the radio set and its wind charger as described here.

The circuit

In figure 1 the part of the circuit to the left of the discontinuous line shows a three-transistor radio fitted with a loudspeaker and powered by a normal three-cell dry battery, shown as "Batt. 1" in the figure. With earphones, two transistors would be sufficient and the set would cost less, but our view is that this solution is "under-developed" and unhygienic. The part of the circuit to the right of the dotted and dashed line shows the powering with an alternating current bicycle dynamo and a rectifier, in which case Batt. 1, the dry battery, is switched off or left out. Storage by three silver cadmium accumulators allows current to be delivered to the radio during calms. The telephone bulb "LA. 1" guards against overloading the Ag-Cd accumulator during strong winds. Wind generating whilst listening provokes no annoying noise. Not shown in the circuit is the normal bicycle light bulb that can be connected across the dynamo in addition to the radio during the dark hours, if the wind is sufficiently strong. Due

* Stichting Dienst Ontwakende Wereld, Amsterdam.

[1] Published by UNESCO in 1950 in the series "Press, film and adio in the world today".

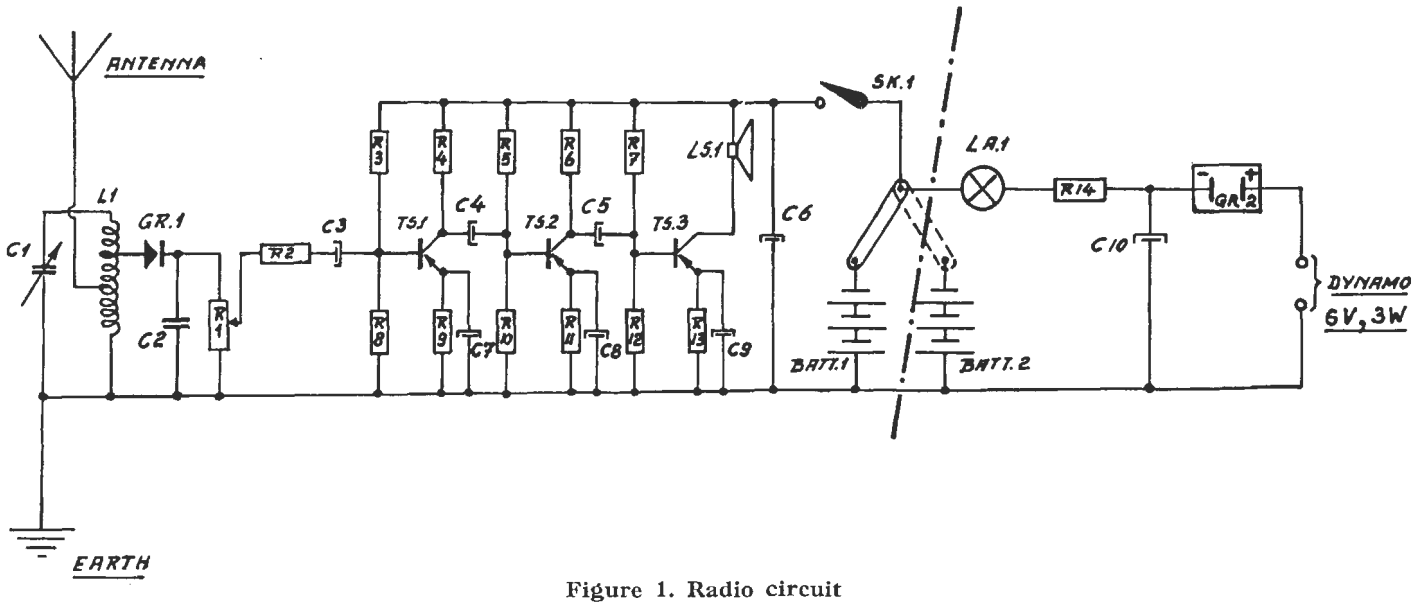

Figure 1. Radio circuit

Table 1. Parts list for transistor-receiver on alternating current delivered by wind-driven bicycle dynamo

				Florins	
Set itself (if wished, powered by direct current from a dry battery; left of dotted and dashed line in circuit, figure 1)					
R1 and SK 1	Potentiometer 50 K incl. switch			1.95	
R2	Carbon resistance 2 200 Ω				
R3 and R5	Carbon resistance 68 000 Ω				
R4, R6, R7	Carbon resistance 3 300 Ω				
R8 and R10	Carbon resistance 12 000 Ω	12 × f. 0.08		0.96	
R9 and R11	Carbon resistance 1 200 Ω				
R 12	Carbon resistance 1 000 Ω				
R 13	Carbon resistance 68 Ω				
C1	Variable condenser	300 pF		1.50	
C2	Ceramic condenser	1 000 pF		0.30	
C3	Electrolytic condenser	10 pF (3 V)		0.60	
C4 and C5	Electrolytic condenser	8 pF (6 V)		1.20	
C6	Electrolytic condenser	100 pF (12½ V)		0.65	
C7 and C8	Electrolytic condenser	32 pF (3 V)			
C9	Electrolytic condenser	100 pF (3 V)			
L 1	Tuning coil			0.50	
TS 1 and TS 2	Transistor OC 3 (Amroh)		2 × f. 3.75 =	7.50	
TS 3	Transistor OC 4 (Amroh)			4.50	
GR 1	Germanium diode OA 79 (Philips)			2.50	
LS 1	Loudspeaker 150 1½ W (Philips)			8.25	
Dialing knobs, case, pertinax, mounting material			about	3.00	
	Parts for radio set sold individually				35.31
Generator and rectifier				0.08	
R 14	Potentiometer	100 F (12½ V)		0.70	
C 10	Electrolytic condenser	(Siemens)		1.35	
GR 2	Rectifier, single phase	12 V 35 mA		0.30	
LA 1	Telephone bulb	3 × f. 3.50 =		10.50	
Batt. 2	Accumulator (Deac, 150 dk)	(Czech orig.)		4.50	
	Bicycle dynamo			0.30	
	Ball-race, k 30	(Star)		2.50	
Tinned sheet, solder, tubes, balsawood			about	—	
	Parts for generator sold individually				20.23
				TOTAL	55.54
Normal reduction for purchase in quantities, 30 per cent					38.88
Lower prices for foreign products, another 20 per cent					31.11

to the characteristic saturation of bicycle dynamos, above a certain limit, the differences in wind velocity do not cause much inconvenience with regard to the intensity of the light.

Costs of parts and materials

Table 1 shows the parts-list separately for the radio set and the generator-rectifier-storage provision. Prices are in Dutch currency for first quality Dutch products for sale by private purchase. Buying in quantity, these prices are reduced by 30 per cent. Foreign, i.e., Japanese, parts will lower the costs another 20 per cent. Originally, we used a "Lucia" dynamo costing 10 D.G., and later the Czech dynamo, shown in figure 2, at 4.50 D.G., including 14 per cent import duty.

Mounting and assembling

We mounted the radio set in a normal tin, as used for paint, and framed it with two sheets of pertinax. At small extra cost, a more luxurious looking casing can be made (3 g semi-transparent tetrahedron). The mounting inside the tin by hand requires a total of three to four hours each, if done in batches of tens. With industrial methods, this time diminishes considerably, but such methods seem unnecessary for producing an article of this nature. Inside the casing is a switch for mounting either a dry battery (Batt. 1) or the Ag-Cd accumulators. One short and one long pole make it impossible to make contact if one places the dry battery in the wrong position. We are still searching for a similar simple safeguard against wrong positioning of the accucells. A simple mistake made with them destroys at least one of the transistors. The generator is shown in figure 2. A normal bicycle hub is provided, running on milled or even pressed soft steel ball races, to ensure the wind rotor a stable bearing on the dynamo. We used curved plate blades, soldered from tinned sheet for simple manufacture. In Holland we used balsa-wood for the streamlined body, but in the arid regions cork pressings are better suited.

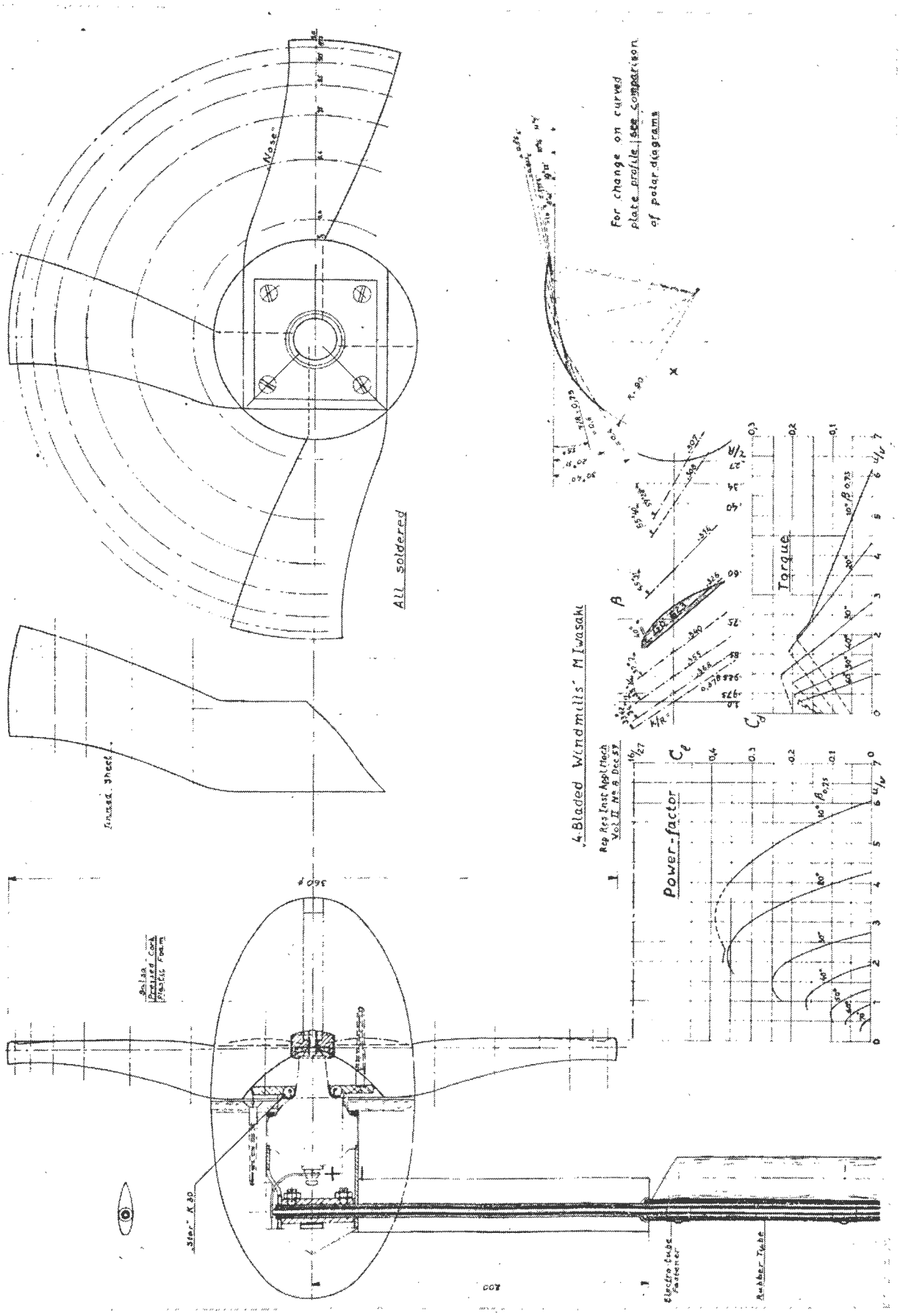
Nose
All soldered
For change on curved plate profile, see comparison of polar diagrams
4 Bladed Windmills" M Iwasaki
Rep Res Inst Appl Mech Vol II No 8 Dec 57
Power-factor
Torque
Balsa
Pressed cork
Plastic foam
Steel
Electric tube
Rubber Tube

Figure 2

Choice of dynamo and wind rotor

For adjustment of the regulator in the generating part of the circuit, the dynamo was driven by a sewing machine motor at varying speeds and different degrees of accumulator-load. By that method, one can change to another type of dynamo, i.e., a lower number of poles if demanded by the wind régime of the region concerned. Initial trial and error in the choice of a two-bladed rotor, the profiles of which were cast in plastic, caused a lot of trouble, as much in the fabrication as in behaviour in the wind. We therefore decided on the multi-poled dynamo and the rather slow-running multi-bladed rotor, delivering high starting torque. But curved plates were, in any case, preferable for ease of manufacture, as well as for their low Reynolds number. An article by M. Iwasaki [2] provided us with a suitable calculation method, executed and proved by experiments for the profile Gö 623. His diagrams for the four-bladed rotor are reproduced in figure 2.

[2] " The investigation of windmills ", *Rep. Res. Ins. of Appl. Mech.*, vol. II, No. 1 (1953).

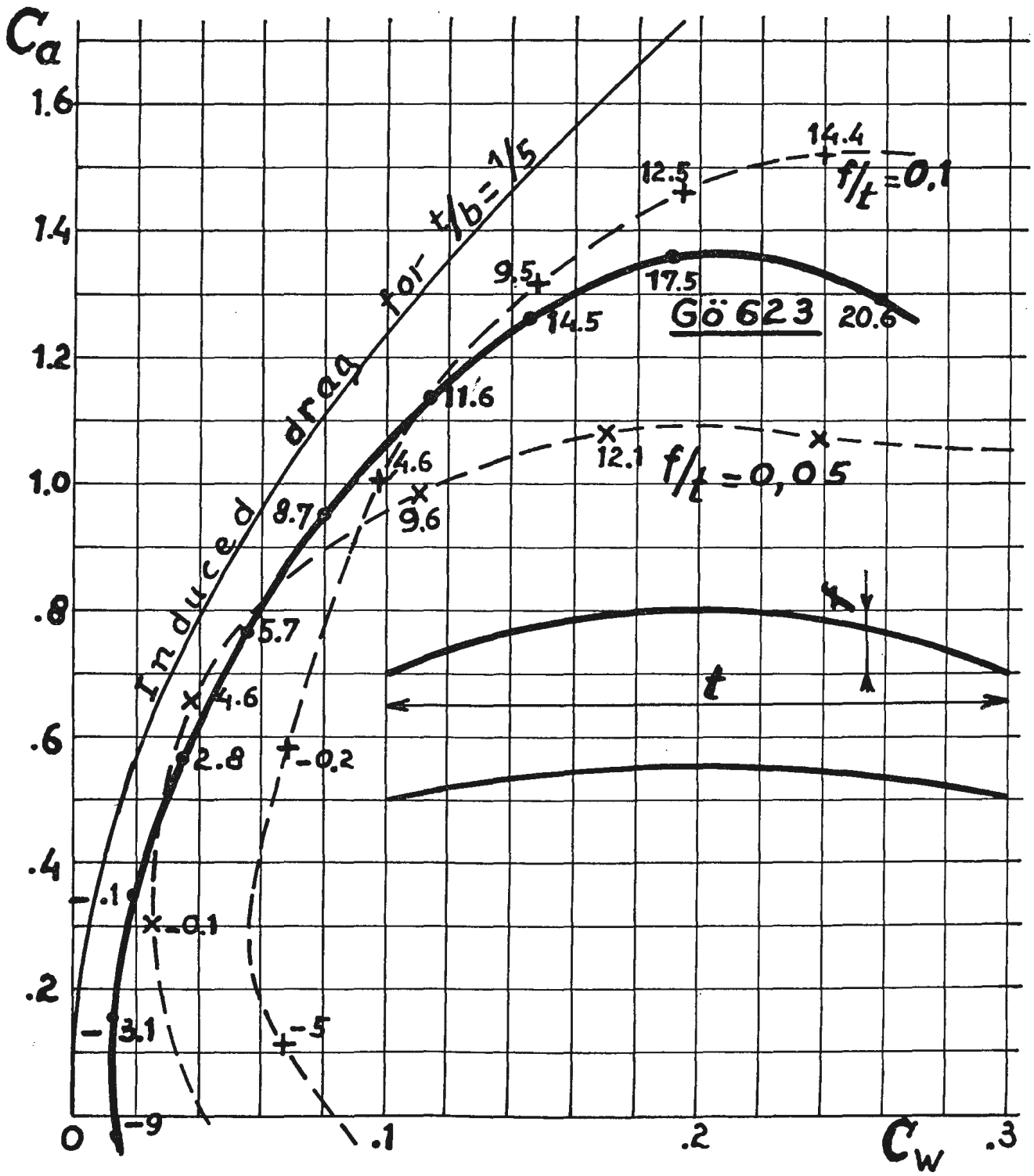

Figure 3. Comparison of profiles

Another article, by O. Flachsbart,[3] provides data for curved plate profiles. The comparison of Gö 623 and the curved plates from polar diagrams is given in figure 3. From this it is estimated that a curvature f/t = 0.075 might offer the closest similarity with Gö 623, but for better starting torque, f/5 = 0.1 was chosen, because the cylindrical form of blade presents an angle somewhat less at the tips than at the root. Instead of setting up exact calculations, it seemed reasonable for our purpose to make the crude approximation, that the Iwasaki diagrams can be used with a correction on the angle of the blades of 3° to 4°.

Easy starting is the key to stable performance, and having regard to the unstable character of the four-bladed rotor at BO, 75 = 10°, we preferred the Iwasaki diagrams for BO, 75 = 19°.

The measured starting torque of the dynamo amounts to 115 gram-centimetres. With a swept diameter of 0.36 m and a starting torque coefficient, c = 0.1, the wind velocity needed for starting is $3\frac{1}{4}$ metres per second.

It was found from the measurements that the full 3 watts output of the dynamo is delivered at 800 revolutions per minute.

Dynamo efficiency was estimated at 0.7, and the power coefficient, from the diagram of Iwasaki, 0.35; the wind velocity for full power is reached at $5\frac{3}{4}$ m/sec. Furthermore, full power is obtained if the ratio tip velocity/wind velocity = u/v = 2.75. At a wind velocity v = 5.3/4 m/s, the tip velocity reaches 15.4 m/s and the 0.36 m diameter rotor rotates at 840 revolutions per minute. From this data, it appears that the designed windmill is suited to regions with modest wind régimes. Two hours of full output from the dynamo is sufficient for ten hours listening. In our climate and wind régime, it would be overpowered. A smaller windmill is therefore needed, or a device for switching off in periods of excess wind.

[3] "Messungen an ebenen und gewölbten Platten", *Gotinger Ergebnisse Lief*, IV, 1932.

Conclusion

Both the receiver set and the generator offer good examples of what here and in other contributions we have called: "innovating handicraft" suited for improvement of rural living conditions. Special conditions brought about the request for such an assembly to our foundation, and we did our best, with considerable success. But the authors are convinced that students and/or instructors in the regions concerned must be able to fulfill this and similar demands in a better way and in far less time.

On the other hand, we recognize that in developing countries, the demand for luxury goods for the few that can pay for them is still unsaturated, and delays the introduction of the forementioned cheap cultural goods for the masses.

From our point of view, a solution may lie in what we have called "innovating handicraft" such as the one described in this paper, developed through co-operative efforts of teachers and pupils, supported by governmental institutions and by scientific instruction of universities and technical schools.

In our opinion, a small two-transistor receiver on dry batteries can be delivered at £2 6*s*. if fitted with an aural speaker, the three-transistor set with loudspeaker on batteries at £3 6*s*, and the same with the wind-driven generator at £5 6*s*. all these are retail prices, assuming that the parts can be obtained on the favourable terms normally available in the trade to manufacturers engaged in assembling and servicing.

Summary

Our Foundation was approached by organizations concerned with refugees and orphanages to design a small receiver which would be easy to assemble by unskilled people under the care of instructors, and which would dispense with the need for dry batteries, because of the difficulty of obtaining them in remote regions.

A thermo-element for a radio using accumulated heat is mentioned in our contribution on solar kitchens, but a wind-driven (bicycle) dynamo offers the cheapest solution for a radio alone and can, moreover, supply some light during night.

The circuit

The left-hand side of figure 1 shows a three-transistor radio, fitted with a loudspeaker and powered by a dry battery (Batt. 1). The right-hand side shows a power circuit using an A.C. dynamo and rectifier with storage by three Ag-Cd accumulators. The telephone bulb (LA. 1) guards against overloading. Not shown is the switch for connecting a light bulb directly across the dynamo.

Costs of parts and materials

Table 1 shows the parts-list in retail prices for first-class Dutch products. These can be lowered by 30 per cent for orders in quantity and a further 20 per cent for cheaper foreign deliveries.

Mounting and assembling

Three to four hours are needed to assemble the set, and a further three hours are required to install the generator shown in figure 2.

Choice of dynamo and wind-rotor

Adjustment of the regulator is obtained by driving the dynamo from a sewing-machine motor. For good starting torque, a multi-poled dynamo and a slow-running multi-bladed motor are combined. A curved plate profile is preferred because of its low Reynolds number. The data compared in figure 3 are derived from a number of sources. The measured starting torque of the dynamo is 115 gr. cm. and with swept diameter 0.36 m and torque-coefficient 0.1, a wind velocity of $3\frac{1}{4}$ m/sec is needed for starting. The full 3-watt output is delivered at 800 revolutions per minute at a dynamo efficiency of 0.7. Full power is reached at $5\frac{3}{4}$ m/sec. The design is suitable for modest wind régimes.

Conclusion

The receiver and generator offer examples of products suitable for handicraft production by the adaptation of ancient handicraft skills to new industries. Such "innovating handicraft", as we may call it, lends itself to co-operative effort by teachers and pupils supported by governments for the improvement of rural conditions. The two-transistor receiver operated on dry batteries with earphones can be delivered at £2 6*s*, the designed three-transistor set, run off batteries, at £3 6*s*. and the same with wind-driven generator at £5 6*s*. all are retail prices, assuming that the parts can be obtained on the favourable terms normally available in the trade to manufacturers engaged in assembling and servicing.

PETIT APPAREIL DE TSF ACTIONNÉ PAR UNE DYNAMO DE BICYCLETTE ENTRAINÉE PAR UNE ÉOLIENNE

Résumé

Les organismes qui s'intéressent, entre autres, aux réfugiés et aux orphelinats, ont chargé notre fondation de réaliser un petit récepteur de TSF facile à monter pour des personnes sans entraînement, sous la surveillance d'instructeurs, et susceptible d'éliminer le besoin de piles sèches, lesquelles sont difficiles à se procurer dans certaines régions peu accessibles du globe.

On mentionne, dans un mémoire soumis par notre groupe sur les cuisinières solaires, l'emploi d'un thermo-élément pour un appareil de TSF qui utilise de la chaleur mise en réserve; mais une dynamo de bicyclette entraînée par une éolienne constitue la solution la plus économique pour un appareil de TSF pris isolément et, qui plus est, peut fournir un peu de lumière pendant la nuit.

Circuit

On voit, dans la moitié gauche de la figure 1, un appareil à trois transistors doté d'un haut-parleur, pour lequel l'électricité est fournie par une batterie de piles sèches (Batt. 1). A droite, on notera le circuit d'alimentation qui se sert d'un petit alternateur (dynamo à courant alternatif) et d'un redresseur, avec mise en réserve du courant dans trois accumulateurs du type Ag-Cd. La petite ampoule de téléphone (LA. 1) protège le système contre toute surcharge. On n'a pas représenté un commutateur qui permet de brancher une ampoule directement sur les bornes de l'alternateur.

Prix des pièces et des matériaux

Le tableau 1 donne les prix des pièces au détail pour des produits néerlandais de première qualité. Ils peuvent être réduits de 30 p. 100 pour les commandes en grandes quantités, plus une autre réduction de 20 p. 100 pour les articles importés qui sont moins coûteux.

Montage et installation

Il faut compter trois ou quatre heures pour monter le poste, et trois heures de plus pour installer l'alternateur, que l'on voit à la figure 2.

Choix de la dynamo et de la roue éolienne

On ajuste le régulateur en entraînant la dynamo avec un moteur de machine à coudre. Pour avoir un bon couple de démarrage, on combine une dynamo multipolaire et un aéromoteur à plusieurs pales à faible régime de rotation. On préfère les pales courbes, en raison du faible nombre de Reynolds qu'elles donnent. Les chiffres dont la figure 3 donne une comparaison sont dérivés de nombres de sources. Le couple de démarrage de la dynamo a été mesuré à 115 g/cm et, avec un diamètre balayé de 0,36 m et un coefficient de couple de 0,1, il faut une vitesse de vent de 3,25 m/s pour assurer le démarrage. Le débit total de 3 watts est fourni à 800 t/m avec un rendement de dynamo de 70 p. 100. La pleine puissance se réalise à 5,75 m/s. La conception de ce dispositif se prête à des régimes caractérisés par des vents modérés.

Conclusion

Le récepteur et la dynamo nous donnent des exemples de produits qui se prêtent à la production manuelle par l'adaptation de certaines adresses

artisanales à de nouvelles industries. Ce genre de travaux d'artisans dits « à innovation », se prête à des efforts coopératifs par les professeurs et les élèves aidés par un gouvernement, pour améliorer les conditions de vie rurale. Le récepteur à deux transistors alimenté par des piles sèches et utilisant des écouteurs peut se livrer au prix de £2 6*s*. le poste à trois transistors tel qu'il a été conçu et alimenté par des batteries de piles à £3 6*s*. le même avec dynamo actionnée par une éolienne à £5 6*s*. tous prix de détail basés sur l'hypothèse que les pièces peuvent s'acheter dans les conditions favorables qui sont normalement faites aux entreprises chargées du montage et de l'entretien de ce genre d'appareils.

ADAPTATION OF WINDMILL DESIGNS, WITH SPECIAL REGARD TO THE NEEDS OF THE LESS INDUSTRIALIZED AREAS

H. Stam *

The Dutch reputation in the field of windmills invites many inquiries for wind power equipment. Indeed, the favourable wind régime of the Netherlands, a flat and open country, made it the wealthiest nation in the world during the seventeenth century. In those days, the wind in the sails of Dutch ships spread the nation's trade over all the oceans, and the wind in the sails of thousands of windmills, each 30 to 70 horsepower, made the Netherlands the most industrialized nation during that period. Not only water pumping for drainage, but above all milling equipment for wood sawing, flour handling, paint mixing, rice scaling, oil pressing and paper fabrication were developed under this favourable providence with mechanical power.

In our day, all this is over. The few traditional windmills still in existence have a purely touristic value; their costly construction in rigid timber has little applicability to the present needs of wind power elsewhere.

Nevertheless, these historical facts contain a promise for solving the urgent problems of the less-industrialized areas of the world that are in need of mechanical power for drainage and irrigation. Dutch history proves that less-industrialized countries can provide themselves with a great deal of applied wind power, if local skills and materials are used through the adaptation of handicraft techniques.

Many countries need to fill the gap between the introduction of industrial products and the decline of traditional means of power—human labour, animal power and, here and there, some few remaining windmills.

On the one hand, the less-industrialized nations must erect basic industry, founded on major power resources and sites of ore, and must provide their populations with modern means of welfare. On the other hand, there is the danger of widespread unemployment among peasants and rural craftsmen if most of the nation's investments become concentrated in a few urban districts. Equilibrium can be maintained if the rural districts play their own part in the nation's development by expanding rural industrialization.

* Stichting Dienst Ontwakende Wereld, Amsterdam.

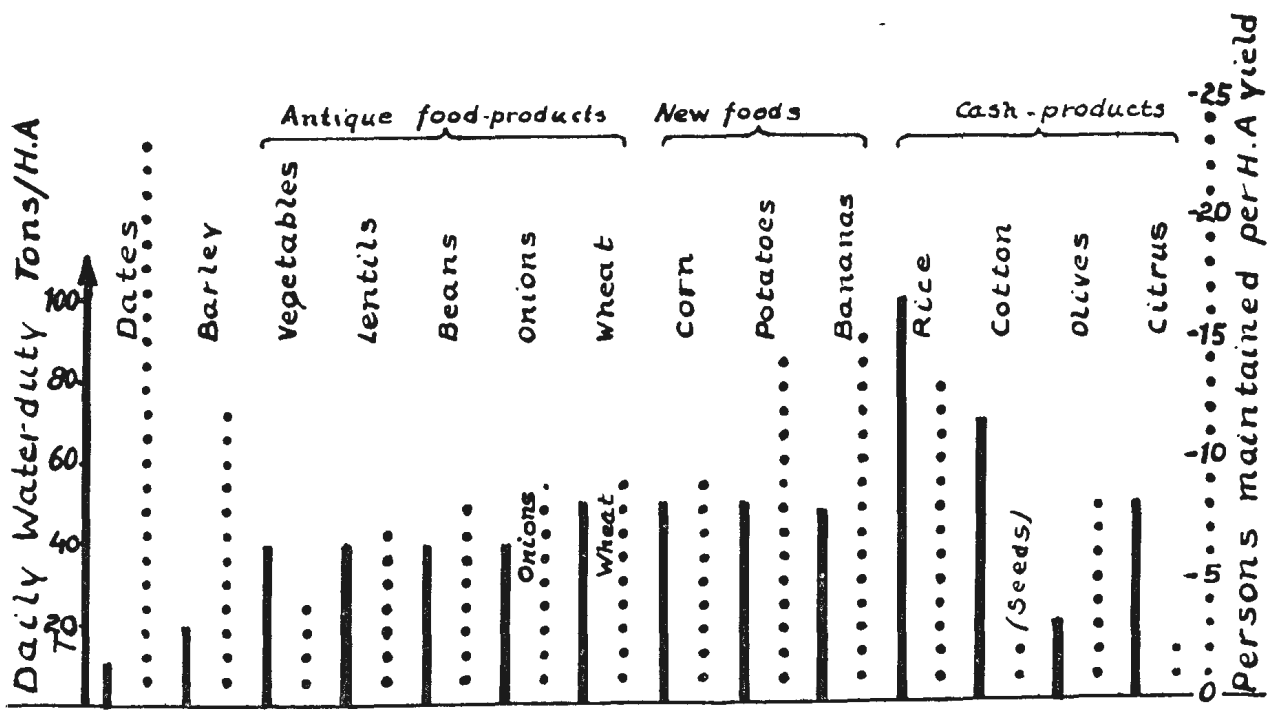

Figure 1. Number of people fed by, and water requirements of, selected agricultural products of the Nile valley

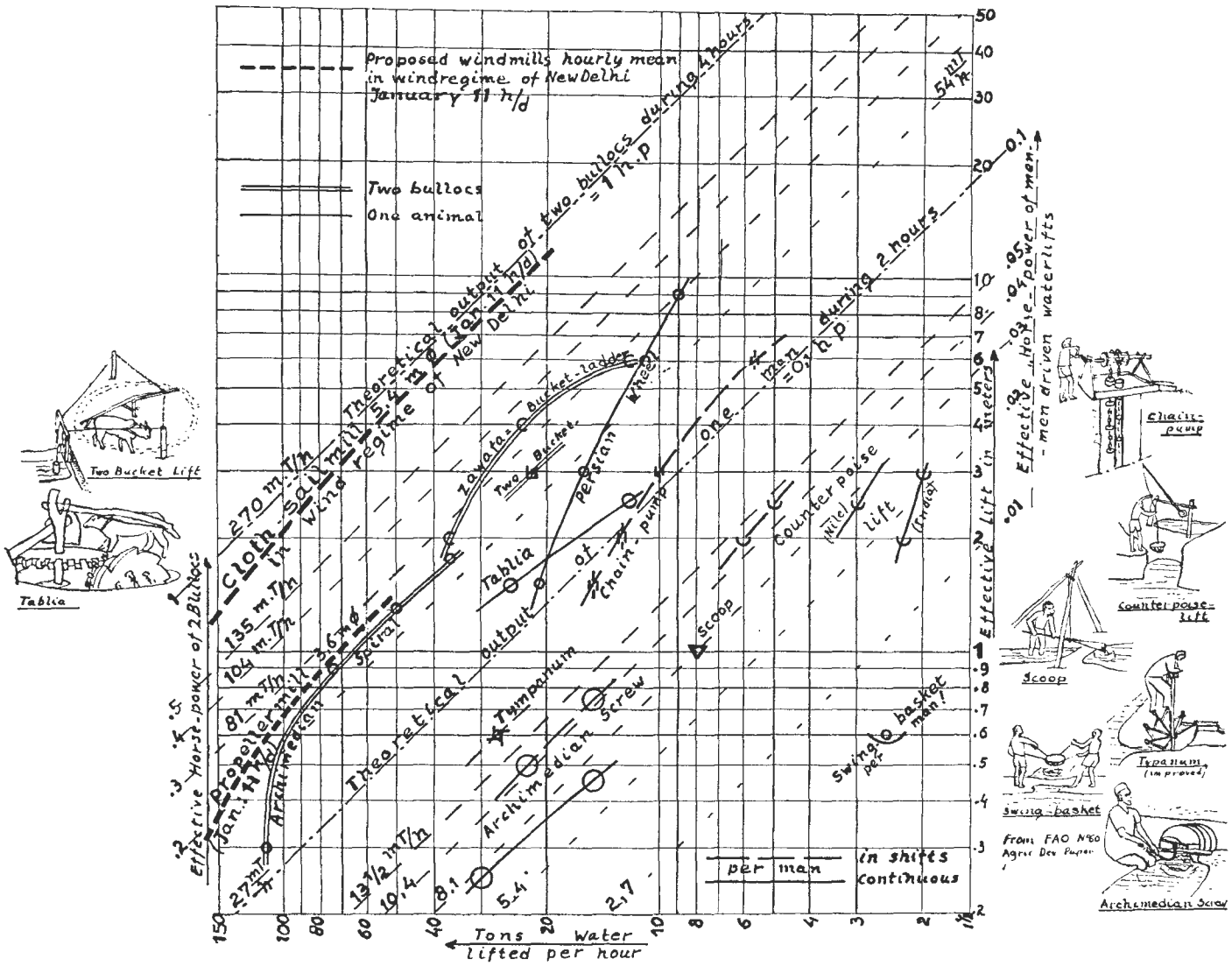

Figure 2. Natural power water-lifts

Rural markets in less-industrialized regions

Sales potential in regard to foreign products

In estimating purchasing power, the following two cardinal factors must be kept in mind, especially by consulting designers:

(*a*) The annual cash income is between $50 to $150 for the large majority of families under consideration. For a smaller group, income ranges between $150 and $500.

(*b*) The prices of products shipped outside the normal routes of world trade multiply, so that peasants in the non-industrialized agrarian countries pay 2 to 3 times the original cost of imported equipment.

Small farmers' needs for waterlifting devices

Most of the population consists of small farmers and cattle breeders. The small farmers are in the main concentrated on irrigated areas of high population density. Others live in remote oases. In all regions where irrigation requires water-lifting by human or animal power, the peasants' yield is limited by the amount of water raised daily by man or animal. Figure 1 shows the number of persons fed by, and the water requirements of, several products of the Nile valley. Depending on the regions of the world, a wide variety of water-lifting devices has been in use since antiquity. Data on them, collected by the Food and Agriculture Organization of the United Nations (1), are illustrated in figure 2. Comparison of this figure with the theoretical limit of normal human and animal power makes it obvious that rural craftsmen can modernize the traditional water-lifts considerably, if only they are stimulated to do so.

Western industrial motor-pumps devalue, in effect, the small farmer's capital outlay, incorporated in his animal-driven, water-lifting devices, and make the peasants more dependent on the rich farmer who can afford the investment. At best, the necessity for co-operation is demonstrated. Engineers with a sense of

responsibility can promote the economical manufacture of a small combustion motor supplying one shaft horsepower at the low revolutions per minute required by these slow-turning traditional devices. It may be that, even then, the cost for fuel and maintenance would be prohibitive, though the food for beasts of burden also places a heavy load on the small plots of the water-lifting farmers.

From this, it is obvious that cheap solar and wind power units, preferably made mainly by hand, are most suitable to free both man and animal from laborious water-lifting. Up till now the soils best suited to agriculture have been overcrowded, and in many regions, because of the excessive labour needed to lift water, second-best soils are underpopulated or even neglected. Moreover, the burdensome water-lifting keeps the farmer from necessary drainage, which he considers as a loss of water. Thus the soil is gradually silting up, with salt or natron.

The family's desire for radio and light

There is nowadays an intense desire to listen to the radio and have electric lighting if only by one bulb. The use of batteries is impractical owing to the cost and the difficulty of obtaining them. Wind-driven bicycle dynamos for radios can be the first step towards generating electricity for light.

The demand for wind power by communities and plantations

Where electric power is the only objective, the wind generator industry of Europe, the United States and the Soviet Union can compete with motor generators in regions which are favoured by strong and continuous winds.

In zones depending on artificially raised water for irrigation, the best solution is to drive a generator by a water turbine, powered by excess water streaming back into the well.

It is in this field that the adaptation of handicraft techniques will have to compete with modern industrial deliveries, after building up its selling market. Rural industrial mills for food processing, etc., are best suited for handmade wind power machines.

Windmills manufactured by hand, using local materials

Types in regional use (2)

The Chinese water-lifting windmill with 6 to 8 rectangular cloth sails has survived since antiquity. Actually, this simple stakes and cloth construction, revived as a power source for rural processing, is a good example of adaptation of handicraft techniques, although perhaps still lacking sufficient scientific guidance.

In Japan and South-East Asia, the needs of the small farmers are met by the village craftsman, following modern aerodynamic design, executed in rigid timber and fitted with solid wooden fixed-pitch blades.

The Mediterranean, Cretan or Syrian windmills possess 6 to 12 triangular cloth sails with variable area. Used for flour milling and oil pressing, they are generally in decay but rather well maintained in Portugal.

The numerous modern Cretan steel mills irrigate the Cretan plain of Lassithi which peasants and a few handicraftsmen have cultivated during the last fifty years. It is one of the few existing examples of the adaptation of handicraft techniques.

Triangular cloth sails are best suited to strong sea winds; the rectangular cloth blades of the Chinese windmills are well adapted to low average wind velocities, but get into trouble, and need pitch changing during the evening with the rather strong wind usual at that time of day in the desert. The turbine blades for high tip speed ratio have a low starting torque.

Newly designed windmills must be adapted to the needs of existing water-lifting devices and to the variations in wind régime.

From the foregoing, the following newly designed types are derived to meet varying demands.

Windmill with self-adjusting cloth sails (figure 3)

This variation on the centuries-old Chinese windmill shows some innovation in comparison with the original. The head can turn with the wind direction. The cloth sails have variable pitch, using springs that veer the sails under gusts or strong winds. The form of the sails is deduced from the measurements of windmills by Mr. M. Iwasaki (3). He used rigid turbine blades following Göttingen profile 623, and from comparisons with curved-plate profiles (4) and Voelz' calculations of the form, lift and momentum of sails hinged between two poles (5), the estimate of the power curve will have a high degree of accuracy. Figure 3 shows the variety of rotating water-lifting devices to be driven by simple (steel) wire transmission of power, easily adapted to the rotational speed of the actual lift. This simple solution requires that the water-lift follow the direction of the wind. Thus the vertical column turns with the head and device as a whole. The guy wires that hold the mast upright are attached to a collar. The wind itself regulates the friction at the collar, damping out undesired oscillations around the vertical axis. The chain pump needs a special feature at the foot of the mast.

There is the problem that the entirely filled water-lifting rotors need a constant momentum while the wind offers a varying momentum on the sails. The best solution would be offered by V-rope transmissions of varying ratio which can be obtained on the market, but these make the mill rather costly. The simplest solution is offered by artificial leakage in the lower part of the water-lifts. The leakage is considerable, and consequently the torque needed during starting is small. With increasing number of revolutions per minute, the volume delivered per

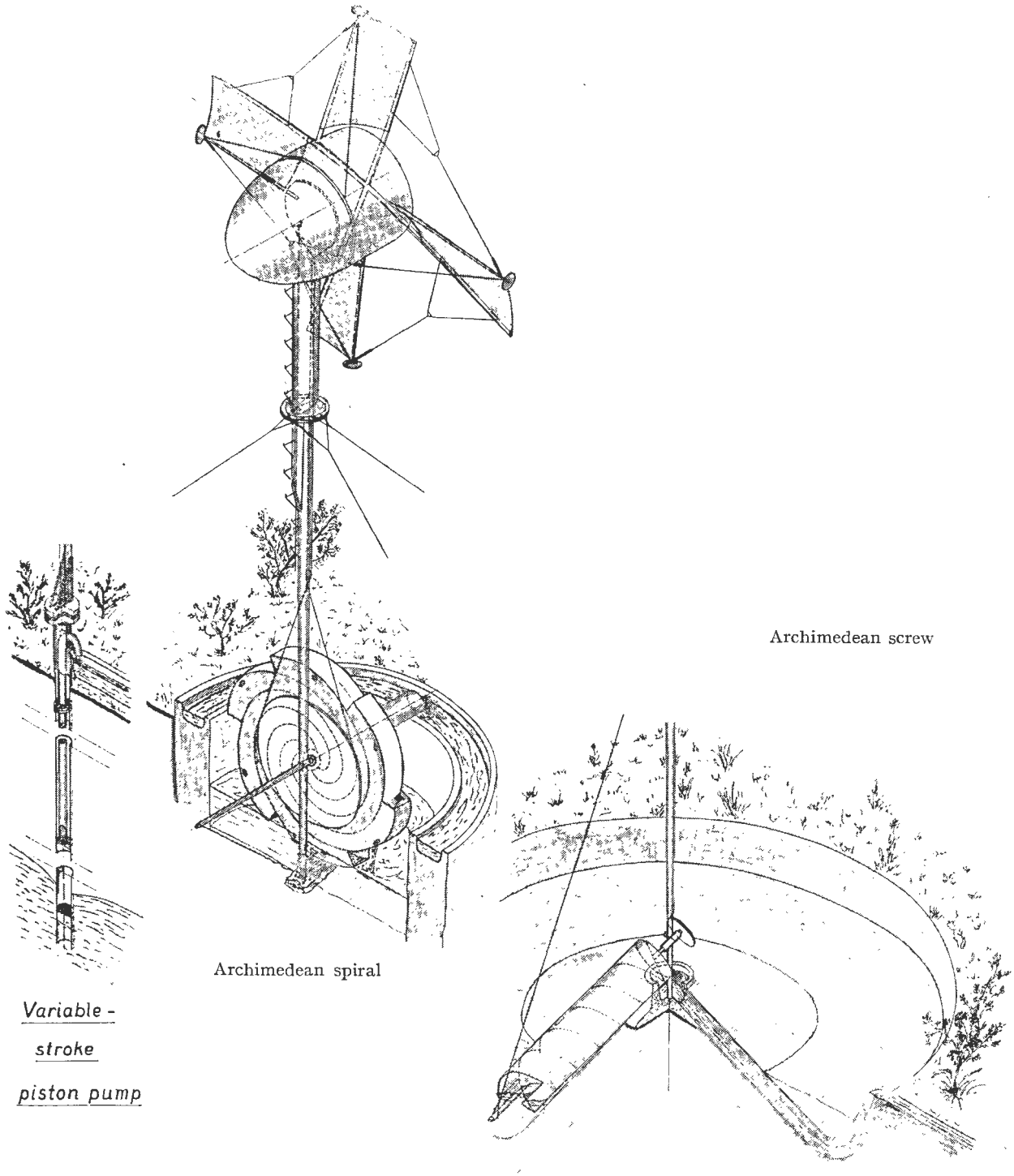

Figure 3

revolution increases and with it the torque. It is difficult to arrange a similar feature with the chain of pots of the Persian water-lift. It is advisable to place a windmill-powered chain-pump in those wells beside the Persian lift. Both are suited for great depths, but the former has far better efficiency. With increasing depth, regulation by leakage may get out of phase with the variations in wind velocity.

Here the piston or membrane-pump with adjustable stroke offers a better solution. We therefore designed the same mill with a crankshaft in the head, adapted to this special deep-well pump. The variation of the stroke is effected through the hollow crankshaft by a spring and the backward poles of the sails. Figure 3 shows the scheme using the piston pump.

The design velocities chosen depend on the wind régime of the region concerned. If, with 5 metres per second, the windmill gets its optimum performance, and pitch variation occurs, at a wind of 9 m/sec, the start of delivery will be at roughly 2½ m/s wind. For all the aforementioned types of water-lifting devices, the yield of water multiplied by height of lift for

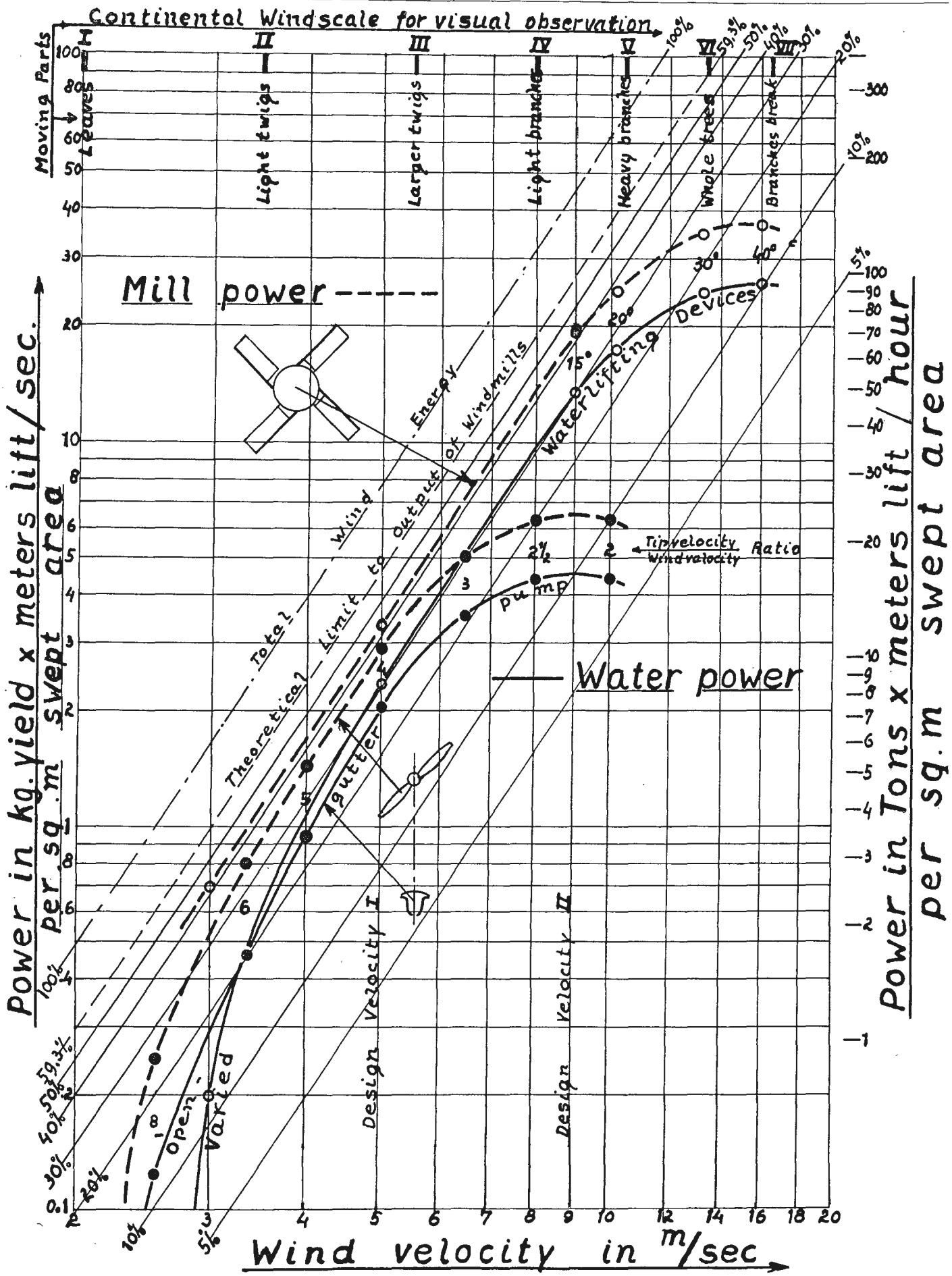

Figure 4. Windmill output

each square metre area swept by the sails is shown by the upper curves in figure 4. Minor differences depending on the kind of lifting device, are ignored in this figure.

It is expected that the smallest sail diameter might be 5.4 metres; but 8 and 12 metres diameter will be asked for too by individual farmers. Machines of 18 and 27 metres diameter are suitable for co-operative and communal service.

Turbine bladed windmill with open-gutter centrifugal pump

Farmers who need to lift their irrigation water less than one metre will find the aforementioned types too large for their needs. Moreover, the existing water-lifts are inefficient at such low lifts.

A two-bladed turbine of 3.6 metres diameter can equal the human output of power with moderate winds of 4½ metres per second and is well suited to drive the type of centrifugal pump shown in figure 5. Based on one of the oldest registered Dutch patents, this comprises a rotating bucket lifting the water through a hole in the bottom by centrifugal force. At sufficient revolutions per second, water is ejected from the bucket at the top. Every particle of fluid gets as much static energy during lifting as it obtains energy of velocity, so that the ideal efficiency is limited to 50 per cent.

By our modification, the rim of the bucket is broadened and vanes are fixed on it to rotate with the bucket. The centrifugal forces on the water transported along the vanes force the water backwards in the direction of rotation, regaining a part of the aforementioned loss of kinetic energy, and the limit of efficiency can easily be increased to 80 per cent. The special advantage of this low-lift pump is that the water during transport from the bottom hole to the ends of the vanes runs through " open gutters ". Thus the quantity transported can change over a wide range, with minor change of velocity and rotational speed. Moreover, the momentum needed is extremely low during the starting period before delivery.

During standstill, no water can run back from the higher to the lower level; thus no check-valve is needed and no leakage can occur. The average wind velocity that one wishes in order to obtain the highest efficiency of the wooden or plastic-bladed turbine depends on the wind régime of the region concerned. Thanks to the almost constant rotational speed of this open gutter pump, the ratio of tip velocity to wind velocity will change considerably with wind strength (figure 6). The rigid turbine blade remains stable in its performance, thanks to this type of pump. Twisting propellers made from, for example, split plastic tube will deliver increasing torque and more water at higher wind.

The torque in the vertical axis of the pump forces the turbine head to rotate out of the wind direction. That torque is counteracted by placing the horizontal axle of the sails at some distance from the vertical axis of the supporting columns. Dividing the torque coefficient of the turbine by its drag coefficient gives the eccentricity in relation to the outer radius of the

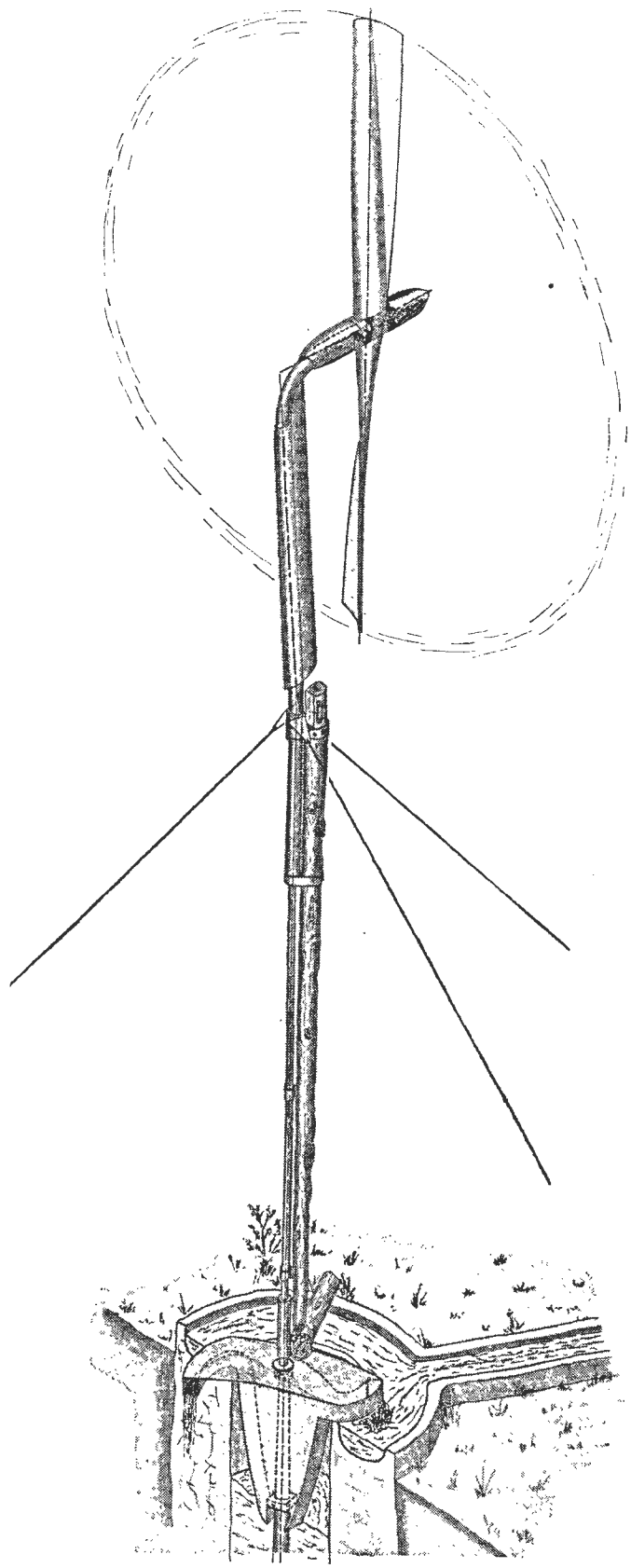

Figure 5

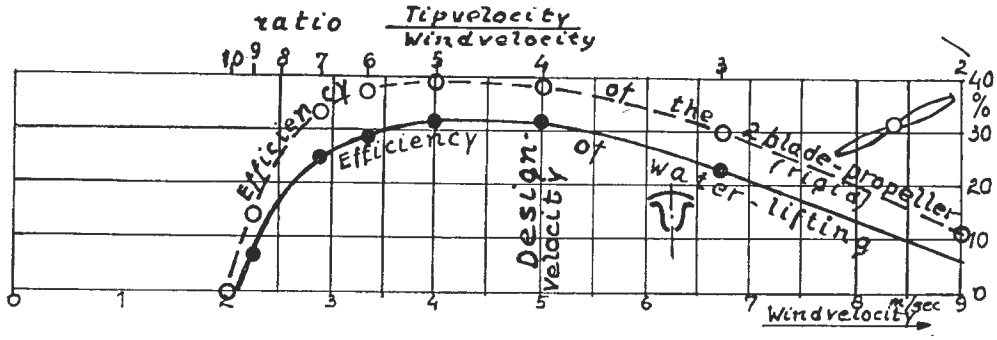

Figure 6. Characteristics of wind turbine and open-gutter pump

vanes (3). (This is derived from classic German research on windmills (6).)

At design wind velocities, the vane/rotor remains almost perpendicular to the wind. With weaker and stronger winds, some deviation will occur.

Mechanical parts and prospects for electricity

Such essential mechanical parts as ball bearings oil seals, flexible spindle, etc., are limited to a few, suited for as many applications as possible. That is the reason why, first, a broad programme was set up and then, taking into consideration all the variations absolutely needed, the details were designed. The parts are all suited to be made by simple carpenter-blacksmith techniques. The modern oil-tight, high quality ball bearings are reckoned to be too costly; the cheaper " bicycle ball-cases " on simply milled bushings are used. Separate sand and water-repellents are envisaged, as well as oil-seals.

The demand of the individual farmer for electricity for radio or for cooking can best be met by mounting a wind-driven generator on the tip of one or more sails on Flettner's principle of the " aerodynamic transformer " (7); because of the coupling with water-lifting, the delivery of electricity will then be already at full capacity with low wind velocity. Without any mechanical transmission, the generator will be driven at high rotational speeds. Thus a normal, or large-size, bicycle dynamo is suitable for the job, together with a rectifier and, perhaps, an H_2O_2 cell.

Wind régime and mills for farmers' and communal needs

The needs at New Delhi during January

For a very unfavourable example, I refer to the data at New Delhi, as given by Ramdas and Ramakrishnan (8). Water is then at its scarcest and the average wind velocity is at a minimum during that month. Supposing that the régime given for the whole month might be representative for every turn of watering, figure 7 shows the specific daily output for each wind-velocity step in wind energy as well as in water power for the turbine bladed mill with open gutter pump as described above. The water power is given in tons lifted, multiplied by metres lifted and with the hours for each wind-velocity step, for the depth of the water level near New Delhi is not known. But if the open-gutter pump should be suited to this depth, the 3.6-metre diameter of the sails will still deliver sufficient hourly output in comparison with human water-lifting, as proved by the appropriate curve in figure 2. Moreover, a windmill at New Delhi would deliver for 13 hours daily even during January, when human labour would be limited to 4 to 5 hours of water-lifting a day. I am convinced that this type of mill and pump are very well suited to the conditions in the delta of the Nile and the coast and Fezzan-oasis of Libya. Should the machine of 3.6-metre diameter deliver insufficient water power for the farmer's needs, the 5.4-metre diameter one — either the two-bladed turbine or the cloth sail mill — will satisfy him in nearly all the cases where he would normally use two bullocks or one camel for turning his traditional devices. Again, assuming the January wind régime of New Delhi, the average delivery depending on height of lift is also shown in figure 2, disregarding minor variations in efficiency of the several water-lifting devices, as shown in figure 3.

Communal services

The examples mentioned for the small farmers prove that even under rather unfavourable wind régimes, it might be possible to satisfy communal needs for irrigation water and auxiliary electricity by means of turbine-bladed or cloth-sailed windmills. Both can be built in diameters of 8, 12, 18, 27 and even 40 metres and made in either wood or steel and plastic. A communal grid utilizing the principle of the Flettner aerodynamic transformer permits cheap and simple generating by asynchronous or even synchronous alternators. In combination with the open gutter pump, with its characteristic constant speed, it is, moreover, possible to place a generator on the pump axle and to regulate the electric power by minor variations of the lifting height of that pumping device. But a great deal depends on the instructional institute co-operating with the handicraft guilds as to how far the adaptation of handicraft techniques will provide the communal services with the essential needs in competition with modern industry.

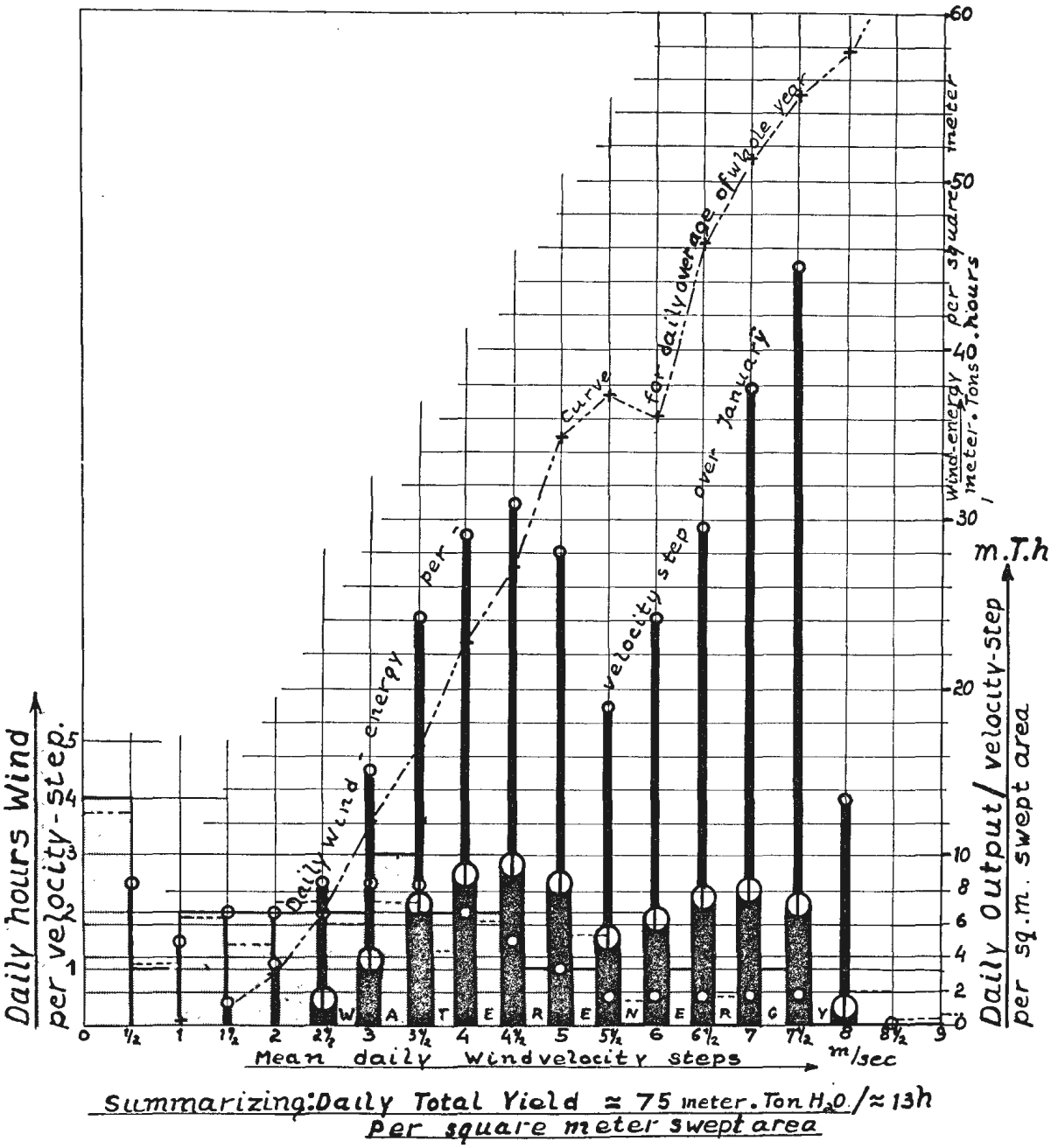

Figure 7. Daily water-power per square meter swept-area in wind régime of January at New Delhi

Stimulation of western "know-how" into oriental handicraft skill

It is quite obvious that adapting modern science and techniques to traditional skills and local materials can best be achieved in the engineering institutions and instructional services of the regions concerned. But in any case it may be insufficient to supply rural craftsmen with blueprints and written instructions only. It is better to sell construction kits to those agrarian families that are willing to build a mill in districts where the selling institute knows the wind régime and conditions of irrigation. Such a kit may include a strip-story illustrated instruction, clearly understandable even for people who cannot read, together with the essential parts that cannot be fabricated with local means. At its best, the kit should also contain a scale model.

The kits themselves can be best made by craft guilds or by technical schools. Guild members or old pupils could sell these kits and erect mills throughout the country.

Because of the very limited financial resources of our foundation, we can only supply a limited number of parts to those co-operatives or institutions in the less-industrialized areas that really intend to further the adaptation of handicraft techniques to industrialization.

A better solution will be offered if the nations concerned establish regional and co-operative institutions for simple application of wind power (and solar

energy) to undertake the co-ordination of activities. By virtue of the social-economic nature of such development programmes as the one suggested here, these institutions and the governments behind them can assure that due emphasis is placed on all the wider aspects and problems encountered in th exploitation of natural power sources for the benefit of the whole population in the new industrializing areas.

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Summary

Wind made the Netherlands the wealthiest nation during the seventeenth century. Thousands of windmills delivered power for water-pumping, wood-sawing, flour-handling, paint-mixing, rice-scaling, oil-pressing, paper fabrication, etc. Today, they have only tourist value.

The less-industrialized countries need to industrialize to provide modern welfare. The problem of the displacement of traditional craftsmen and peasants which may result may be faced partly by adaptation of ancient handicrafts to local small-scale production of modern products.

Rural markets in less-industrialized regions

Sales potential in regard to foreign products. Consulting designers must keep in mind that most of the families under consideration earn $50 to $150 a year.

The small farmers' needs for water-lifting devices. With non-gravity irrigation, yield is limited by the water raised by man or animal (figure 1). Data on traditional devices are illustrated in figure 2. Motor pumps have the effect of devaluing the small farmer's capital incorporated in his animal-driven devices and making him dependent on the rich farmer. Cheap solar and wind power will free both man and animal from laborious water-lifting and may leave him free to pay more attention to drainage and avoidance of salination.

The family's desire for radio and light. Wind-driven bicycle dynamos for radio can be the first step towards generating electricity for light.

The demand for wind power by communities and plantations. The wind generator industry of Europe, the United States and the Soviet Union can compete with motor generators. Rural industrial mills for food processing, etc., are best suited for fabrication by hand.

Windmills manufactured by hand, using local materials

Types in regional use (2). The Chinese stakes and cloth mills undergo a revival for water-lifting and rural processing. Japanese aerodynamic design is executed by village craftsmen in South-east Asia. Mediterranean mills are well maintained in Portugal. Modern mills irrigate the plains of Crete.

The following newly designed types are derived from these to meet varying demands.

Windmill with self-adjusting cloth sails (figure 3). The form of the sails is deduced from Japanese measurements (3, 4, 5). Figure 3 shows the rotating water-lifts to be driven by wire transmission. Artificial leakage torque during starting is small; it increases with rotational speed. A windmill powered chain pump needs to be installed alongside existing Persian lifts because leakage gets out of phase with wind variations as pumping depth increases.

The membrane pump with adjusting stroke offers the best solution for great depth; thus we designed the same mill with a crankshaft, the adjustment being effected by wind pressure on the sails.

Figure 4 shows mill and water-lift performance depending on design velocities. Individual farmers will require machines of 5.5 metres diameter; co-operative and communal services, from 18 to 27 metres diameter.

Turbine bladed windmill with open gutter pump. A two-bladed turbine of 3.6 metre diameter gives an output similar to one manpower and is suited to drive the type of pump shown in figure 5. Our adaptation of an old Dutch patent increases the efficiency of pumping to 80 per cent. The open gutters transport changing quantities with minor

changes of rotational speed, and during starting the momentum needed is low. No check valve is needed and no leakage can occur. Figure 6 shows the characteristics of the wind turbine and of the pump.

Mechanical parts and prospects for electricity. The parts are few in number and are suited to normal carpentry and blacksmith techniques. The "aerodynamic tranformer" (7) generates electricity, without any mechanical transmission from bicycle or car dynamo.

Wind régime and mills for farmers' and communal needs

Small farmers at New Delhi, in January. Using the figures of ref. 8 as an unfavourable example, figure 7 shows the output for the turbine-bladed mill with open gutter pump. As shown in figure 2, the machine having a 3.6 metre diameter rotor delivers sufficient water; on an average, the mill operates 13 hours per day. This type of mill and pump are also suited for the Nile delta and for Libya. The 5.4 metre diameter cloth saill mill in the wind régime for New Delhi easily outworks two bullocks.

Communal services. How far communal services may be supplied through these techniques may depend on effective co-operation between handicraft organizations and instructional institutes.

Stimulation of western "know-how" into oriental handicraft skill

Adapting handicrafts requires instructional services in the regions concerned. Construction kits with illustrated instructions, essential parts and a model can be fabricated by craft-co-operatives or by technical schools. A limited number of kits can be financed by our foundation. The best solution is the creation of regional institutions for wind power and solar energy by the interested governments.

ADAPTATION DES CONCEPTIONS CLASSIQUES DES ÉOLIENNES SPÉCIALEMENT A L'INTENTION DES PAYS PEU INDUSTRIALISÉS

Résumé

C'est le vent qui a fait des Pays-Bas le pays le plus riche du monde au cours du XVIIe siècle. Des milliers de moulins à vent fournissaient la force motrice nécessaire au pompage de l'eau, assuraient le sciage du bois, la manutention des sacs de farine, le mélange des peintures, l'écossage du riz, le pressage des graines oléagineuses, la fabrication du papier, etc. Aujourd'hui, ces moulins à vent n'ont plus d'intérêt que pour les touristes.

Les pays peu industrialisés ont besoin de corriger cette déficience pour garantir le bien-être moderne à leurs citoyens. Le problème que soulève le déplacement des artisans et des paysans qui peut en résulter pourra être résolu partiellement en adaptant les anciennes techniques artisanales à la fabrication sur place à petite échelle des produits modernes.

Marchés ruraux dans les pays peu industrialisés

Potentiel de vente en ce qui concerne les produits étrangers. Les ingénieurs-conseil doivent se rappeler que la plupart des familles en cause gagnent seulement de 50 à 150 dollars par an.

Besoins du petit agriculteur en ce qui concerne les matériels d'élévation d'eau. Quand l'irrigation est assurée autrement que par la pesanteur, le rendement est limité par la quantité d'eau que l'homme ou un animal peuvent élever (figure 1). Les données sur les dispositifs traditionnels sont illustrées à la figure 2. Les pompes à moteur provoquent une dévaluation du capital du petit fermier, lequel est immobilisé dans les appareils entraînés par des animaux. Il tombe ainsi sous la dépendance des agriculteurs plus riches. L'énergie solaire et l'énergie éolienne fournies à des prix modiques libéreront l'homme et l'animal de travaux pénibles consistant à élever l'eau et laisseront le petit agriculteur peut-être libre de prêter plus d'attention au drainage, lui permettant d'éviter l'accumulation de sels.

Besoins de radio et d'éclairage. Les dynamos du genre que l'on emploie avec les bicyclettes entraînées par le vent peuvent constituer le premier pas vers la production de l'électricité en vue de l'éclairage et, entre temps, on peut s'en servir pour les appareils de T.S.F.

Demande d'énergie éolienne par les communautés et les plantations. L'industrie des éoliennes en Europe, aux États-Unis et en Union Soviétique peut faire concurrence au groupe électrogène classique à moteur-générateur. Les usines industrielles rurales de transformation des denrées alimentaires se prêtent spécialement à la fabrication à la main.

Éoliennes à fabriquer à la main avec des matériaux locaux

Modèles utilisés régionalement (2). Le matériel chinois est en train d'être ressuscité pour élever l'eau et réaliser certains traitements de produits ruraux. La conception aérodynamique japonaise est exécutée par des artisans de village en Asie du sud-est. Les moulins méditerranéens fonctionnent bien au Portugal. Des moulins modernes servent à l'irrigation des plaines de la Crête.

Les modèles récents qui suivent dérivent de ces dispositifs pour faire face à des demandes diverses.

Moulins à vent à ailes en tissu à auto-réglage (figure 3). La forme des ailes découle des cotes japonaises (3, 4, 5). La figure 3 montre les dispositifs d'élévation rotatifs qui doivent être entraînés par des liaisons à câbles. Le couple artificiel de fuite au départ est faible et augmente avec la vitesse de rotation. Une pompe à chaîne sans fin, entraînée par un moulin à vent, doit être installée le long des norias persanes parce que les fuites perdent la phase avec les variations du vent tandis que la hauteur sur laquelle l'eau doit être élevée augmente.

La pompe à membrane à course réglable constitue la meilleure solution pour les grandes profondeurs. Nous avons donc réalisé le même moulin avec un vilebrequin, le réglage étant assuré par la pression aérodynamique du vent sur les ailes. La figure 4 montre le fonctionnement du moulin et de l'élévation d'eau suivant les vitesses de régime. Les agriculteurs exigeront des machines ayant un diamètre de 5,5 m et les services coopératifs et communaux des diamètres de 18 à 27 m.

Moulins à vent à aubes de turbine avec pompe à gouttière ouverte. Une turbine à deux pales de 3,6 m de diamètre donne un débit analogue à celui d'un homme et se prête bien à l'entraînement de pompes que l'on voit à la figure 5. Notre adaptation d'un vieux brevet hollandais augmente le rendement du pompage, le portant à 80 p. 100.

Le système à gouttière ouverte transporte des quantités variables avec de faibles changements de la vitesse de rotation et le couple nécessaire au démarrage est faible. Point n'est besoin de soupape antiretour et toute fuite est impossible. On voit, en figure 6, les caractéristiques de la turbine et de la pompe.

Éléments mécaniques et perspectives pour l'électricité. Les pièces sont peu nombreuses et se prêtent bien aux travaux de menuiserie normaux et aux techniques de la forge de village. Le « transformateur aérodynamique » (7) produit de l'électricité sans transmission mécanique en se servant d'une dynamo de bicyclette ou de voiture.

Régime des vents et moulins pour les agriculteurs et les besoins communaux

Petits agriculteurs à New Delhi, en janvier. En se servant des chiffres de la référence 8 comme un exemple défavorable, la figure 7 montre le débit d'un moulin à ailes de turbine avec une pompe à gouttière ouverte. Comme l'indique la figure 2, la machine qui a un rotor de 3,6 m de diamètre fournit assez d'eau; ce moulin fonctionne en moyenne 13 heures par jour. Ce type de moulin, avec sa pompe, se prête également au delta du Nil et à la Lybie. Les ailes en tissu de 5,4 m de diamètre, pour le régime des vents que l'on trouve à New Delhi, donnent facilement plus de travail que deux jeunes bœufs.

Services communaux. La mesure dans laquelle on peut les satisfaire en ayant recours à ces techniques dépendra d'une collaboration efficace entre les organisations artisanales et les centres d'instruction.

Connaissances occidentales et artisanat oriental.

L'adaptation des techniques artisanales exige des services d'instruction dans les régions en cause. Les nécessaires, avec instructions illustrées, les pièces essentielles et un modèle, peuvent être fabriqués par des coopératives d'artisans et par des écoles techniques. Notre fondation pourra financer un nombre limité de nécessaires. La meilleure solution est constituée par l'établissement d'instituts régionaux d'énergie éolienne et d'énergie solaire par les gouvernements intéressés.

OPERATION OF ALLGAIER TYPE (6-8 KW) WIND ELECTRIC GENERATOR AT PORBANDAR, INDIA

S. P. Venkiteshwaran *

There is no doubt that wind electric generators will play a much greater part in the use of wind power than the ordinary type of direct acting windmills for pumping water, etc. In this connection, India has had the opportunity to gain some experience in the installation, maintenance and performance of a 6 kW Allgaier wind electric generator presented to the Wind Power Division of the National Aeronautical Laboratory by the West German Government. This equipment, which is of the " High Speed " type, is supported on a mast 10 metres high (figure 1) and has three blades, each of 5 metres length. Variable pitch blades are used; for wind speeds between the starting speed and the rated speed, the pitch of the blade remains constant, and when this is exceeded, a regulating mechanism, which consists of a swinging plate placed in the wind stream, comes into operation thereby modifying the pitch of the blades and thus maintaining the rate of revolution and the power constant. The vertically hanging plate gets tilted in strong winds and thereby actuates the piston in a hydraulic jack and furls the propeller. An electromagnet also controls the hydraulic jack when the voltage generated is too high.

A DC generator (6 kW, 220 volts) is coupled to the rotor with a train of gear wheels, so that one revolution of the rotor corresponds to 17.4 revolutions of the generator. These gear wheels work in oil.

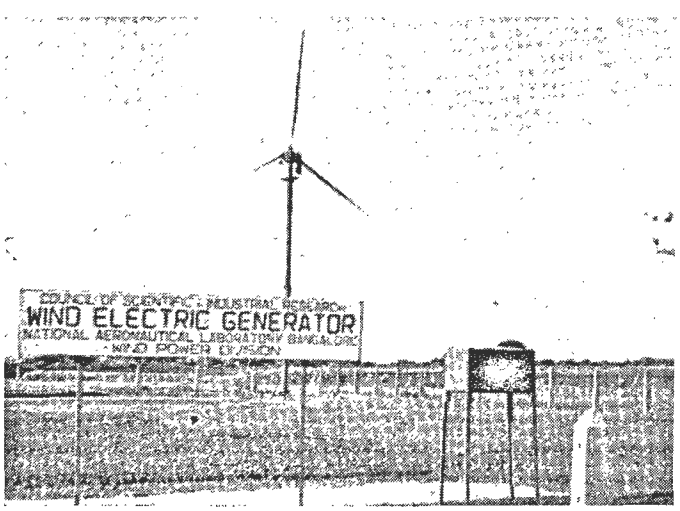

Figure 1. Allgaier wind electric generator, Porbandar (India)

The switchboard for use with the generator has arrangements to charge a battery or to keep it floating, the current being used for any external loads. The generator operates automatically without attention in charging the battery and keeping the voltages within adjusted limits.

The power generated by this plant for various wind speeds is as follows:

Table 1

Wind speed kmph	*Total output*	*Speed of wheel (rpm)*
11	0.3	38
14	1.0	51
18	2.0	63
22	3.5	72
25	4.8	78
29	5.6	83
32	6.0	86

Meteorological conditions at site selected for the erection of the wind electric generator

For testing the performance of this wind electric plant, the most favourable region of India with maximum availability of wind and good exposure was selected. It is well known that Saurashtra is one of the most windy parts of India and the rainfall is comparatively very small during the monsoon compared to other regions of India. Figure 2 shows the mean monthly wind distribution over this state. The site for installation was chosen at an agricultural farm in Porbandar, where electricity was not available. A 10 hp diesel operated pump supplying 6 000 gallons per hour was being used to irrigate the farm. Thus the installation of the electric generator would enable its performance to be examined from many aspects, under the best available meteorological conditions.

It will also serve a very useful purpose in the agricultural farm by providing water.

Table 2 gives the mean monthly wind speeds in kmph at Porbandar during 1960 during the different periods of the day.

* National Aeronautical Laboratory, Bangalore, India.

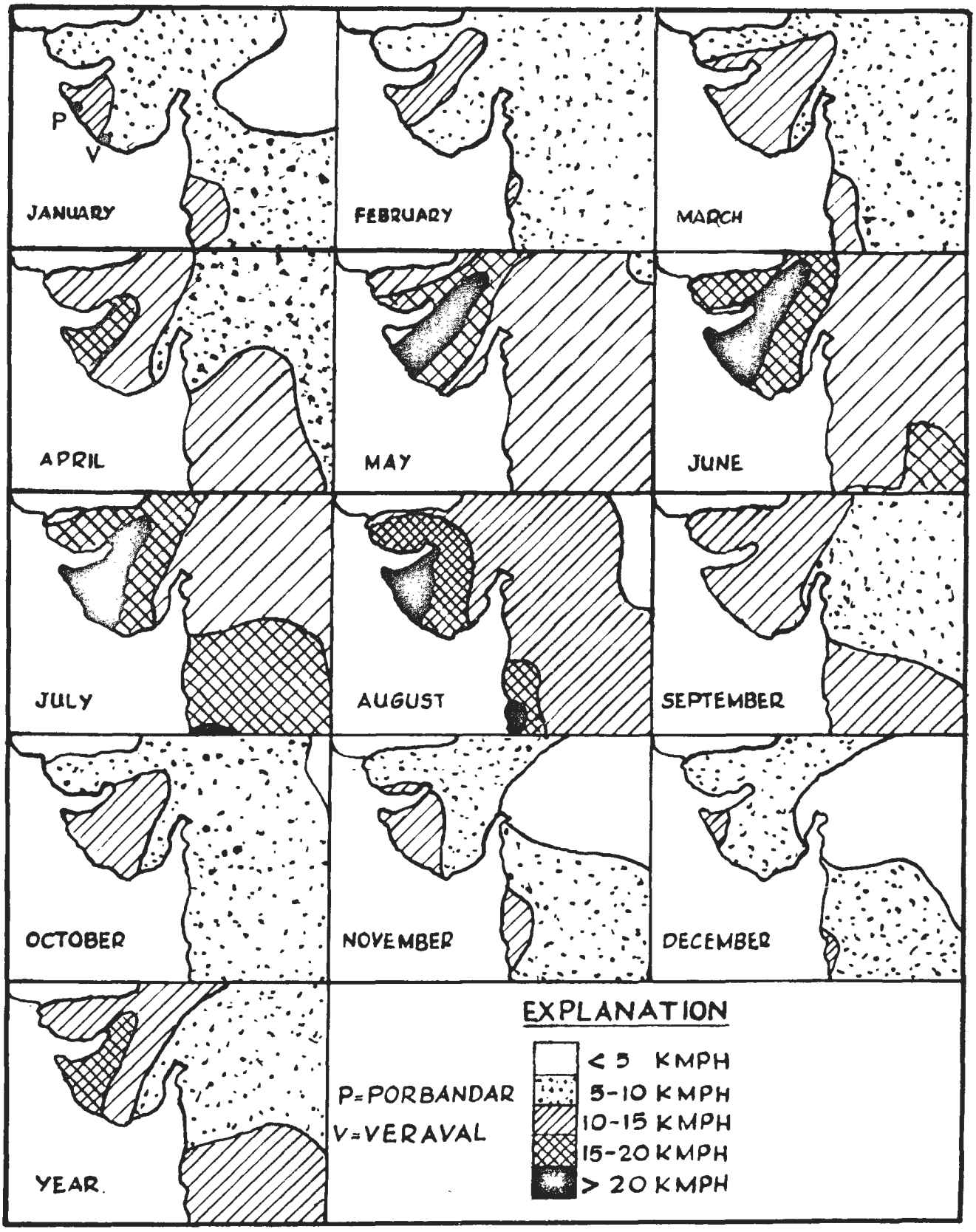

Figure 2. Mean wind speed (kmph) in and around Kathiawar in each month of the year

Table 2

Period of day	J.	F.	M.	A.	M.	J.	Jy.	A.	S.	O.	N.	D.	Year
0830-1730 IST . .	15	15	18	21	23	22	26	24	22	18	16	15	19.4
1730-0830 IST . .	12	11	12	15	15	16	21	19	12	9	8	10	13.4
0830-0830 IST . .	13	12	15	18	18	18	23	21	15	13	11	11	15.7

Table 3 gives frequencies of specified mean daily wind speeds for different periods of the day at Porbandar during 1960.

Figure 3 gives the mean hourly wind from Dines' anemographic records at Veraval, which is also situated in Saurashtra (lat. 20° 55′ N, long. 70° 22′ E) at about 70 miles from Porbandar. It may be assumed that the general pattern of wind at Porbandar is the same as at Veraval.

Table 3. Number of occasions in a year when wind speeds at Porbandar Airport lay in specified ranges

(*a*) From 0830-1730 hrs., (*b*) From 1730-0830 hrs. and (*c*) 0 830-0 830 hrs.
Year : 1960

Wind speed range (kmph)	a	b	c
0-5	0	20	0
6-10	22	115	72
11-15	74	107	115
16-20	100	85	114
21-25	111	26	50
26-30	47	8	9
31-35	11	5	6
36-40	1	—	—
TOTAL	366	366	366

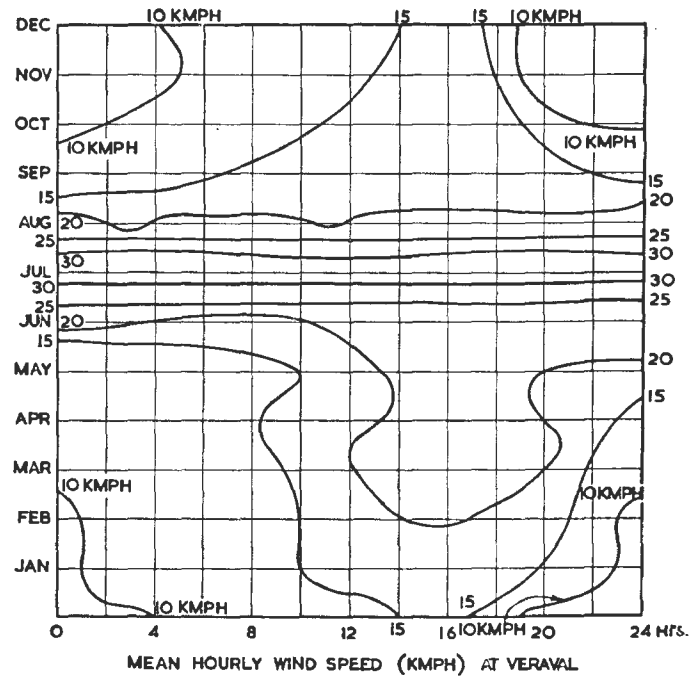

Figure 3

The mean total monthly rainfall and the number of rainy days at Porbandar are given below :

Table 4. Porbandar — rainfall and number of rainy days

	J.	F.	M.	A.	M.	J.	Jy.	A.	S.	O.	N.	D.	Year
Rainfall inches . .	.09	0.12	0.07	0	0.18	4.45	8.27	3.74	1.23	0.29	0.30	0.10	18.84
Number of days. .	0.2	0.3	0.1	0	0.2	3.4	8.7	6.7	3.1	0.5	0.2	0.1	23.5

The agricultural farm at Porbandar represents the usual conditions prevailing at most other farms in India where electrical energy is not available. The main difference between them is only in the meteorological conditions relating to the period and intensity of the monsoon and the related crops that are grown. Water is either pumped with diesel engines or by bullocks and in some areas by lifts operated by manual labour. There is generally no need for electric power at these farms for other purposes and if available it is used for operating agricultural machinery. But even these have not come into general practice yet. Bullocks are generally maintained in all farms for ploughing and for other work. The common difficulties usually met with in all farms in operating diesel engines are experienced in this farm also, i.e., the availability of engines, their overhaul and supply of spare parts, regular supply and storage of diesel oil, etc.

Operation of the wind electric generator at Porbandar

Table 5 gives the expected mean power output from the wind electric generator during the different periods of the day in different months. This has been obtained from tables 1 and 2.

If we assume that at Porbandar electric energy will be used mainly for pumping water as with the

Table 5. Mean power output from the wind electric generator (kW)

Period of day	*J.*	*F.*	*M.*	*A.*	*M.*	*J.*	*Jy.*	*A.*	*S.*	*O.*	*N.*	*D.*	*Year*
0830-1730 IST . .	1.3	1.3	2.0	3.1	3.9	3.5	5.0	4.4	3.5	2.0	1.5	1.3	2.7
1730-0830 IST . .	0.5	0.3	0.5	1.3	1.3	1.5	3.1	2.4	0.5	0.2	0.2	0.3	1.0
0830-0830 IST . .	0.8	0.5	1.3	2.0	2.0	2.0	3.9	3.1	1.3	0.8	0.3	0.3	1.5

diesel engine and that it will therefore work only by day, it will be seen from table 5 that the wind electric generator will supply about 1.5 kW during 6 months and about 4 kW in the other months. The energy available at the station is lowest during the winter months when less water may be needed for agriculture. The total energy available during the year during the daylight hours 0830-1730 IST is approximately 8 900 kWh. If we assume that the cost of the generator, installation, pumps, etc., is 20 000 rupees and that its maintenance cost is about 500 rupees per annum and that the life of the generator is 10 years, the cost per unit of electricity will be approximately 28 nPs. It will be cheaper if energy is used for more hours of the day. The well, fitted with an electric pump of about 1.5 kW, delivers approximately 4 000 gallons of water per hour (total head of 40 ft). Assuming that one pump will work for 6 months and 2 for the rest of the year, cost per 1 000 gallons of water is approximately 10 nPs and 5 nPs respectively.

The diesel engine now in operation (10 hp) requires 3.3 litres of oil per hour and pumps 6 000 gallons of water per hour. The cost of oil for pumping 1 000 gallons of water is approximately 25 nPs. Assuming cost of the engine at 4 000 rupees — and maintenance and repair at 5 % and 10 years life, the cost per 1 000 gallons of water is approximately 28 nPs.

In the above programme of operation of wind electric generator, no battery has been used. The use of batteries in the agricultural farm is both costly and difficult. There appears to be no need for them, since electricity may not be needed during the night and if used, it will be negligible. However, there is one aspect, that the energy available at night can be stored in the batteries and used during the day. If we assume that this can be done, and estimating the cost of a suitable battery and installation at 15 000 rupees, the life of the battery at 10 years, and cost of maintenance, 600 rupees per year, the cost of one kWh of energy is approximately 32 nPs. On the other hand the cost of energy per kWh, without the battery, used only for pumping water during daylight hours, works out to 28 nPs.

Future programme

The experience gained at Porbandar with the wind electric generator has been encouraging and it will be worth while trying out a few more of them, in other regions of India. The initial attempt will be to use smaller size equipment of 1.5 to 2 kW which will be more easily portable and simpler to erect. Future programmes will be based on the experience gained.

Acknowledgements

The author is grateful to the India Meteorological Department for the data used in this paper and to Dr. P. Nilakantan for his interest and encouragement in this work.

Summary

The Allgaier wind electric generator presented to the Wind Power Division of the National Aeronautical Laboratory by the West German Government is described briefly in this paper. It is capable of giving 6 kW on 220 volts DC at a wind speed of about 32 kilometres per hour. This equipment is installed at an agricultural farm at Porbandar (lat. 21° 38′ N, long. 69° 37′ E) where a diesel operated pump is at present working for supplying water for irrigation purposes. The meteorological conditions, including detailed information about the wind speed, are given for Porbandar. The mean power output from the wind electric generator for different periods of the day during the year are also given. The cost per kWh electricity with the wind electric generator without employing a battery works out to 28 nPs if energy is used only during the daylight hours of morning 0830 to 1730 IST. The cost of pumping 1 000 gallons of water against a total head of 40 ft in the different seasons is also estimated and compared with the present cost of operating a diesel engine for the same purpose. It is found that while the cost of pumping 1 000 gallons of water with the present diesel engine is about 28 nPs, the cost with the wind electric generator is between 5 to 10 nPs.

FONCTIONNEMENT DE LA GÉNÉRATRICE ÉOLIENNE DU MODÈLE ALLGAIER (6 A 8 KW) INSTALLÉE A PORBANDAR, INDE

Résumé

Le groupe électrogène à aéromoteur qui a été offert à la section d'énergie éolienne du Laboratoire national d'aéronautique, par le gouvernement de la République Fédérale Allemande, fait l'objet d'une brève description dans le présent mémoire. Il peut débiter 6 kW sous 220 V.C.C. pour une vitesse de vent de l'ordre de 32 km à l'heure. Le matériel est installé dans une exploitation agricole à Porbandar (lat. 21° 38′ N — long. 69° 37′ E) où une pompe actionnée par un moteur diesel assure actuellement le pompage de l'eau d'irrigation. On donne les conditions météorologiques, notamment des renseignements détaillés sur le régime de la vitesse des vents pour Porbandar. On indique également le débit moyen d'énergie du générateur à aéromoteur pour diverses périodes de la journée au cours de l'année. Le coût par kW/h de l'électricité produite par la génératrice sans batterie d'accumulateurs, s'établit à 28 nPs si on ne se sert de l'énergie que pendant les heures de jour, notamment du matin, en tout cas de 8 h: 30 à 17 h: 30 (heure standard de l'Inde). Le coût de pompage de 1000 gallons d'eau (4 540 l) contre une pression totale de 10 pieds (12 m) au cours des diverses saisons fait également l'objet d'une évaluation et on le compare avec les frais actuels d'exploitation d'un moteur diesel servant au même objet. On a établi que tandis que le coût de pompage de 1 000 gallons d'eau (4540 l) avec le moteur diesel actuel est de l'ordre de 28 nPs, ce même coût, avec la génératrice éolienne, ressort à une valeur comprise entre 5 et 10 nPs.

A METHOD FOR IMPROVING THE ENERGY UTILIZATION OF WIND-DRIVEN GENERATORS, AND THEIR OPERATION WITH CONVENTIONAL POWER SETS

J. G. Walker *

Among the natural forces that man can attempt to utilize, wind possesses the peculiarity of being reasonably easy to harness when the power demand is small. When wind power plants have been designed for higher power ranges, however, difficulties have been encountered which have not even yet been overcome completely, and economically.

Given unlimited time and money there remain very few problems that are insurmountable, but, for wind power to compete on a cost basis with steam or diesel-driven electricity generating sets, it is essential that the proposed installation be planned thoroughly from the outset. A detailed study of the area is required before a wind power plant is erected, in order to ascertain the most favourable site for the machine. Special regard should be made to local topography and then, from the site chosen, accurate wind records must be obtained over a period of at least a year. This will enable a wind-driven generator, having the most suitable characteristics, to be operated economically.

The records obtained should provide the potential user with the annual average hourly mean wind speed for the site and thus sufficient data to enable the velocity duration curve to be drawn. Tests carried out by the Electrical Research Association on medium-sized machines have shown that a reasonably accurate power coefficient (or efficiency) characteristic can be estimated for a given plant. Knowledge of this characteristic, together with the information obtained from the wind records, will enable an assessment to be made of the annual amount of energy available at the chosen site and, thus, the cost per unit of this energy (1).

The importance of full utilization

To enable the cost per unit of the energy produced to be kept as low as possible, it is essential to utilize, fully, the output from the wind-driven generator. In particular, utilization of the power available between "cut-in" and rated output should be catered for.

Thus, to follow the ideal power output-wind speed characteristic of the plant over the complete operating range, the connected load should be infinitely variable. In practice, however, when supplying the needs of a large farm or small isolated community, this infinitely variable load is almost impossible to achieve. It is therefore necessary to divide the total electrical load on the wind power system into as many small units as possible. These smaller loads can then be switched in and out of circuit in an endeavour to match the power in the wind.

Past experience shows that a fraction only, at best perhaps half, of the energy potentially available from the wind-driven generator is usefully employed if the loads are switched manually. When only limited storage is available, it is essential that the loads be switched automatically, to ensure that all the energy available is put to some useful purpose whenever it chances to occur. Such an automatic system has been developed and constructed by the E.R.A. for use with a 7.5 kW Allgaier wind-driven generator (System Dr. Hütter), when the plant is used to supply the electrical needs of an isolated household (2).

Automatic load control and load selector

The automatic control system for the complete installation was designed to be operated by a non-technical user and, at the same time, to give the user full control over the selection of the priorities of the various loads.

The load-distributing device, operating on variations in the voltage of the wind-driven alternator, consists basically of a moving coil relay supplied, through a rectifier, from this alternator. Increases or decreases of alternator voltage cause the moving contact of the relay to energise and operate a small motor which drives, through gearing, a series of 28 cams (figure 1). The cams are arranged to close one micro-switch for every 6 degrees of shaft rotation. A single pole supply, taken from the three phase busbars, is fed, via the micro-switches, to a vertical row of 28 sockets. The number of cams, micro-switches, sockets, etc., is entirely dependent upon the number of installed loads, one complete circuit being required for each load. The sockets are so connected that an increase in the output voltage — and therefore power — of the wind power plant causes them to be energised in an ascending order, a decrease in output voltage de-energising them in the reverse order.

Each load contactor operating coil has one pole connected to the a.c. busbars, the other being connected to a suitable plug marked with the name of the

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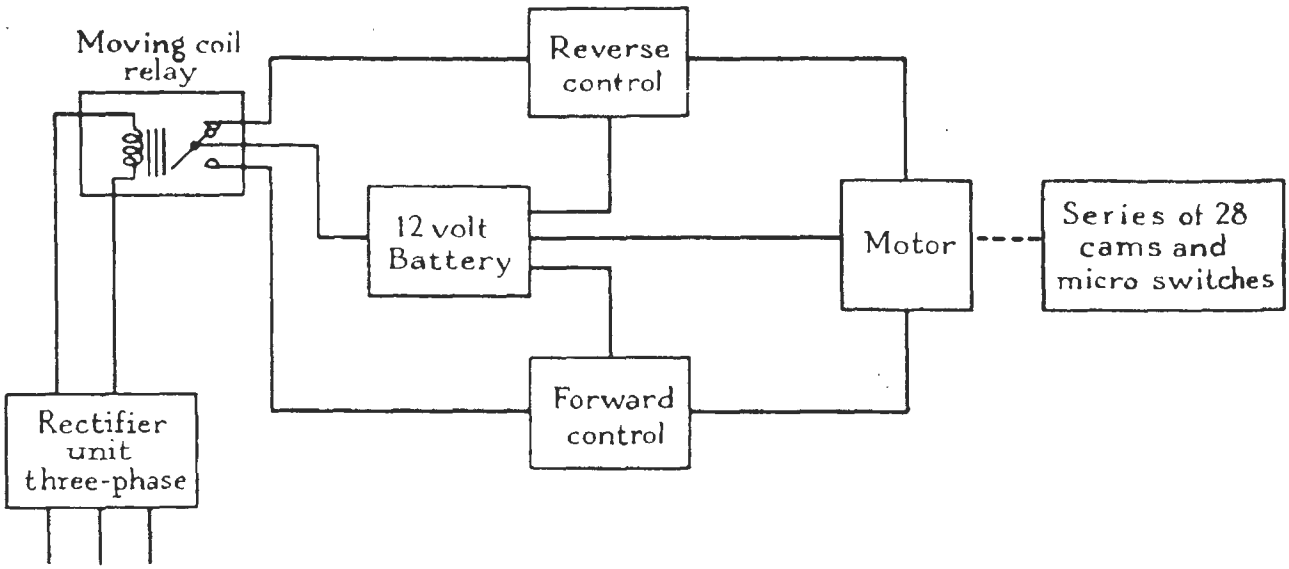

Figure 1. Schematic diagram of load regulator

load connected to it. By inserting the plugs into the vertical row of sockets, the operator can select at will the order in which the loads are to be connected to the supply as the energy becomes available (figure 2).

The windmill itself, being entirely automatic in operation, allows the complete plant, including selection of the load priorities, to be under the control of a non-technical user. The types of loads connected to the E.R.A. wind power installation, together with their installed capacities, are shown in table 1.

The basic design of the load-selector system described above can be applied to any type of medium-sized machine up to, say, 50 kW capacity, provided that the rating and number of load contactors, micro-switches, etc., is adjusted to suit any specific requirement. It should be mentioned here that the speed of operation of the motor-driven cams is entirely dependent upon the type of loads connected to the supply. If the loads are purely resistive — heating loads, etc. — the frequency of contactor operation, as governed by the moving coil relay is, in the limit, dependent only upon the variations in wind speed that can be followed by the installation. If, however, motor loads are connected to the supply, the frequency of switching should not exceed the maximum recommended number of starts per unit time as given by the motor manufacturer. The control system can be used with various types of wind power plant. The Allgaier type of machine, having either variable pitch blades and centrifugal governor system for speed control or the fixed pitch stalling blade type of machine where the connected load acts as the overspeed control, can in either case be fitted with the load selector.

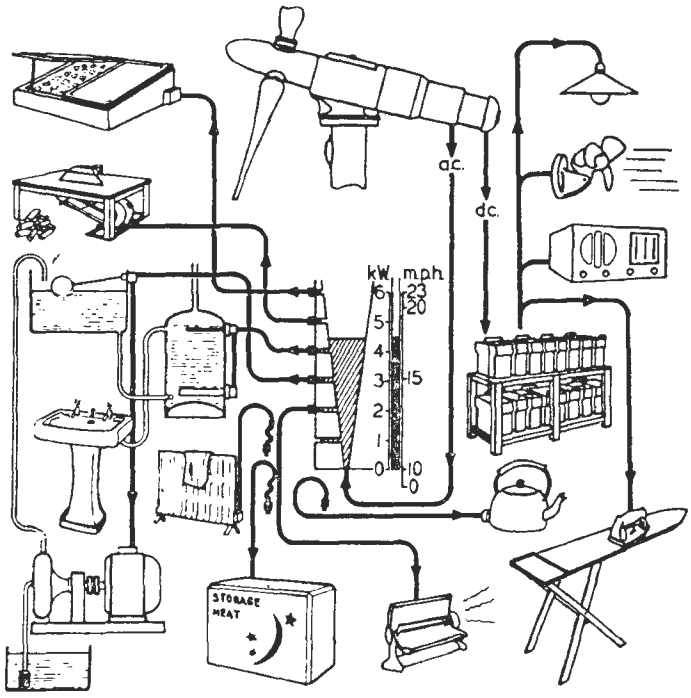

Figure 2. Arrangement of services using load selector

Auxiliary power supplies

The wind power plant was backed, in the E.R.A. installation, by a small 240 volt lead-acid battery having a capacity of 20 amp-hrs. This battery was installed to provide firm power for such loads as lighting, ironing, radio, refrigeration, etc., these loads being termed "on demand" loads to distinguish them from those which can only be supplied when the windmill is operating. In order to allow for excessive periods of calm and, should it occur, mechanical failure of the windmill, a 2 kVA, three phase alternator, together with a 2 kW, 240 volt d.c. generator, were installed. These two stand-by machines were coupled to a 5 hp diesel engine. In the installation described, it was found necessary to have the stand-by alternator to provide power for the water pumping plant during periods of calm weather. Due to the

Table 1

Situation	*Type of load*		*Installed rating (watts)*
Bedroom 1	Tubular heaters,	1 ph., a.c.	720
Bedroom 2	Tubular heaters,	1 ph., a.c.	720
Bedroom 3	Tubular heaters,	1 ph., a.c.	360
Front room	Tubular heaters,	1 ph., a.c.	720
Office	Tubular heaters,	1 ph., a.c.	720
Living room	Reflector fire	1 ph., a.c.	750
	Immersion heater	1 ph., a.c.	3 000
Bathroom	Tubular heaters	1 ph., a.c.	540
Attic	Tubular heaters	1 ph., a.c.	660
Linen cupboard	Tubular heaters	1 ph., a.c.	180
Water tank cupboard	Tubular heaters	1 ph., a.c.	180
Diesel engine shed	Tubular heaters	1 ph., a.c.	240
Control room	Tubular heaters	2 ph., a.c.	480
Garage	Storage heater	3 ph., a.c.	1 500
Soil warming No. 1	Heating wires	3 ph., a.c.	300
Soil warming No. 2	Heating wires	3 ph., a.c.	300
Water pump	1.25 h.p. motor	3 ph., a.c.	1 200
Saw bench	1.75 h.p. motor	3 ph., a.c.	1 450
Main dwelling	Lighting	d.c.	1 000
Main dwelling	Ironing	d.c.	450
Main dwelling	Radio	d.c.	75
Main dwelling	Extractor bars	d.c.	50
Outside buildings	Lighting	d.c.	600

small capacity of the water tanks already on the site chosen for the experiment, sufficient water storage was not available to cater for these calm periods.

Stand-by plant of the conventional type, when connected to an automatic system should, obviously, be arranged to start under two main loading conditions. These are low battery voltage, indicating a discharged battery, and excessive battery discharge on load.

Should the battery voltage fall below the normal discharged value, as might occur in prolonged periods of calm, a voltage sensitive relay should operate to start the diesel set. This relay can be reset to stop the set, by the action of a special type of ampere-hour meter, registering on battery charge only. The type of meter installed should be fitted with a dial marked off in Ah. A small, manually adjustable pointer allows a preset number of ampere-hours — dependent upon the battery capacity and the wind régime of the site — to be set against the dial. When the battery has received the charge indicated, contacts inside the meter close momentarily and reset the voltage sensitive relay, thus stopping the diesel set. The meter contacts reset automatically for the next operating sequence.

This type of meter enables the operator to find the minimum battery charging period required for any particular site and installation, with a consequent saving in diesel fuel. However, should the wind rise during the battery charging period, the windmill and diesel-driven generator will run in parallel to charge the battery, the diesel set shutting down when the indicated charge has been reached.

In order to prevent a heavy battery discharge, as might occur if most of the d.c. loads in table 1 were switched on at the same time, a differential current relay should be fitted. This relay must be arranged to operate when the load current is greater than the windmill output current by a preset value. This difference would, naturally, be supplied by the battery. When the battery discharge is greater than the preset value, the differential relay will operate to start the stand-by set. A time delay mechanism should also be incorporated in this circuit, to prevent the diesel set starting up on momentary overloads. This latter control assumes the use of a small capacity battery. The d.c. control circuit diagram for the E.R.A. installation is shown in figures 3 and 4. Figure 4 also shows the wiring arrangement for the water pumping plant. It will be noted that only one of the stand-by generators is connected to an electrical load at any one time. This was done to enable a diesel engine having a much smaller rated output than 5 h.p. to be installed at a later date.

Results obtained with automatic load control

During a test period covering 5 months of continuous operation, the total energy output from the windmill was 4 510 kWh. From the records of wind speeds which occurred during this period and from a knowledge of the maximum power output of the machine in different wind speeds, an estimate can be made of the maximum potential energy output which could have been obtained. Using the method outlined in reference (1), this estimate was found to be

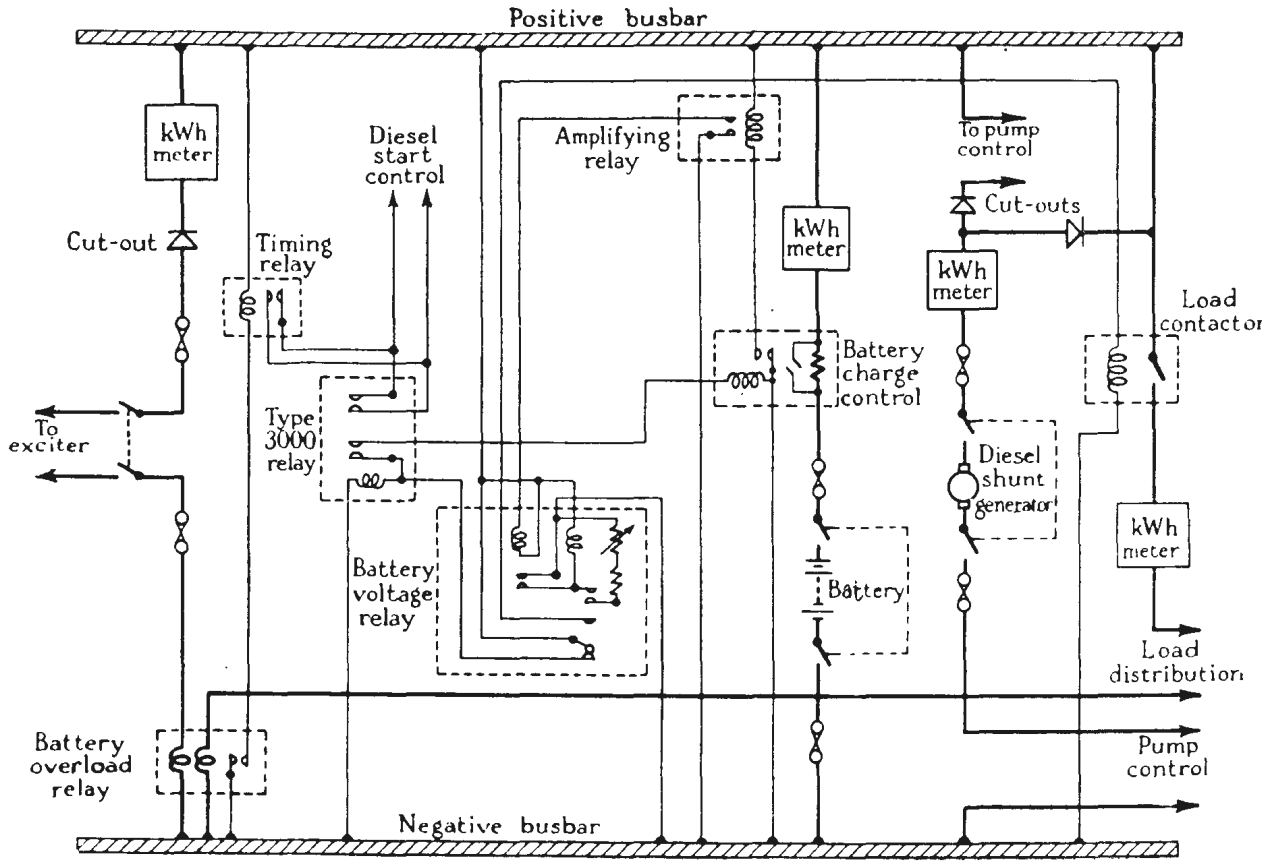

Figure 3. D.C. system circuit diagram

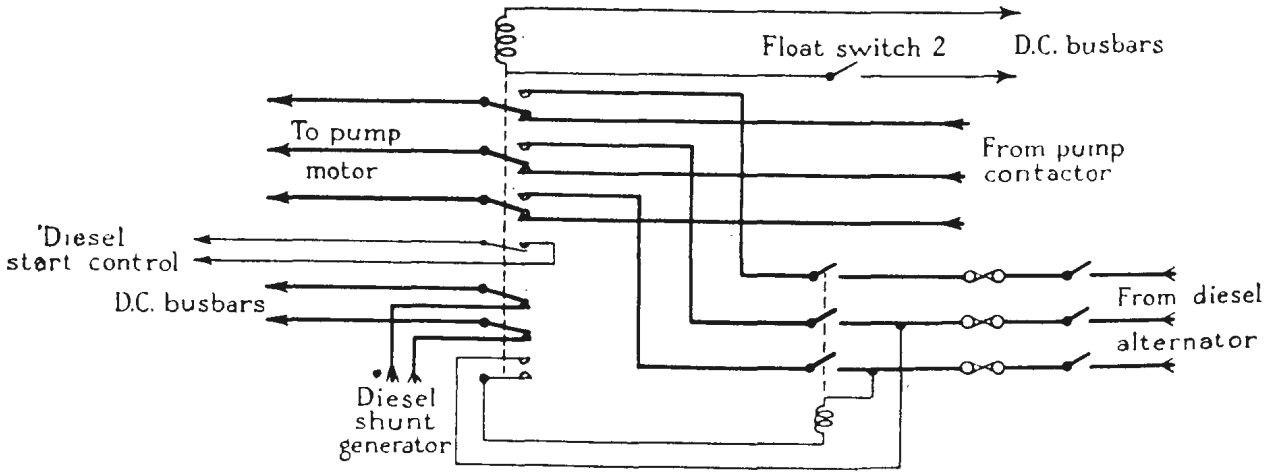

Figure 4. Water pump motor control circuit diagram

4 400 kWh which compares very favourably with the experimental result.

Of the total energy used by the household during this period, the diesel set was called upon to supply only 1.4 per cent. This percentage is remarkably low when it is considered that the annual average hourly mean wind speed for the site was only 3.8 metres per second, whilst the rated output of the 7.5 kW wind power plant occurs at 10.3 metres per second.

Need for careful planning

Both the diesel set and the 20 Ah battery were available before the installation was finally planned and, further, on the site selected for the tests, water storage tanks were already installed. It was therefore necessary to fit these items into the final scheme, irrespective of their exact suitability. Operational experience of the plant has shown that, using suitable storage tanks, the stand-by alternator could have been

omitted from the scheme. If the capacity of the water storage tanks could have been increased to 700 gallons (3 200 litres) from the original 175 gallons (800 litres), the windmill alone could have supplied all the energy required for water pumping duties.

At the site in question, increasing the battery capacity to 40 Ah would, almost certainly, obviate the need for a stand-by battery charging set. To cater for emergencies, however, it is necessary, when the installation is used to supply the needs of an isolated community, to have some form of small stand-by set. This could take the form of a portable, petrol-driven generator, having a capacity of, say, 1 000-1 500 watts. This unit, being portable, would serve many uses, other than that of battery charging only.

It has been stated by various authors that the capital cost of storage batteries, together with their limited life, precludes their use with wind power installations of medium size. This only applies if provision is made to store the full energy output of the windmill. It is necessary, if "on demand" loads are to be supplied, to include in the installation either a battery or stand-by set. Knowledge of the capacity and duration of the "on demand" loads, together with a detailed record of the wind régime at the site, govern the size of storage battery needed. Wind records are required to estimate the power that would be available for battery charging. The modern station type battery, given reasonable maintenance, would have a probable life of 10 years. With expert maintenance and close battery charge control, this life could be extended to over 12 years.

Costs of installation

A reasonable figure for the cost of a 7.5 kW, fully automatic installation, as described in the foregoing paragraphs, should be in the region of £1 800 or less, when based on a probable production quota of 200 units. Of this initial cost, some 20 per cent would be required for the battery.

To enable a comparison to be made between the cost of the energy produced by a wind-driven plant and that produced by conventional means, three distinct facts must be shown. These are:

(*a*) The capital cost per kW of the installed capacity,

(*b*) The annual energy output expressed in kWh/annum/kW, and

(*c*) The percentage of the capital charges required to cover interest, depreciation and maintenance.

Assuming an annual energy output of 1 415 kWh/annum/kW — as obtained from the E.R.A. experimental unit — and a capital cost for the plant of £1 800, a reasonable figure for the annual charges would be in the region of 12 per cent. From these figures the cost per kWh can be obtained and is, in fact,

$$\frac{12}{100} \times \frac{1\,800}{7.5} \times \frac{1}{1\,415} = £0.0203 = 4.87 \text{ pence.}$$

It should be remembered here that the figure for the "specific output" of 1 415 kWh/annum/kW has been obtained from a site having an annual average hourly mean wind speed of only 3.8 metres per second. A comparable figure for the annual energy output — using the same installation — at a site having an average wind speed of 4.3 metres per second, would be 1 810 kWh/annum/kW. Assuming the same capital costs and annual charges the price, per unit, of the energy produced would now be 3.6 pence per kWh. Thus, for an increase in the annual average hourly mean wind speed of only 0.5 metres per second, the energy cost per unit has been reduced by over 25 per cent. This further emphasises the need to survey accurately any area in which it is proposed to establish a wind power site.

General maintenance and operation

If it is essential that the complete wind power installation be made fully automatic in operation, it will be necessary to obtain the services of a skilled electrician to maintain the plant. However, should the unit be used to supply a small community, only the load distributing device need be automatic. The diesel set can be operated manually, as and when desired, by a member of the community who, apart from undertaking part-time duties, would be required to maintain the plant. Fully automatic operation combined with skilled maintenance, when compared with semi-automatic operation and semi-skilled maintenance, will again influence the capital cost of the plant.

Other considerations

In arid and semi-arid areas, water pumping for irrigation will, obviously, be the main duty of the wind power plant. A large tank or reservoir, giving a head of water of about 30 metres, would, except for a small battery, be the only form of storage required. The wind power plant would be used solely to drive the submersible or surface pumps supplying the reservoir. The main "draw off" pipe from the reservoir would feed water to a small hydro-electric set, before being distributed to the areas requiring irrigation. Thus, irrigation carried out during the night would have the dual advantage of greatly reducing water losses due to evaporation and also, via the hydro-electric set, of providing electrical power when it is most needed. When considering evaporation during daylight hours, a thin film of oil on the surface of the water would obviate the need to totally enclose the reservoir. This would, obviously, reduce the initial cost considerably. Experiments carried out in Australia, using eucalyptus oil, have proved quite successful.

In the preceding paragraphs, emphasis has largely been placed on an installation in which the wind power plant is the main supplier of energy, the conventional power sets being used only during periods of calm. This form of application would

apply, in the main, to windmills having a capacity of up to 25-30 kW. For larger communities, requiring an installed generating capacity greater than 30 kW, the wind power plant would be called upon to act as a "fuel saver" for the main conventional generating plant.

Another point relevant to the type of installation considered is the need or otherwise for voltage regulation of the wind-driven generator output. The load selector described above worked on an average voltage swing of plus or minus 30 volts about a nominal 380 volts. A more modern moving coil relay could reduce the voltage tolerance to, say, plus or minus 10 volts. However, when considering a windmill having a synchronous alternating-current generator, supplying resistive loads, the voltage and frequency at which these loads can be supplied is dependent, only, upon their maximum rating. Further, if induction motor loads are supplied, voltage *and* frequency variations are again of less consequence than has previously been supposed.

As it is desirable, from efficiency and power factor considerations, to maintain an almost constant flux density in the iron of the induction motor, it is necessary that any change in voltage is accompanied by a proportional change in frequency. It will be realised that the required change in voltage and frequency can easily be obtained from the alternator of the wind power plant. To effect this proportional change, it is necessary to keep the excitation of the alternator as near constant as possible. An over-sized alternator exciter controlled by, say, a carbon pile regulator, enables this constancy of excitation to be attained. It is realised that with the above system the variations of the supply will be too great for those loads requiring a fixed voltage. A small magnetic transducer, however, can be incorporated in, say, the battery circuit, to produce a constant voltage battery charging supply. This constant voltage method of charging will again have the effect of prolonging the battery life.

It has been shown in the preceding paragraphs that before any wind power installation is contemplated, it is essential to plan carefully every detail of the unit. Wind power plant working in isolation, with or without backing from conventional power sets, is far more susceptible to economic considerations than that designed for feeding into main networks.

References

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Summary

Before any wind power installation is finally planned, it is essential to carry out a careful survey of the area in which the plant is to be erected. Not only is it necessary to obtain accurate hourly mean wind records for the chosen site, preferably over a period of at least a year, but also an advance knowledge of the loads, degree of storage required, etc., is needed.

The size, or capacity, of the "on demand" loads which are essential and for which the supply must be continuous, is a critical factor in deciding the size of the storage battery. A further factor governing the size of this battery, is the average duration of calm spells during which the "on demand" loads must be supplied. Provision for charging this battery during excessive calm spells must also be made.

The maximum utilization of the power available in the wind is of the utmost importance, if the cost of energy produced by the wind power plant is to be competitive with that produced by conventional means. An automatic load distributing device is described, which gives the operator complete freedom of load selection and priority, and enables the energy in the wind to be utilized whenever it becomes available.

Results obtained when using this device, in conjunction with an experimental installation, are referred to. The installation, consisting of a 7.5 kW Allgaier wind power plant, diesel-driven generators and storage battery, was completely automatic in operation. A special form of battery charge meter, controlling the operation of the diesel set, is described.

An accurate choice of the site for any proposed wind power installation is shown to be important. An increase in the annual average hourly mean wind speed of as little as 0.5 metres per second, can reduce the cost, per unit, of the energy supplied, by over 25 per cent.

The effects on the capital cost of a fully automatic plant employing skilled labour for maintenance, as opposed to semi-automatic operation employing semi-skilled part-time labour, should be considered.

A further consideration is the role played by the wind power plant, either as the main supplier of

energy, or, when used solely as a "fuel saver", backing up a conventional power generating set.

The need for voltage regulation is not as essential as was once supposed. The upper limit of voltage applied to a resistive load depends only upon the rating of that load. Further, induction motors will accept variations in voltage *and* frequency up to at least 30 per cent of their nominal rating.

MÉTHODE PERMETTANT D'AMÉLIORER L'UTILISATION D'ÉNERGIE PAR LES GÉNÉRATRICES ENTRAINÉES PAR AÉROMOTEURS ET LEUR INTÉGRATION DANS DES SYSTÈMES CLASSIQUES

Résumé

Avant que l'on passe aux derniers stades d'établissement des projets de centrales éoliennes, il est essentiel de procéder à une étude serrée de la région dans laquelle on doit la construire. Il ne faut pas seulement établir des moyennes horaires exactes des données anémométriques au lieu choisi, de préférence sur une période d'un an au minimum. Il faut connaître d'avance les charges, le degré d'emmagasinage cherché, etc.

L'importance ou la capacité des charges « instantanées » qui sont essentielles et pour lesquelles la fourniture d'énergie doit être continue, est une exigence impérative quand il s'agit de décider de la taille de la batterie. Un autre facteur ayant trait aux dimensions de la batterie est la durée moyenne des périodes de calme pendant lesquelles ces charges « instantanément exigibles » doivent être fournies. On doit également prévoir le moyen de charger la batterie pendant les périodes de calme d'une durée exagérée.

La pleine utilisation de l'énergie éolienne est d'une importance capitale si le prix de la force motrice qu'elle représente doit pouvoir faire concurrence à celle qui est fournie par d'autres moyens. On décrit un dispositif automatique de répartition de la charge, qui donne pleine liberté de choix de charge et de priorité à l'opérateur et permet la pleine utilisation de l'énergie éolienne chaque fois qu'elle se manifeste.

Les résultats obtenus au moyen de ce dispositif font l'objet d'une mention, en liaison avec une installation expérimentale. L'installation, constituée par une centrale éolienne Allgaier de 7,5 kW, de groupe diesel-génératrices et d'une batterie d'accumulateurs est complètement automatique quant à son fonctionnement. On décrit une forme spéciale d'indicateur de charge de la batterie, servant à la surveillance de la marche du diesel.

On indique l'importance du choix exact de l'emplacement de toute centrale à énergie éolienne. Une augmentation de la vitesse moyenne horaire annuelle du vent ne dépassant pas 0,5 m par seconde peut réduire de plus de 25 p. 100 le coût unitaire de l'énergie fournie.

Les répercussions sur les frais de premier établissement de l'emploi d'une centrale totalement automatique faisant usage d'un personnel spécialisé pour l'entretien du matériel, en lieu et place d'une installation semi-automatique faisant usage d'ouvriers semi-spécialisés et travaillant une partie du temps seulement, doivent être prises en considération.

Une autre considération a trait au rôle que joue la centrale éolienne, soit comme source principale d'énergie, soit simplement comme moyen d'économiser du combustible en fonctionnant comme renfort à un groupe classique.

Le besoin de régulateurs de tension est moins impératif qu'on ne l'avait supposé. La limite supérieure de la tension que l'on doit appliquer à une charge constituée par une résistance pure ne dépend que de cette charge. Au surplus, les moteurs à induction tolèrent des variations de tension et de fréquence allant jusqu'à 30 p. 100 au moins des valeurs spécifiés.

UTILIZATION OF RANDOM POWER WITH PARTICULAR REFERENCE TO SMALL-SCALE WIND POWER PLANTS

J. G. Walker *

Wind power, when used for the generation of electricity, has the great advantage of a free and inexhaustible supply of energy without the problems of production, transport or storage of fuel, associated with conventional generating sets. A very obvious disadvantage is the uncertainty of power being available at any given time. When the wind-driven generator is the sole source of power, some form of storage for the energy generated is essential, to ensure continuity of supply and to take full advantage of the wind throughout the year.

Small wind power plants, varying in capacity from 250 watts to around 2 or 3 kW, have been available commercially for some years. These plants operating in parallel with 12, 24, 32 or 110 volt batteries have been used to supply domestic needs, requiring only small power.

Installation

The effective operation of a wind-driven generator when used in conjunction with full battery storage is dependent upon many factors. Unlike medium-sized sets, these smaller installations utilizing direct current generators operate at low voltages. This fact, combined with the low power capacity, must limit the choice of site available and implies that the generator must be sited as near as possible to the load being supplied.

To illustrate this point, consider a 1 000 watt generator having a terminal voltage of 24 volts, the full output current thus being 41.5 amperes. If a cable having a cross-sectional area of 14.5 sq mm is used to carry the current for a distance of, say, 50 metres, the voltage drop would be of the order of 5.6 volts. The resulting power loss is thus 23 per cent of that generated. Use of a more heavy cable would reduce the figure for the power loss, but would also increase the over-all cost of the installation.

A further point is the height above ground, at which the windmill should be erected. The most suitable height, in order to clear surrounding obstructions to wind flow, would be of the order of 10 to 15 metres. However, the cost of such a tower and foundations might easily cancel out the benefits obtained from a higher energy output. It is thus apparent that, as with all wind power installations, an examination of each particular site is necessary to ascertain the most suitable type of plant to be erected.

Operating characteristics

In order to minimize both the cost and physical size of the generator unit, it is essential that it should be driven at a high rotational speed. Generators having propeller diameters of 1.75 to 3 metres, can be designed for high rpm thus cutting out the need for gearing. The limit to the rotational speed is set by the maximum allowable blade tip speed. As the speed of the plant varies with wind speed, a point is reached at the rated output of the generator when some form of governing mechanism is required to limit the output.

When considering the performance of small battery charging sets, three main characteristics must be compared. These are:

(*a*) The blade characteristic;

(*b*) The generator-load characteristic, varying with rotational speed;

(*c*) The battery load characteristic.

The power characteristics, for a 2 metre fixed pitch wooden propeller, at different values of wind speed, are shown in figure 1. Assuming, for this discussion, an efficiency for the plant of 100 per cent, then, the power output from the blades — which will be equal to the generator output — should follow the "maximum watts line" shown in the figure. The curve of actual generator output is seen to be far to the right of the maximum watts line. For a high efficiency to be obtained in practice, it is clear that the blade and generator characteristics should be more closely matched. The generator input curve, however, should not approach the maximum power line too closely, in order to avoid the possibility of stalling.

The aerodynamic efficiency of the blade system depends upon the "tip speed ratio", that is — the ratio of the peripheral speed of the blade tips to the velocity of the wind through them. This efficiency reaches a maximum at a particular value of the ratio, depending upon the blade design. It follows, therefore, that to maintain the optimum efficiency, it is necessary to operate the plant at a rotational speed which bears a continuously fixed relationship to the wind speed.

When a shunt generator is used, connected to a battery, a large increase in output current will

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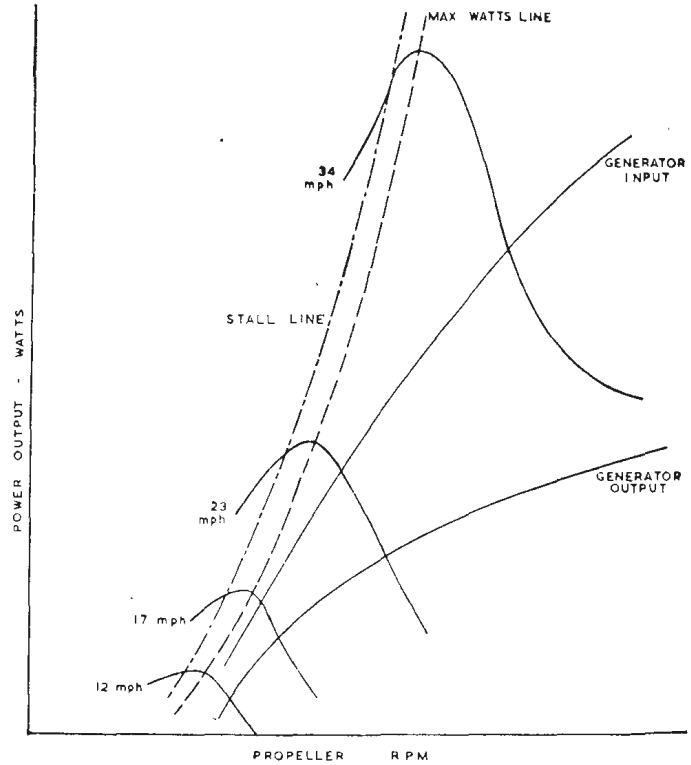

Figure 1

occur for a small increase in rotational speed. This can be seen from the shunt generator characteristics shown in figure 2 on which the battery characteristics for the fully charged and half charged conditions are also shown. It will be noted that at the half charged battery condition, a 25 per cent increase in generator speed from 0.8 N to N, increases the charging current from 3 to 18 amperes. Since the battery terminal voltage rises only slightly with charging current, the increase in generator output current from 3 to 18 amperes is due, almost entirely, to a proportionally small rise in rotational speed. The sixfold increase in power naturally assumes that power is available at the blade. This fact tends to show that a plain shunt generator does not lend itself to efficient matching with the blade system. For this reason, a generator with a more steeply drooping characteristic is preferable and can be either a three-brush or negatively compounded machine.

With small-scale wind power installations working in conjunction with battery storage, current can only be supplied to the battery when the voltage of the generator exceeds that of the battery. A certain minimum wind speed, the magnitude of which depends upon the design of the plant, is thus essential before the generator can "cut in" to supply power to the battery and load circuits. Further, it would be uneconomical to design wind power plants to take advantage of very high wind velocities that may only occur for a few hours each year. Thus, operating limits of wind speed are set for the "cut in" and "rated output" values, depending on the probable wind regimes likely to be encountered. The lower limit of wind speed is governed by the value at which the generator voltage exceeds that of the battery, the upper limit being controlled by some form of governor mechanism.

The function of the governor is to reduce the efficiency of the blade system in such a way as to try and maintain the rated output power at a constant level. This governing action does not normally come into operation, suddenly, as the rated output wind speed is reached, but acts gradually on the blade system, taking over full control at or about rated output. The governor thus influences, to a certain extent, the efficiency of the blade system within the normal operating range.

When considering small sets up to, say, 750 watts capacity, it is worth noting here that the increased efficiency brought about by well designed blades, under compounded generators, etc., can only be obtained with an increase in capital costs. The source of energy being free, a small increase in propeller diameter can easily be made to offset reduced efficiency. It will be realised, from the foregoing paragraphs, that the over-all efficiency of the wind power plant involves not only the individual characteristics of the blade system, generator and battery, but also their relationship to one another under different operating conditions. With wind power installations having a capacity of 1 000 watts or more, considerations of efficiency and utilization become more important.

As the capacity of the wind power generator increases, so also must the diameter of the blade system. In order to keep the tip speed at a safe value, the rotational speed of the blades must be reduced. If, at this lower rotational speed, direct coupling were used between the wind rotor and the generator, the plant could become extremely costly, due to the increased physical size of the generator. A design point will be reached where the cost of the gear box — high speed generator combination, is much less than that of the slow speed generator alone. Again, with increased capacity and therefore, capital cost,

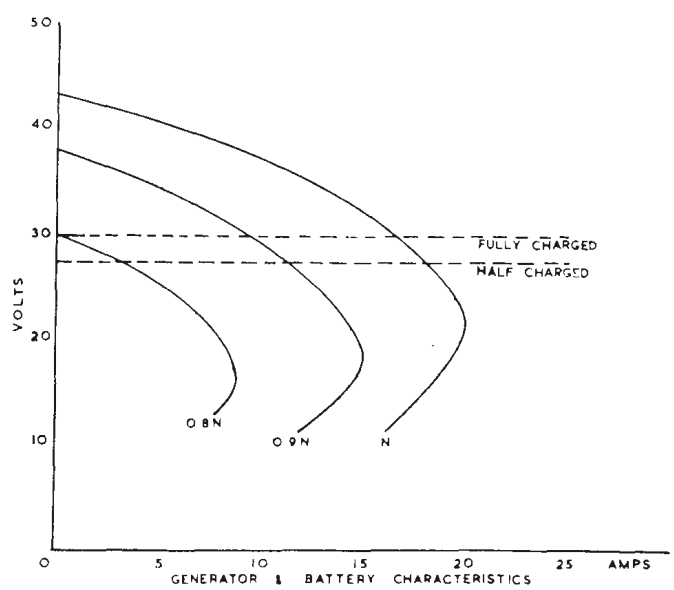

Figure 2

the amount of energy usefully employed will have an important bearing on the cost per kWh. With larger machines full utilization of the energy, as and when it becomes available, is of the utmost importance economically. A fully automatic device — for use with medium-sized wind power plants — ensuring the best utilization of the energy available, has been described above (paper W/18). Although, with small wind power sets, the need for a completely automatic load connector and selector unit is not justified economically, some method should be considered whereby the energy available in the wind below the "cut in" point, can be made use of.

Directly connected loading

When the wind-driven generator is connected to a battery, via a cutout, no power is supplied to the battery until the generated voltage is sufficient to close this cutout. If, however, a directly-connected resistor element is connected to the machine in place of the battery-cutout arrangement, power is dissipated in this resistor as soon as the machine commences to generate. If the value of the resistor is carefully selected, good matching between the propeller and load should be possible. This is especially true at low wind speeds. To obtain this efficient matching, the output characteristic of the generator and load combined should lie just below the maximum power line of the propeller output characteristic. The minimum value of load resistance must not, however, approach the critical value of external resistance which will allow the generator to excite and supply the load. Ideally, a knowledge of the output characteristics of the propeller is required, but as these are not generally available, experiments will be necessary with trial values of resistance.

To estimate a suitable value for the resistor element, the output power of the generator when connected to a battery should be noted for different values of wind speed. These readings can be obtained from indicating instruments, the values obtained serving only as a guide. The value for the equivalent resistor to dissipate the same power under the same wind conditions can thus be calculated and connected in place of the battery. By gradually reducing the value of resistance, a point will be found at low wind speeds when stalling of the blades will occur. Increasing the value, until stability is re-established, will give a fairly accurate figure for the final resistance value. This value may be of the order of 1 or 2 ohms depending upon the type and size of shunt generator used for the tests. A necessary precaution with the above arrangement is the need to wire the resistor element with several paths in parallel. This is to protect the blade system from severe over-speeding, should part of the element fail electrically.

During tests carried out with a resistor element, the value of which was obtained by the method described above, water in a small tank of 25 litres capacity was heated to a temperature of 50°C to 80°C, whereas under normal operation no power would

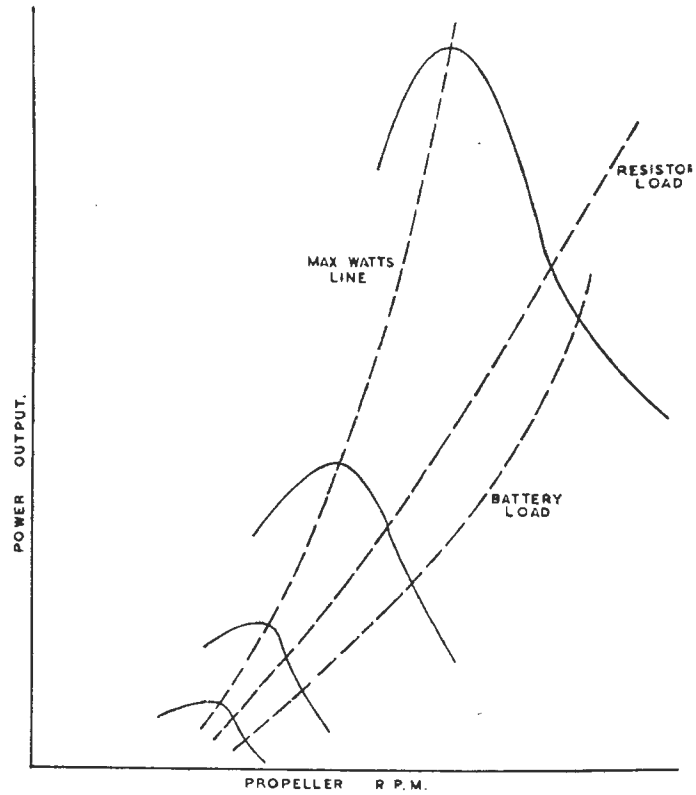

Figure 3

have been fed to the battery. Although such a heater could serve as an additional load to the normal battery installation, the most simple and efficient arrangement results when it is the only connected load. Figure 3 shows the resistor load and battery load characteristics, super-imposed on typical output characteristics for a fixed pitch propeller. The system could be divided into a small-capacity, fast heating unit in, say, the kitchen and a larger capacity unit elsewhere. Thermostatic control on the smaller unit could be arranged to switch the wind power plant to the large unit, when the preset temperature has been reached. A manually operated switch would be used to connect either the battery or the water heating unit to the windmill. A load, such as the water heater, has the added advantage of being able to replace the battery as the generator main load. It can thus used to prevent overcharging of the battery and, therefore, help to prolong the battery life.

Planning an installation

When deciding the size of generator and battery that would be required for a particular installation, the two most important factors are:

(*a*) The average value of connected load;

(*b*) The average duration of calm spells, likely to occur at the site.

It would be preferable to obtain accurate wind records for the site, taken over a considerable period of time, in order to ascertain the duration of the

calm spells. However, if this procedure is impracticable, Meteorological Office records will give a fair indication of the wind speeds and calms to be expected in the region. In this context, a calm refers to periods during which the wind speed is too low to allow the battery to be charged. An assessment should be made of the loads likely to be connected at any one time, together with their probable duration.

If, for example, a site situated in, say, northern Europe is considered, the following figures might apply. To allow for the maximum duration of loading, requirements during the winter months are examined. Naturally, in summer time and more southerly latitudes, the times for which the loads are required will be considerably shortened.

	Watts
Main room, lighting	100
Radio	40
Secondary room, lighting	60
	200

Assuming "time on" for the main room to be 7½ hours per 24 and the secondary room 3½ hours per 24, then the total load is 1 260 watt hours. During the winter months, in northern latitudes, the average period of calm would be of the order of 2 days. Thus, full storage for this period would be 2 520 watt hours. The battery capacity for various voltages is therefore

	Ampere/hours
At 12 volt	210
24 volt	105
32 volt	79
50 volt	50
110 volt	23

Assuming a battery ampere-hour efficiency of 80 per cent and, if the battery is fully discharged and the wind speed is such that charging can only take place for 8 hours out of a period of 48, then, the actual battery capacities and charging currents are as follows:

Volts	*Ampere/hours*	*Amperes*
12	260	32.5
24	130	16.25
32	100	12.25
50	62.5	8.0
110	29	3.6

The capacity of the wind-driven generator is thus 400 watts. If the overall efficiency for the generator and blade system is taken as 18 per cent, rated output of 400 watts would be obtained with a machine having a 1.8 metre diameter blade, at a wind speed of 12.5 to 13.5 metres per second.

It should be realised that the figures quoted in the preceding paragraph, although remarkably accurate, are intended only as an example. It may be, with a particular installation, that the lighting requirement differs from that quoted, thus altering the capacity of the battery. Calm spells, having a duration greater than 2 days, would, again, need a battery in increased capacity. Also, no provision has been made for the change in battery voltage between the limits of charge and discharge. Should the rated wind speed of 12.5-13.5 metres per second to be too high for the particular site, the same output of 400 watts could be obtained from a similar machine having a 2.75 metre diameter blade system, at a wind speed of 10.3 metres per second. Again, a 3.6 metre diameter blade, operating in a wind speed of 8.5 metres per second would give the same output, assuming the same over-all efficiency.

Comparative costs

The cost of the various capacity batteries referred to in paragraph 18 are shown in table 1, together with the approximate prices for plain shunt, direct current, generators. The three design speeds of 600, 400 and 200 rpm refer to wind power units having blade diameters of 1.8, 2.75 and 3.6 metres, respectively. It will be noted, from the table, that it is essential to have a high generator speed in order to keep the cost of the unit as low as possible. Low voltages have become standard for isolated electric lighting systems which makes a more economical battery size possible. However, since the low voltage requires an increased current to provide any specified amount of power, due attention must be paid to the size and cost of the cables required, to prevent excessive volt drop. The current of a 24 volt system is 4.5 times as large as that of a 110 volt system and, therefore, the voltage drop is also 4.5 times as great. The heating effect, which is proportional to the square of the current, is thus increased twenty-fold. Table 1 also shows the comparative costs of the 600 rpm generator coupled to the blade system

Table 1. Battery and generator costs

Nominal volts	*Direct-coupled generator (rpm)*			*600 rpm generator gearbox ratio*		*Battery*	
	600 £	*400* £	*200* £	*1.5:1* £	*3:1* £	*Capacity Ah*	*Cost* £
12	46	57.5	74.5	56	60	260	96
24	44	57.5	74.5	54	58	130	112
32	43	57.5	74.5	53	57	100	117
50	42	57.5	74.5	52	56	62.5	135
110	40	57.5	74.5	50	54	30	175

via a gearbox, as against the cost of a direct coupled, slow speed generator. The use of a gearbox reduces the overall cost of the original slower speed unit by 19.5 per cent to 27.5 per cent, depending upon the voltage of the generator. The extra weight of the gearbox would be offset by the reduced frame size used for the generator. Battery costs limit the voltage of the generator to 12, 24 or 32 volts. However, the increased cost of cabling precludes the 12 volt unit and, if a costing study were undertaken for an average installation, a 32 volt system would, most probably, prove to be the least costly.

Although the average battery installation is normally of low voltage, high voltage units are often necessary when required for more specialized applications. In 1926 a wind power station was erected on the island of Neuwerk, in the Elbe estuary, to supply electricity to a tower with navigation lights, for ships sailing up the Elbe (1). The plant was fitted with an 8 kW generator feeding into a 220 volt, 440 Ah battery.

In the foregoing paragraphs, an attempt has been made to show the problems involved in matching the various units of a small-scale wind power installation. It is worth-while considering whether or not the small advantages gained by the use of more efficient individual units for the plant, are offset by the increased cost.

Reference

1. Baumeister, J., A Wind Power Station for the Operation of Navigation Lights., *E.T.Z.* (*B*) *Vol*, 7, No. 12, December, 1955.

Summary

Low voltage, direct current wind power plants of small power capacity are used fairly extensively to supply the domestic needs of isolated premises. The type of load that can be supplied by these wind-driven generators consists of lighting, radio, refrigeration, fans, etc., and, in the larger capacity plants, ironing and small motor loads.

Knowledge of both the wind régime of the selected site and the estimated average maximum loading for the household is required in order to fix the battery capacity.

For ideal efficiency, all the various components of the plant require perfect matching. Although this can be partly achieved by a high efficiency blade system and an under-compounded generator unit, the extra cost involved, when compared with the standard shunt generator unit, may easily outweigh the advantages gained. To enable battery and cabling costs to be kept to a minimum, the choice of voltage for a proposed system would appear to be 24 or 32 volts. Higher voltage battery installations have been used, where the special application demands this.

Voltage regulation is not normally employed on low volt installations. The use of end cells or counter emf cells is advised on high voltage batteries, to counter the effects of the wide battery voltage fluctuations between the fully charged and discharged conditions.

Better utilization can be obtained by harnessing the energy available below the "cut in" point with a directly connected load. This load could take the form of a water heater or some other form of thermal storage device.

UTILISATION DE L'ÉNERGIE FOURNIE PAR LE HASARD ET OFFRANT UN INTÉRÊT PARTICULIER POUR LES CENTRALES ÉOLIENNES A PETITE ÉCHELLE

Résumé

On fait un usage assez étendu des centrales éoliennes à basse tension à courant continu de petite capacité pour faire face aux besoins ménagers des lieux isolés. Le genre de charge auquel ces génératrices éoliennes peuvent avoir à être soumises est constitué par l'éclairage, la radio, la réfrigération, les ventilateurs, etc. et pour les centrales de plus grande capacité, le repassage et certains petits moteurs.

Une connaissance du régime des vents au lieu choisi et de la charge maximum évaluée pour la maison à fournir s'impose pour le calcul de la capacité de la batterie.

Pour que le rendement soit voisin du niveau idéal, tous les éléments de l'usine doivent être parfaitement appareillés. Bien que ceci puisse se faire partiellement avec un système de pales à grand rendement et une génératrice dont la tension baisse quand la

charge augmente, le supplément de frais à subir, par rapport à la situation qui existe avec une génératrice à excitation mixte standard, peut facilement contrebalancer les avantages. Pour permettre de réduire au minimum les frais dus à la batterie et au câblage, le choix de la tension, pour le système envisagé, semblerait s'arrêter sur 24 ou 32 volts. Des installations avec batteries à plus haute tension ont été utilisées lorsque certaines applications spéciales l'exigeaient.

La régulation de la tension n'est pas normalement employée dans les installations à basse tension. L'emploi d'éléments terminaux ou d'éléments producteurs d'une force c.e.m. est recommandé, avec les batteries d'accumulateurs à haute tension, pour amortir les effets des grandes fluctuations de la tension des batteries d'accumulateurs entre les états pleinement chargés et déchargés.

On peut réaliser une meilleure utilisation de l'énergie disponible en exploitant celle qui est fournie au-dessous du point normal où commence le débit, avec charge directe. Cette charge pourrait être constituée par un chauffe-eau ou tout autre dispositif de mise en réserve de l'énergie thermique.

DEVELOPMENTS AND POTENTIAL IMPROVEMENTS IN WIND POWER UTILIZATION

J. T. Arnfred *

Poul la Cour's laboratory tests

In 1891, Professor Poul la Cour started a series of experiments for a rational utilization of wind power for the generation of electrical energy.[1]

In 1892, a small scale experimental mill was built and in 1897, a larger one. The latter contained a well equipped aerodynamic laboratory.

Two Danish engineers, H. C. Vogt and I. Irminger, had previously been experimenting with wind power and found that the effect of the wind on a plate is not solely dependent on the thrust of the air particles against it, but also on the suction created on the other side.

Poul la Cour was the first to make experiments with an artificially created air flow and measure the wind effect on metal plates of different shapes and the air pressure at different angles between wind and plate. Through these experiments, he arrived at the elementary laws of aerodynamics: that the centre of pressure does not fall on the centre line, but a little in front of it, that the resultant pressure forms an angle with the normal of the plate, and that the greatest pressure is not achieved when the wind is at right angles to the plate, but when it falls on the plate at angles between 45° and 84°.

However, not only the pressure is of interest, but also the energy that can be obtained from the wind when the plate or the wing moves at right angles to the wind. Poul la Cour found that a plane surface moving at a speed twice that of the wind can obtain 45 gr m/sec at a wind velocity of 1 m/sec.

However, the experiments proved that the capacity was considerably greater when the plane surface was replaced by a cylindrically shaped or ridged surface where the ratio of the blade width is 1:4 and forms an angle of 165°. The capacity then reached 108 gr m/sec. As all the energy in a wind with a cross section of 1 sq m at a velocity of 1 m/sec is 66 gr m/sec a mill arm can also utilize some of the energy in the winds that flow past without hitting the arm direct.

In order more directly to test the results arrived at, Poul la Cour then constructed a series of mill models, placed them in a constant air flow and measured their energy-producing capacity. It turned out that the traditional 4-arm mill won itself a handsome position. It is impossible to obtain the same amount of energy from each sq m of vane surface. The outermost areas give the highest amount of energy, the innermost travelling at the lowest speed, the lowest amount of energy. Poul la Cour found, however that the average capacity was 60 gr m/sec per sq m of vane surface at a wing tip speed of 2.4 times that of the wind.

Poul la Cour presumed that, all other things being equal, the capacity was directly proportional to the vane surface. Later experiments proved that this was not the case. G. Eifel thus states that the vane area is to be multiplied by 1.1 when the laboratory tests are carried out with 1/10 scale models.[2]

It was obvious from Poul la Cour's experiments that propeller-shaped wings give a considerably greater capacity, but as windpower is "free" it is not decisive that the effect per sq m of the wing surface is the greatest possible. It is more important to achieve a simple, robust and dependable mill which gives the greatest possible kW-hr a year in proportion to initial and running costs. In addition, none of the windmill builders of those days would be able to construct a well-shaped propeller-type wing, just as regulation of the large expanse of wing surface in relation to the wind velocity was difficult in those days.

Therefore Poul la Cour recommended, as the most practical solution, the use of a 4-wing multi-bladed mill with adjustable blades where the length of the maximum wing surface is ¾ and the width ¼ of the total length of the wing arm. A multi-bladed mill is a mill in which the wing surface is made up of transverse wind blades forming an unbroken surface and in which the individual blades are kept in position by a counter-weight. The counter-weight is balanced so that the vane surface swings open when the wind velocity reaches the highest value which it is desirable to utilize. This regulation prevents the mill from running wild in a hurricane.

Utilization of the wind power

It was obvious that the wind power should be transformed into electrical energy, but the problem was how to store and spend the electrical energy.

At first Poul la Cour used the electric current for electrolysis of an aqueous solution of sodium hydroxide (NaOH). The developed oxygen and hydrogen

* Director of the Experimental Mill, Askov, Denmark.

[1] Poul la Cour (1846-1908), Danish physicist and meteorologist who in 1878 was attached to the extended high school of Askov as a teacher of natural science.

[2] Eifel, G., *La resistance de l'air*, page 118, Paris, 1911.

were stored in gasometers and led through lead pipes to the place of consumption. For many years before the turn of the century, a great number of rooms at Askov High School were illuminated by Drummond light, i.e., an oxyhydrogen flame directed on a zirconium cylinder emitting a dazzlingly white light. On the other hand, a satisfactory way of employing oxyhydrogen as a motive power in the internal combustion engine was not found, and Poul la Cour therefore chose to use lead accumulators and ordinary incandescent lamps.

Dansk Vind Elektricitets-Selskab (Danish Wind Power Association)

At the turn of the century there were only power stations in very few of the larger towns in Denmark, but as early as 1902 the experimental mill supplied Askov High School and most of the village with electric current. The windmill and the accumulator managed fine with an auxiliary kerosene engine for calm periods.

As many villages and large estates wished to be supplied with electric light and power they applied to the experimental mill for advice — to the man about whom popular humour said that he could turn rain and wind into light and power. In 1903 this led to the establishing by a number of well known men of "Dansk Vind Elektricitets-Selskab", D.V.E.S., which for a number of years up to 1915 published "Tidsskrift for Vindelektricitet" (periodical for wind electricity), employed an engineer and acted to a wide extent as an advisory body in matters of engineering. As early as 1907 D.V.E.S. had projected 27 wind power stations of which some, however, only catered for a single large estate.

Furthermore, D.V.E.S. held courses where young men with interest and skill qualified for "rural electricians" and attendants of small power stations.

The years before World War I saw the erection of many d.c. generators for 220 volt with a supply range of 1.5 km. The older stations used the suction gas engine as a source of power. Later on the Diesel engine made its appearance.

When the war broke out in 1914, the country ran out of fuel oil for the Diesel engines, and the interest for wind power increased.

In the beginning of the war, the experimental mill sent out a report to the rural power stations containing information about acquired experience with windmills.

In 1918, the number of rural power stations was 418, of which 120 or about one fourth had installed a windmill. After the war the number decreased again. In 1920 only 75 were left.

It may be added that the windmills of those years were used not only at the power stations, but in many parts of the country there was a windmill of wind-rose on the roof of every farm as tractive force for threshing machine, grinding mill, water pump, etc. There were many thousands of them. In 1916 alone, 1,300 new ones were built.

New mill experiments

Methods of measurement

Experience in times of war had stressed Denmark's dependence on supply of energy from outside and increased the interest for the domestic sources of energy. It was therefore decided that Poul la Cour's wind power experiments were to be continued. This time, however, it was decided not to work with models, but with real full-scale windmills to be exposed to natural wind power.

The experiments were carried out over the years 1921-24 in co-operation with "Statens Redskabsudvalg" (Government Committee on Machinery and Implements) on the one side and the experimental mill at Askov on the other.

In order to find the best-suited measuring methods, two new experimental mills were erected. One was a 4-wing adjustable multi-blade experimental mill according to la Cour's design with a wing diameter of 16 m, which was mounted on a 20 m high tower. The other was a wind-rose with a diameter of 7.6 m on a 16 m high tower.

The mills were erected at Askov at the highest point in that region with a free horizon on all sides.

Measurement of wind power proved to be done best by a cup-anemometer mounted on a pole at the same level as the mill axle and at a suitable distance from the mill. The anemometer was connected with an apparatus drawing a line on a revolving drum and putting a mark on the line every time 100 m of wind had passed. The drum made one revolution per hour, and it was then easy to read the wind force from minute to minute all around the clock.

In the same way and on the same record sheet it was possible to register the actual energy yielded by means of a kW-hr meter. From this diagram it is possible directly to read the output of the mill at different wind velocities.

If the values are marked off on a graph (figure 1) we have the characteristic of the mill. Losses in the dynamo and the transmissions must be added to the figures of measurement. These losses were measured and the overall output marked on the graph. The reason why the curve is broken at a wind velocity of about 9 m/sec is that the wind blades began to swing open at this velocity.

Of course the results were average values both as far as wind velocity and output were concerned, and wind velocity can vary much in one minute, but the interdependent immediate values were difficult to measure both because the anemometer must be placed at some distance from the mill and because the starting torque of the wing span delays the mill in accelerating to a speed similar to that of a gust of wind.

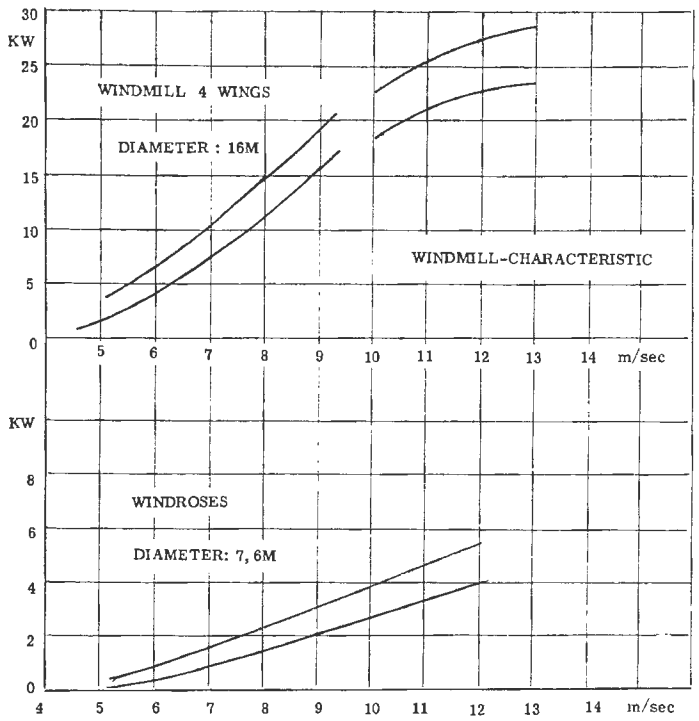

Figure 1

If the wind velocities through all the hours of the year are known, the annual production can now be calculated by means of the characteristic.

On the basis of previous wind measuring in this region, the Meteorological Office in Copenhagen stated that the following wind velocities can be expected:

5 m/sec	for 1 796 hours	at 1.2	kW
6 m/sec	for 1 080 hours	at 4	kW
7 m/sec	for 899 hours	at 7	kW
8 m/sec	for 720 hours	at 11	kW
9 m/sec or more	for 1 225 hours	at 16	kW

This should give an annual production of about 40 000 kW-hr which was also calculated by the manufacturer. The mill was started on 28 June, 1921, and operated for 105 days during which it produced 9,030 kW-hr. Proportionally the annual production would be

$$\frac{9030 \times 365}{105} = 31\ 500 \text{ kW-hr}$$

i.e., considerably below the calculations. Since, however, the average wind velocity in the months of July, August, and September according to the mentioned measurements is 5.1 m/sec, while it is 6.3 m/sec for all the year, there is reason to presume that the final result would have been satisfactory.

Now it is reasonable to ask how la Cour's formula for the capacity of a 4-wing mill corresponds to the characteristic of the mill. If the average output of 60 gr m/sec for a wind velocity of 1 m/sec found by Poul la Cour is used as a basis, la Cour's formula is:

$$\text{Energy} = \frac{\text{vane area} \times \text{wind velocity}^3}{1\ 700} = \text{kW}$$

At a wind velocity of 9 m/sec the said mill would give:

$$E = \frac{48 \times 9^3}{1\ 700} = 20.6 \text{ kW}$$

From the characteristic it appears that the output of the dynamo is 16 kW, but the total output of the mill is 19 kW.

In la Cour's formula air resistance is not taken into account, and as far as the multi-blade adjustable mill is concerned this is by no means inconsiderable. When considering the losses through air resistance, it almost seems as if the mill has produced more than presupposed by the formula. As the air resistance increased with the speed of the wing, it proved that the most favourable wing tip speed was not 2.4 times that of the wind but only 2.0 times. From 28 June and for 114 days the wind-rose produced 1 500 kW-hr. The calculated annual production was then

$$\frac{1\ 500 \times 365}{114} = 4\ 800 \text{ kW-hr}$$

Here, too, it should be borne in mind that the wind-rose operated during the months notorious for low winds.

From the characteristic it will appear that the output is 3.1 kW at 9 m/sec. The starting torque of the wind-rose was also measured, and it is considerably greater than that of the multi-blade adjustable mill. This is of no importance for power production but significant, e.g., for pumping purposes.

The ambulant experiments

After the experience gained, a study was made of eight wind power stations and their characteristics constructed. The stations were spread all over the country. Five of the stations were driven by multi-blade adjustable windmills; two were propeller-type mills and one was a specially constructed wind turbine.

None of the adjustable multi-blade windmills could reach the standard of the Askov mill. The performance of an old Dutch mill was indeed only one fourth of the capacity to be expected according to la Cour's formula. This was due partly to the fact that the arm is idle when passing the body and partly that the transmissions in the old mills were heavy consumers of power.

The greatest interest centred on a propeller-type mill constructed by P. Vinding, engineer. The wing span had a diameter of 11 m; there were five wings, and the vane area was 28 sq m. The tower was 22 m high. As it was hard to regulate, it was difficult to construct a correct characteristic. During a period of 240 days, the mill had produced 11 000 kW-hr giving an annual production of 16 700 kW-hr. In proportion to the vane area the annual production was not better than that of the adjustable multi-blade mill, but measured by the characteristic it could produce 12 kW at 9 m/sec, a particularly satis-

factory result. The experiments also comprised three windmills for water pumping. These experiments proved that here the wind-rose maintained a better position, because it could make better use of the many hours of comparatively light winds.

Efficiency comparison

Though the efficiency of windmills is far from being of the same interest as steam turbines and diesel engines, comparisons between the various types of mills may, however, be of some interest.

If the wing span diameter is 16 m, the wing span area is 200 sq m, and the wind power represents about 95 kW at a wind velocity of 9 m/sec. As the adjustable multiblade mill produced 19 kW at 9 m/sec its efficiency was 20 per cent or 80 per cent measured in proportion to its wing span area of 48 sq m. The wing span area of the wind-rose was 44 sq m and the energy of the air flow 20.8 kW. As the capacity at 9 m/sec was 3.1 kW the efficiency was here 15 per cent, or measured by the wing area 30 per cent, because here the wings covered half of the wing span circle. Finally the wing span circle of the propeller mill was 95 sq m and the energy of the air flow 45 kW. As the capacity at 9 m/sec could be fixed at 15 kW the efficiency was 33 per cent, and 112 per cent in proportion to the wing area which was 28 sq m.

Experiments during World War II

The publication of these experiments[3] had no immediate effect, but the situation changed after the occupation of Denmark in 1940 by the German Wehrmacht. On 1 January 1940, only 25 windmills were in operation at the power stations, but in 1943 the number rose to 87 after which year the number of mills again began to fall.

Most of the new mills were 4-wing adjustable multi-blade mills according to la Cour's design, but a number of propeller mills were also built where both the initial cost and the annual production were higher than in the case of mills with adjustable blades. The annual production by wind power was about four million kW-hr during the war years. The peak annual production of an 18 m mill was 69 080 kW-hr, and in 1943 the peak output for a 24 m propeller mill was 135 670 kW-hr. In 1960 the output of a similar mill was 370 000 kW-hr.

Regulation and maintenance of the mills

As mentioned above the mills are self-regulating. In the case of adjustable multi-blade mills regulation is accomplished by the wind blades swinging open when the wind pressure becomes dangerous. Propeller mills are also self-regulating.

Originally Poul la Cour regulated the transmission to the dynamo through a sliding belt which could be set through varying loads for transmitting a certain quantity of energy; but nowadays the power is transmitted from the slow-running windmill to the fast-running dynamo through a gearbox where milled gearwheels submerged in oil make transmission losses inconsiderable. In addition the use of differentially wound dynamoes makes it possible for the mill to increase its speed without a similar rise in voltage of the dynamo. If all bearings are fitted with ball bearings the mill can operate for long periods without any inspection or maintenance whatever.

For many years the Rødding Wind Power Station in Sønderjylland had an 18 m adjustable multi-blade mill at a distance of 1.6 km from the station. Starting and stopping was electrically controlled from the station, and for a 20-year period the annual average output was 43 000 kW-hr. No daily attendance or inspection of the mill was necessary, and it also served as a positive booster of the electric mains.

Production cost of the electrical energy

It is difficult to answer the essential question: What is the cost of the electrical energy generated by wind power? It is difficult because a great number of windmills were built under extraordinary conditions and had a relatively short period of life so that their production often became comparatively expensive. But during times of war and crisis other sources of energy were costly too, so wind power has nevertheless been of great importance to power stations in rural areas — both early in the century and during two world wars.

The widest experience has been gained by the experimental mill at Askov (figure 2), which from 1902 to 1960 supplied the village of Askov with electricity, mainly produced by wind power. The original experimental mill was destroyed by fire in 1929 and the present mill dates from that year. It has been in operation for more than 30 years and might well continue for some time yet, but in 1960 the village was supplied with electricity from Sønderjyllands Højspændingsværk (Sønderjylland High-Voltage Power Station).

After 20 years of operation the wing span was subjected to a major overhaul and some cast iron gear wheels were replaced by steel wheels. There have also been minor repairs, painting, etc. The total cost of maintenance was 15 089 D kr — i.e., 500 D kr per year.

The experimental mill is an adjustable multi-blade mill with an 18 m wing span. The highest annual production was 53 641 kW-hr, but the average annual production was only 40 000 kW-hr. (The reason why the actual production has been lower than the theoretically possible production is generally due to the fact that the small wind power stations cannot utilize the entire output during a windy period and must consequently stop the mill.)

[3] *Statens Redskabsprøver* (*Government Implement Tests*), 36th report, Copenhagen, 1925.

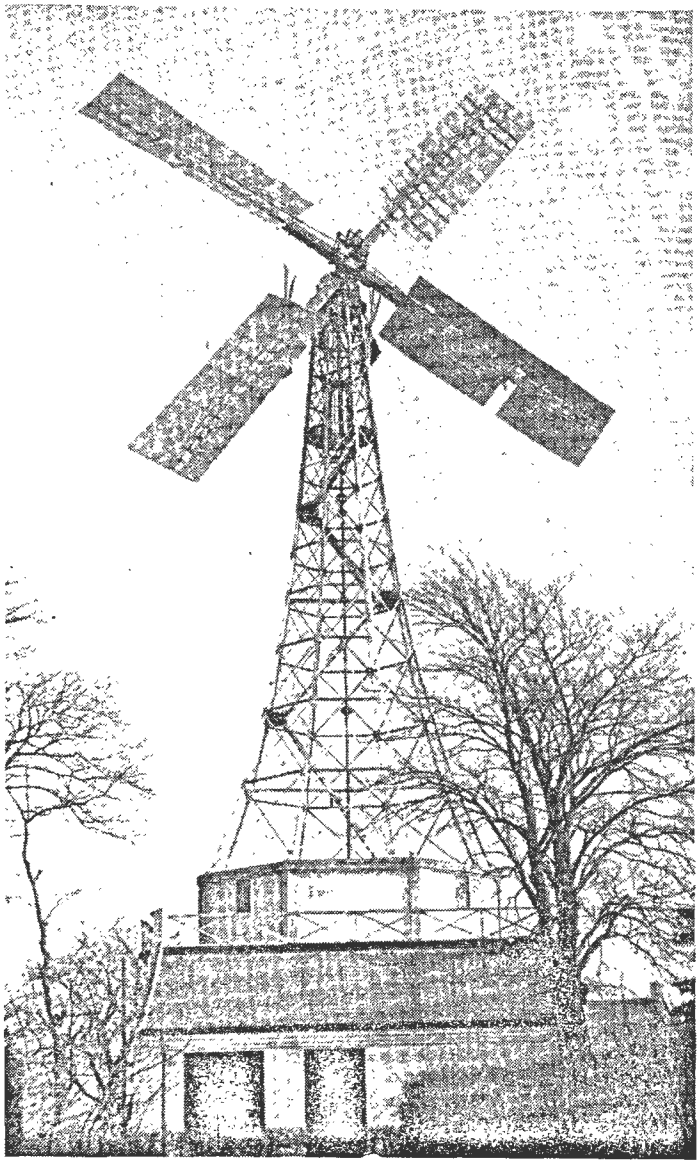

Figure 2. Experimental windmill at Askov

If r = 0.05 and the period of amortization is fixed at 30 years, the annual expenses of the experimental mill which cost 16 000 D kr inclusive of dynamo, were :

	D kr
Interest on 16 000 D kr at the rate of 5 per cent per annum	800
Amortization 1.5 per cent	240
Repairs	500
TOTAL	1 540

As the annual production was 40 000 kW-hr the average price is :

$$\frac{1\,540.00}{40\,000} = 0.0385 \text{ D kr}$$

Normally a 30-year life period cannot be expected, but a 20-year period is more probable.

Before the Second World War the over-all cost of construction of an 18 m windmill with dynamo and a 20 m tower was 14 000 D kr. The annual expenses were then :

	D kr
Interest on 14 000 D kr at the rate of 5 per cent per annum	700
Amortization 3 per cent of 14 000 D kr	420
Repairs 3 per cent of 14 000 D kr	420
TOTAL 11 per cent of 14 000 D kr	1 540

Based on experience during the Second World War, the average output per year of the 10 best of such mills was 48 000 kW-hr. The price of each kW-hr produced was thus :

$$\frac{1\,540.00}{48\,000} = 0.032 \text{ D kr}$$

All wind power stations which had installed their windmills before the war could thus rejoice in cheap production, but it is obvious that if the initial cost of a mill is three times as high, the cost of production per kW-hr will also be three times as high.

Forms of organization of wind power stations in rural areas

Nearly all wind power stations in rural areas and now also the big high-voltage power stations are organized as co-operative societies. This means that the undertaking is governed on democratic lines. Each member of the society has one and only one vote at the general meeting — no matter whether he is a large scale or small scale power-consumer. The capital necessary for the establishing of wind power stations was borrowed from the banks — and as is customary in Denmark — on joint and several surety.

Summary

The report is an account of Poul la Cour's experiments for a rational utilization of wind power made at the experimental mill at Askov at the end of the 19th century. Through model tests in a wind tunnel with an artificially created air flow, Poul la Cour found some of the elementary laws of aerodynamics. He ascertained that a cylindrically shaped or ridged plate of 1 sq. m moving at right angles to the wind at a speed of 2.4 times that of the wind could obtain 108 gr m/sec at a wind velocity of 1 m/sec.

On the basis of the tests Poul la Cour set up a formula for the capacity of a right-formed 4-wing mill :

$$\text{Effect} = \frac{V.a \times V^3}{1\,700} \text{ kW}$$

where $V.a$ is the vane area and V the wind velocity.

Furthermore it is an account of the establishing of the Danish Wind Power Association — a private organization which supervised the erection of the firts

rural power stations in which the dynamo was driven by wind power and thus paved the way for the electrification of Danish agriculture.

An account is given of the use of wind power during the First World War and the mill experiments which were started immediately afterwards. These experiments were made with full scale mills in natural winds. Suitable methods were found for the measuring of wind force and mill capacity in order to be able to construct the characteristic of the individual mills. The characteristic is a graph showing the efficiency of the mill at varying wind forces.

As a result of a comparison between the various mill types, it can be said that out of the wind energy hitting the wing area the 4-wing adjustable multi-blade mill utilized 80 per cent, the wind-rose 30 per cent and a more modern propeller mill 112 per cent.

However, it was shown that the efficiency was of far less importance in the case of windmills as opposed to the steam turbine and the diesel engine. The decisive thing is that the mill gives a maximum annual production of kW-hr on a minimum of initial and running costs.

Wind power stations are self-regulating and demand little attendance.

Running expenses and payment of interest can be estimated at 11 per cent of initial costs, and the mills which were built before the Second World War could supply one kW-hr at 0.03-0.04 D kr. Nearly all Danish power stations in rural areas are co-operative undertakings.

RÉALISATION ET PROGRÈS POSSIBLES DANS LE DOMAINE DE L'EXPLOITATION DE L'ÉNERGIE ÉOLIENNE

Résumé

On donne, dans le présent mémoire une description des expériences de Poul la Cour en vue de l'utilisation rationnelle de l'énergie éolienne, exécutée avec l'aéromoteur expérimental d'Askov, à la fin du XIXe siècle. Poul la Cour, en soumettant des maquettes à des essais en tunnel dans un courant d'air forcé, établit quelques-unes des lois élémentaires de l'aérodynamique. Il détermina d'une plaque de forme cylindrique ou striée d'un mètre carré se déplaçant à angle droit par rapport au vent à 2,4 fois sa vitesse pouvait donner une poussée de 108 grammes m/s, pour une vitesse de vent de 1 m/s.

Sur la base de ses essais, Poul la Cour formula la capacité d'un aéromoteur droit à quatre ailes par l'expression suivante :

$$\text{Effet} = \frac{V.a \times V^3}{1\,700}\ \text{kW}$$

formule dans laquelle $V.a$ est la surface des pales et V la vitesse du vent.

On décrit également, dans le mémoire, l'établissement de l'Association danoise de l'énergie éolienne, organisme privé qui a dirigé la construction des premières centrales rurales dans lesquelles la dynamo était entraînée par l'énergie éolienne, frayant ainsi le chemin à l'électrification de l'agriculture danoise.

On donne une description de l'utilisation de l'énergie éolienne pendant la première grande guerre et les expériences, commencées immédiatement après ce conflit, avec des aéromoteurs. Ces expériences ont été faites dans le vent naturel avec des éoliennes en grandeur naturelle. On a mis au point des méthodes appropriées pour mesurer la force du vent et la capacité de chaque aéromoteur, de manière à pouvoir en établir la caractéristique. Celle-ci est une courbe qui donne le rendement de l'aéromoteur en fonction des variations de la force du vent.

On peut dire, à la suite d'une comparaison entre plusieurs types d'éoliennes, que l'aéromoteur à quatre pales réglables utilise 80 p. 100 de l'énergie fournie à l'aire de l'aile, le type rose des vents 30 p. 100 et l'éolienne moderne à hélice 112 p. 100.

On a démontré, toutefois, que la question du rendement était beaucoup moins importante pour les aéromoteurs que pour les turbines à vapeur et les moteurs diesel. Ce qui compte, c'est de s'assurer que l'aéromoteur débite un maximum annuel de kilowatts avec des frais de premier établissement et d'entretien aussi réduits que possible.

Les centrales éoliennes ou aéro-génératrices sont à auto-régulation et n'exigent que fort peu de surveillance.

Les frais d'exploitation et l'amortissement des intérêts peuvent être évalués à 11 p. 100 des frais de premier établissement, si bien que les aéromoteurs construits avant la seconde guerre mondiale pourraient fournir du courant au prix de 0,03 à 0,04 couronne danoise par kWh.

Presque toutes les centrales danoises situées dans des régions rurales sont des entreprises coopératives.

WINDMILL TYPES CONSIDERED SUITABLE FOR LARGE-SCALE USE IN INDIA

P. Nilakantan, K. P. Ramakrishnan and S. P. Venkiteshwaran *

The large-scale use of wind power in any country will largely depend on the economic condition, climatic factors and special energy needs. A programme for utilization of wind power will naturally involve consideration of the following aspects:

(*a*) The current position as regards availability of various sources of energy, particularly electrical energy and the geographical distribution of energy sources;

(*b*) The economical and technical aspects of utilization of available energy in various localities;

(*c*) Human factors involved in the use of available energy;

(*d*) The seasonal requirements of water and power in rural areas in relation to the practical availability of energy during the various seasons of the year in different localities;

(*e*) The amount of wind energy available during various months of the year and its geographical distribution;

(*f*) The advantages of using wind energy in rural areas as compared to alternative methods for lifting water and other uses currently employing animal power or human muscle power;

(*g*) Special climatological factors, such as the monsoon in India.

It is perhaps a truism to say that what is good for one country will not be good for another since no two countries in the world are identical. Most developing countries have their own problems and distinguishing characteristics. The habits of the people, the distribution of population, the type of food they eat, their social behaviour, topography of the land, agricultural and farm requirements, availability of water resources and climatic factors may all vary considerably. Hence, in planning for large scale utilization of wind power in India, it is of importance to consider our specific needs against the social, agronomic, geographical and climatological background and also the alternative energy resources available to the rural population. It must be borne in mind that India's millions mostly live in more than 500 000 villages spread all over the country and use of windmills should specifically refer to meeting the needs of this rural population. The great problem for India, as for other developing countries, is that of meeting the minimum requirements of energy to maintain tolerable living standards during the next few decades in the light of the rapid population growth.

As is well known, there are several basic sources of energy such as fuel, wood, coal, oil, farm wastes, water power, solar energy, wind power and so forth. We have also the newer source of nuclear energy. A practical programme of wind power utilization would therefore have to fit in with the general pattern of development of all other sources of energy in the various regions. There is no doubt that, say after 15 or 20 years, this pattern of energy development, distribution and consumption in India will change and it is not easy to predict exactly to what extent the proposed targets will be achieved.

However, as pointed out by Professor Thacker, the per capita consumption of energy in a developing country like India is extraordinarily low at present and quite inadequate to meet her needs. During the next 20 years, despite our greatest efforts, we shall continue to be short of energy due to our limited resources of oil, coal, hydroelectric power and nuclear fuels. There is a likelihood that even the cost of energy production by conventional methods will go up. The last census in India has shown that on the average there has been an increase in population over the last 10 years of nearly 21 per cent. Even if the birth rate and the death rate were to continue at the same level as at present, the population of India by A.D. 2 000 could be of the order of 900 million. The problem of maintaining minimum living standards for this large population would be of enormous dimensions. It is very difficult to foresee how this problem will be solved unless there is some revolutionary technological advance in the method of tapping available sources of energy. We have no doubt an unlimited quantity of solar energy which now goes to waste. Nuclear power would definitely have great potentialities and even water power would satisfy a great part of the future requirements. But it will be admitted that despite all this we should still be lagging far behind advanced countries. In a country of vast extent and a low level of industrial development, the problem of distribution of available power will also present many difficulties. Hence every ounce of additional energy that can be obtained locally from wind, solar power or waste products for the benefit of rural areas would obviously be very much worth while and should be exploited to the fullest extent.

The monsoon: nature's provision of water

The problem of food production in India with an enormous and growing population is of vital import-

* National Aeronautical Laboratory, Bangalore, India.

ance; not only agriculture but even the day-to-day existence of the villager depends on a plentiful supply of water. Hence, prosperous communities are found mostly on the banks of rivers and large populations have grown up in the fertile plains where the great rivers of India flow and are replenished by the seasonal rain-bearing wind known as the monsoon. The Indian farmer through times immemorial has ever prayed to the "rain Gods" to shower timely and plentiful rains on his land.

An examination of the past records based on reliable information, particularly of the last 75 years, would clearly reveal that parts of the country have been subject to famine owing to failure of the rains over many years, and that occasionally the entire country has had to suffer from this calamity. In recent history, the years 1877, 1899 and 1918 will long be remembered as disastrous famine years due to the failure of the monsoon rains.

Figure 1 shows the distribution of the normal annual rainfall of India and table 1 gives the normal rainfall in different seasons of the year and during the year as a whole in various subdivisions of India. The four seasons are: (1) winter, December to February; (2) summer or pre-monsoon, March to May; (3) monsoon, June to September; (4) post-monsoon, October and November. The figures within brackets are the seasonal amounts, expressed as percentage of the annual rainfall.

A study of these figures reveals at once that India is truly the land of the monsoons. With the exception of Kashmir in the north, south-east Madras in the south, a very large percentage of the annual rainfall over the country occurs during the south-west

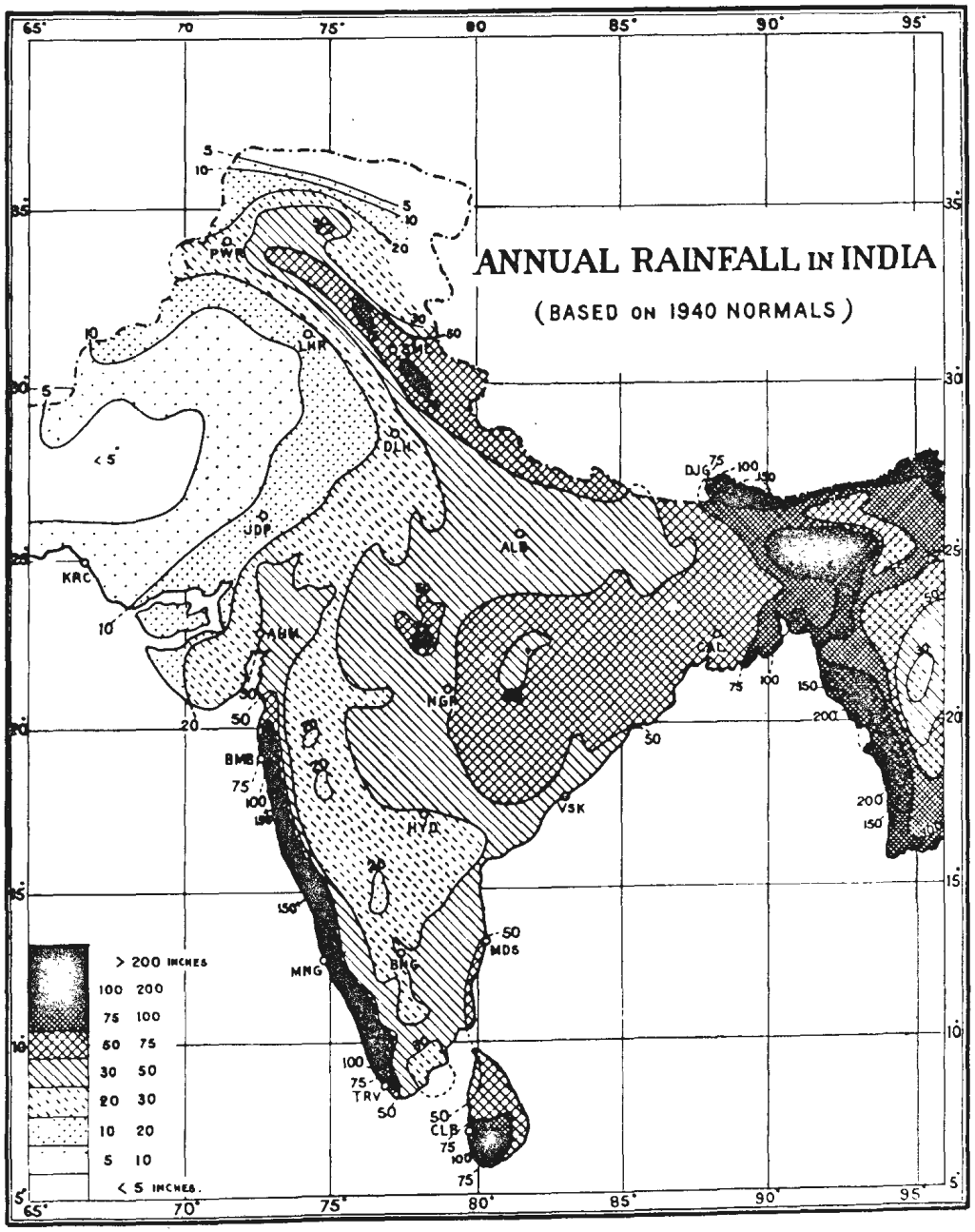

Figure 1

Table 1. Normal seasonal rainfall in the rainfall subdivisions of India in inches

Subdivision (1)	*Winter, December to February (2)*	*Summer, or pre-monsoon March to May (3)*	*Monsoon, June to September (4)*	*Post-monsoon, October to November (5)*	*Year (6)*
1. Assam	2.38 (2.4)	25.06 (25.7)	64.26 (65.8)	5.96 (6.1)	97.66
	per cent	per cent	per cent	per cent	
2. Bengal	1.53 (2.0)	12.42 (16.5)	56.01 (74.5)	5.17 (6.9)	75.13
3. Orissa	1.82 (3.2)	5.62 (9.9)	44.49 (78.2)	4.98 (8.8)	56.91
4. Chota Nagpur	2.57 (5.0)	3.64 (7.1)	42.71 (83.4)	2.26 (4.4)	51.18
5. Bihar	1.41 (2.9)	3.30 (6.8)	40.96 (85.0)	2.54 (5.3)	48.21
6. U.P. East	1.53 (3.9)	1.12 (2.9)	34.44 (88.0)	2.04 (5.2)	39.13
7. U.P. West	2.27 (6.0)	1.36 (3.6)	32.98 (87.8)	0.97 (2.6)	37.58
8. Punjab, E and N	2.76 (11.9)	1.89 (8.1)	18.23 (78.4)	0.37 (1.6)	23.25
9. Kashmir	9.12 (22.1)	9.09 (22.0)	22.19 (53.7)	0.94 (2.3)	41.34
10. Rajasthan, W	0.62 (4.8)	0.56 (4.3)	11.74 (90.0)	0.12 (0.9)	13.04
11. Rajasthan, E	0.96 (3.8)	0.78 (3.1)	22.91 (90.9)	0.55 (2.2)	25.20
12. Gujarat	0.22 (0.7)	0.24 (0.7)	31.46 (96.2)	0.77 (2.4)	32.69
13. Madhya Bharat, W	0.85 (2.5)	0.47 (1.4)	31.56 (93.8)	0.75 (2.2)	33.63
14. Madhya Bharat, E	1.44 (3.7)	0.79 (2.0)	35.05 (90.9)	1.30 (3.4)	38.58
15. Madhya Pradesh, W	1.47 (3.2)	1.14 (2.5)	41.04 (90.4)	1.76 (3.9)	45.41
16. Madhya Pradesh, E	1.58 (3.0)	2.10 (4.0)	46.37 (89.1)	1.99 (3.8)	52.04
17. Konkan	0.28 (0.3)	1.85 (1.7)	102.45 (93.7)	4.75 (4.3)	109.33
18. Bombay, Deccan	0.51 (1.7)	2.13 (6.9)	24.41 (79.1)	3.82 (12.4)	30.87
19. Hyderabad, N	0.67 (1.9)	1.53 (4.4)	29.51 (84.5)	3.20 (9.2)	34.91
20. Hyderabad, S	0.57 (1.9)	2.10 (7.0)	23.38 (78.1)	3.88 (13.0)	29.93
21. Mysore	0.73 (2.0)	5.47 (15.2)	22.27 (61.8)	7.54 (20.9)	36.01
22. Malabar	2.73 (2.6)	12.61 (12.2)	71.47 (68.9)	16.93 (16.3)	103.74
23. Madras, SE	4.76 (13.6)	4.53 (12.9)	12.01 (34.2)	13.80 (39.3)	35.10
24. Madras, Deccan	0.74 (3.0)	2.42 (9.9)	15.27 (62.3)	0.09 (24.8)	24.52
25. Madras, Coast N	1.69 (4.2)	3.44 (8.9)	25.03 (62.3)	10.00 (24.9)	40.16

monsoon (June to September). In the extreme north, a good portion of the annual rainfall is contributed by winter precipitation, whilst in south-east Madras nearly half the annual rainfall occurs during the retreating monsoon period (i.e., after September).

Also, while the rainfall during the monsoon period may be normal over a region, unless the day-to-day distribution of the rainfall is satisfactory, it may not be beneficial to the agriculturist. There are critical periods in the life history of the crops, from the date of sowing to the date of harvesting, when there should be either rain or dry weather. Sowing time is one of no small anxiety to the farmer for if it is followed by prolonged drought the tender seedlings will wither away and the entire crop may need resowing. While the farmer cannot control the effects of untimely rains, except by arranging to drain away the untimely rainfall, periods of drought are a great anxiety, and any help he can get during these spells can save the crops to a great extent.

From all the above considerations, India has in recent years launched large irrigation projects. Wherever the precipitation falling over a wide catchment is drained into large river systems, it is obvious that irrigation projects will be successful. Large reservoirs are being built to collect the rain water and the water so collected is being made available for agricultural purposes as required. This programme has already made great headway in the economy of India. Thus the agriculturist gets water in the irrigated areas not only during the monsoon, but throughout the year.

While these schemes have increased both the water resources for agriculture and power over a great part of the country, there are still vast tracts of India where they cannot be provided and other sources have to be examined and tapped. There are regions where wind and solar energy are available; it is just a question of devising suitable means to make economical use of them.

While the Indian monsoon is nature's large scale example of a judicious combination of solar and wind energy, the possibility of combining these artificially through human ingenuity is worth examining. There are large tracts in India where considerable wind energy is available almost throughout the year and there are also regions where solar energy is available in plenty. During the monsoon, the sun is obscured, but the wind is strongest. At other periods, the winds are feeble but the sun is hot. Therefore if solar heat and wind power could be converted into a common form of energy, e.g., electricity, one could get an assured supply of energy throughout the year over the whole country. The wind and sunshine regimes over India have been presented separately by Ramakrishnan and Venkiteshwaran (1) and Venkiteshwaran (2).

Windmills for water supply

The importance of the monsoon for India would only serve to emphasize the necessity for water in plenty for irrigation. It is of still greater importance

that the water obtained in the rainy season should be collected in tanks, ponds, lakes, or artificial reservoirs and stored up so that as and when the crops need water it is available. While the monsoons feed vast tracts of India, there are many other regions not so blessed and very large areas of arid and semi-arid land are available in the country which only need water to make them fertile. Some of this acreage is brought under cultivation by canals, but there are limitations to the use of open canal systems. While the rivers are harnessed by dams and the stored water distributed by canals, there is a larger reservoir of water in the sub-soil. This water has to be recovered by digging hundreds of thousands of wells and tanks. For many years to come a prosperous rural economy of India would very much depend on the existence of hundreds of thousands of these wells and tanks spread all over the country, each unit serving several acres of agricultural land. Obviously the sub-soil water will have to be lifted over heights which may range from 10 to about 50 ft in most cases and in some cases as much as 100 ft. In many parts of India the water for lift irrigation is obtained with the help of animal power. The Persian wheel turned by bullocks, camels, or buffaloes, as the case may be, is not uncommon, but for the most part we have primitive devices such as the " Kapila Etha " or " Kalatheku " (the bullock lift). The " Etham " or " lift " working on the lever principle worked by human labour is also common in some parts. These are laborious and time consuming devices. A conventional multibladed windmill capable of doing useful work at wind speeds of 5 to 6 miles per hour would be a very useful replacement for these primitive devices in most parts of India since wind speeds of this magnitude are not uncommon. The majority of even the moderately windy areas in India have annual mean speeds of the order of 6 to 8 mph only. There are few places where windmills designed to cut in at 10 mph can operate economically. From this it may be inferred that the standard type of windmill that will be of use over a large part of the year should have a fairly large swept area and at the same time its capital cost should be as low as possible to be within the means of rural communities.

Windmill types suitable for Indian conditions

We have now to consider the types of windmills that will suit India best. For supply of water for domestic purposes and lift irrigation one may employ water pumps either directly operated by a windmill or by electricity generated by a wind electric plant. There is no doubt that wind electric generators will be more adaptable, since the electric energy can be used for both pumping water and for other purposes. But from economic and maintenance considerations, storing of electricity may not be easy at the present stage. Experiments have been undertaken for gaining experience in the operation of direct acting windmills manufactured of indigenous materials designed to suit Indian conditions and also in the operation of an Allgaier 6 kW Wind Electric Generator (3) kindly presented by the West German Government.

While the design and construction of suitable and cheap types of wind electric generators and the organisation to maintain them in India may take some time to materialize, the immediate need for water in most of the villages could be satisfactorily met by the low cost conventional type of windmill installed in as large numbers as possible. Our initial effort has been directed to this end.

The Wind Power Division of the National Aeronautical Laboratory has so far been engaged in developing the use of low cost conventional type windmills made of indigenous materials, with the technical resources now available in India; they are intended to operate in moderate to low wind velocities. A few foreign made mutibladed windmills and two types of indigenous windmills, the first prototype of which incorporates four aerofoil type blades and a geared head mechanism while the second type has a conventional multibladed rotor and a direct acting head mechanism have been tested under Indian conditions. The experience gained so far would indicate that for the moderate to low wind velocities prevailing over most parts of India, the type designated as the WP-2 windmill is very satisfactory (figure 2).

The major characteristics of the type WP-2 windmill are as described below:

1. The rotor is 18 ft in diameter and has 12 blades which can be easily replaced.

2. The head mechanism is direct acting with a stroke of 5″. The shaft rotates on two ball bearings.

3. The windmill head mechanism is seated on a ball bearing turn-table.

4. For furling, the axis of the shaft is offset from the centre of the tower so that the wind wheel does not present its full area when the wind exceeds 30 mph. A pull-out winch is also provided to enable the windmill to be braked by pulling the tail vane away from the wind.

5. The tower is a 4-post design and the height may vary from 30 to 50 ft according to the topography of the land.

6. The pump is of the conventional reciprocating type.

The estimated optimum pumping capacity of this type of windmill for a wind speed of 10 mph is given below:

Total lift in feet	*Diameter of pump cylinder*	*Estimated hourly output in gallons*
10	10	3 000
25	8	1 500
50	6	750
100	3	400

An average daily output of up to 30 000 gallons is possible under the prevailing wind conditions in the windy regions of Saurashtra, Maharashtra and Mysore.

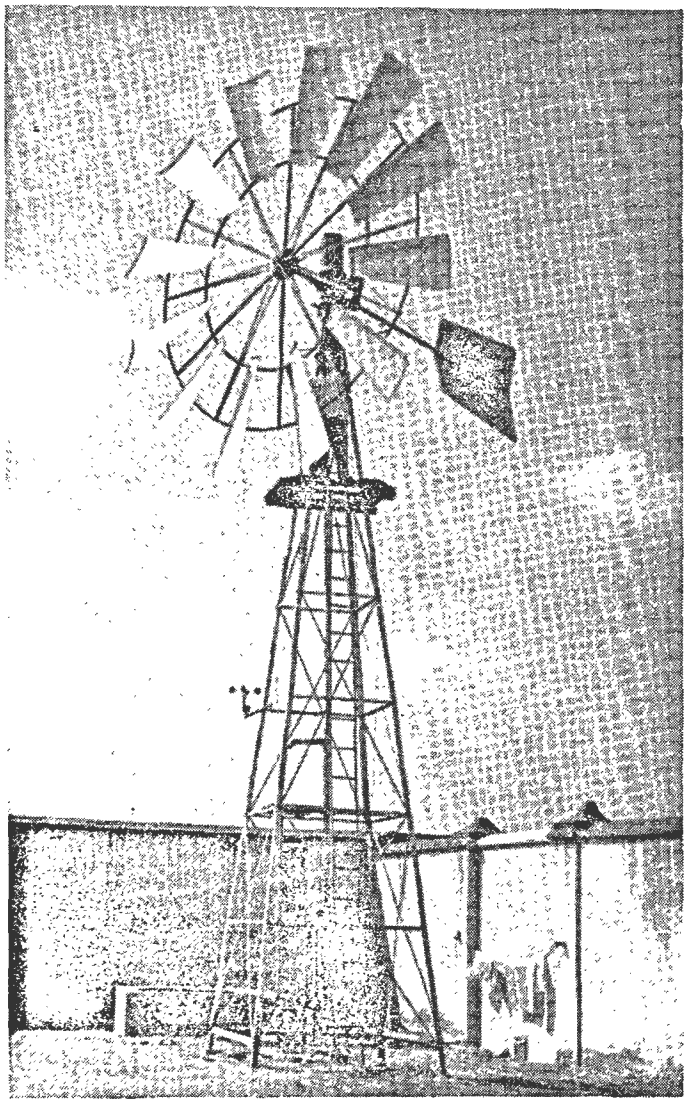

Figure 2. WP-2 windmill

The over-all economics of the windmill has been worked as under:

1. Capital cost of windmill and pump .	Rs 2 500/—
2. Annual cost of depreciation at 10 % and maintenance at Rs 50/— . . .	Rs 300/—
3. Annual quantity of water that could be lifted under optimum conditions and at full capacity	10 million gallons
4. Cost of 1 000 gallons of water lifted .	3 naye paise

The WP-2 type windmill was specially developed to suit the prevailing wind conditions in India in regions where low to moderate wind velocities of the order of 5 to 8 mph are met with. Imported windmills of the conventional multibladed type designed to give optimum performance at wind velocities of about 10 mph and above have certain disadvantages. The wind speed required to start these windmills from rest is high and hence their performance is unsatisfactory under low wind conditions. The WP-2 type windmill has a larger rotor and a proportionately higher starting torque and at the same time the capital cost is kept as low as possible by using commercial quality indigenous materials which are readily available and by adopting well proven economic methods of design and fabrication.

Performance of the WP-2 type windmill

In order to determine the actual performance of this windmill in regions where the wind velocities are only low to moderate, observations were made on a prototype windmill at New Delhi. The prototype windmill was fitted with a 17 ft rotor only instead of the standard 18 ft rotor. It had a 6″ diameter reciprocating pump having a stroke of 5 inches and was erected on a tower 50 ft high. Water was pumped from a tank at ground level up a vertical pipe of 3″ diameter and 45′ high. Two outlets to the vertical pipe were located at 25 ft and 40 ft respectively above the water level in the reservoir. By means of isolating cocks, either a 25 ft or 40 ft head could be used. The water at the outlet was discharged through a 2″ water meter. For measuring the wind velocity, a cup counter anemometer of the integrating type was erected in a 30-foot tower near the windmill and an automatic recording anemometer was also installed on the tower for purposes of checking. For the measurement of the rotor rpm, an ordinary counter was used, the mechanism being operated by means of a lever device attached to the reciprocating pump rod. Each revolution of the rotor was registered as a unit on the counter.

In evaluating these observations, due allowance had to be made for fluctuations in the wind. There was also a lag in the starting and stopping of the rotor in relation to the wind speed. For instance, the wind velocity had to be above 4 mph for the rotor to start from rest. However, once the rotor had started, it continued to rotate for some time even when the velocity had dropped below 4 mph. Readings of the run of wind every 15 minutes were recorded and average values of the wind speed obtained. Mean values of the output, rpm and the corresponding wind speed were determined for a total lift of 25 ft for a period of 8 days. The results are shown in figure 3.

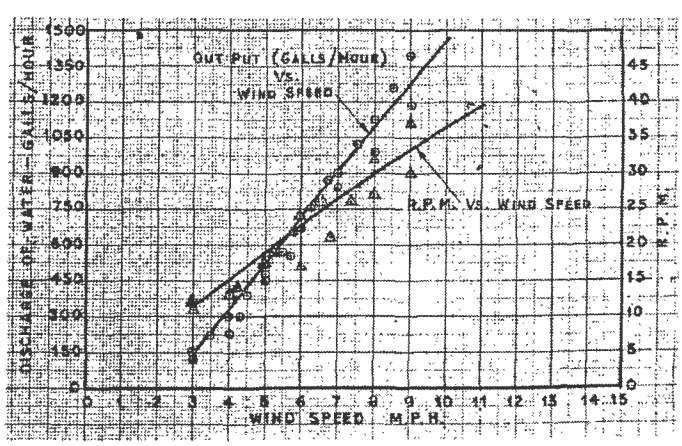

Figure 3

It will be seen from this that the performance of the WP-2 type windmill is satisfactory and the achieved output of 1 300 gallons per hour at a wind speed of 9 mph would indicate that the windmill-pump can be an economically sound proposition.

Future developments in windmill design to suit Indian conditions

While the conventional type windmill has proved itself to be of general usefulness all over the world, and may be safely used in many parts of India during the years to come, it would be certainly worth while investigating the possibility of developing newer types particularly adapted for the wind regimes in various localities where the rural communities are not highly advanced and the people are not mechanically minded. Even the conventional steel windmill may be too much of an advance and one may consider cruder devices such as the windmills made of bamboo and reed mats used in China. Golding (4) had suggested that it might be worth while developing a vertical axis type windmill for the desert or semi desert areas using bamboo or reed mats as sails. This type should be capable of being easily dismantled and moved in order that bullocks could be used alternatively for pumping if necessary when there is no wind. The suggested design has not been worked out yet but the idea is very promising and it is proposed to investigate a few preliminary designs of the vertical axis type windmill using locally available material for sails, mostly made of reed or bamboo but for the bearings.

Again recent advances in the aerodynamic design of windmills would highlight the advantages of using more advanced types in very windy areas where the annual average wind speed is more than 10 mph. In such windy areas it would also be of advantage to have wind electric generators rather than conventional type windmills since the electricity generated could be used for either pumping water or for other purposes. In general, India is not a place of very high winds such as Northern Europe or the North of England and it would not be worth while at this stage to experiment with medium and high wind electric plants with capacities of the order of 100 kW or 1 000 kW. A rational approach would be to experiment with small wind electric generators of about 1-5 kW capacity and develop their use in rural areas to serve small communities. As stated earlier, the primary need would be for pumping water in most places and even the demand for electricity would be secondary. Hence, the wind electric plant should be mostly used for driving electric motor pumps, the water being used directly for lift irrigation. The excess may be stored in reservoirs, so that even when there is a lull in the wind a constant supply of water is assured. Storage batteries are very expensive to maintain and while a small part of the electricity generated may be stored in small storage units to serve limited requirements for lighting it would not be economical to use large storage units for storing all the electricity generated.

It has been suggested by Dr. Hütter that it would be more economical to employ a propeller type windmill for directly driving a reciprocating pump, the stroke being made variable according to the wind speed in order that even at low and moderate wind speeds the windmill could work. The stroke is adjusted to be small when the windmill is at rest so that it can start easily, but as the wind speed increases and the rotor speed picks up the stroke automatically increases to a value corresponding to the wind speed. Such a device would make the windmill adaptable and particularly suitable for Indian conditions. This type of windmill is not yet available. It would indeed be very much worth while developing a 2-3 hp windmill plant working on the above principle and test it in India.

Some special problems of windmill design

There is a serious problem which is peculiar to the tropics and which has an important bearing on wind power utilization, namely, the occurrence of cyclonic storms and heavy gusts during certain seasons. Even in places in India where the annual average wind is fairly low, the monthly average wind speed during the monsoon becomes quite high and gusts of 60-70 mph are not infrequent. During cyclonic weather the wind speed may even reach 100 mph. This raises the problem of providing adequate strength to the windmill structure. It has been found that despite the usual furling devices, if the tower and the head mechanism are made strong enough the rotor gets damaged. But if the rotor system is made too strong there will be a tendency for the head mechanism to be dislodged from the tower. While small variations in wind speeds, say, up to 30 mph can be taken care of by the furling mechanism, it is found inadequate for strong gusts and storms when the wind direction and speed undergo rapid variations. The high "shock" loads acting on the windmill can cause severe damage. It has been found that in most parts of India which have high annual average wind velocities, the storms are also correspondingly more severe in intensity. Some development work is therefore called for to get over the effects of storms. One direct way would be to remove a few blades from the conventional type windmill rotor during the monsoon. Another would be to introduce some dynamic device for automatically feathering the blades when they are hit by gusts.

Future programmes of research and development

Progress in the use of the direct acting windmill for supplying drinking water and for minor irrigation purposes in India has been described above. The scheme for the utilization of wind power in India is a very recent one. Since it has now become a branch of the National Aeronautical Laboratory it will have greater facilities for development of growth.

The scope of research in the Wind Power Division will be mainly concerned with the utilization of wind

power and would involve on the one hand the adaptation of standard designs of windmills to suit the prevailing wind regimes in the country and facilitation of their indigenous production using simple techniques and locally available materials and, on the other, the undertaking of extensive wind velocity surveys and studies for selecting suitable areas and sites for economic extraction of wind energy.

This programme of the National Aeronautical Laboratory will include the following broad fields of investigation :

Research on the aerodynamics of wind turbines and methods of conversion of wind energy into electrical and mechanical energy; design of small and medium capacity windmills intended for specific purposes; experimental testing of prototype windmills and pumps and evaluation of their performance; economic studies of wind power based on velocity surveys carried out in different areas; pilot experiments on medium and large capacity wind electric plants at selected sites; problem of storage, distribution and utilization of wind electric power; adaptation of special devices for use with windmills in rural areas, such as corn grinding, threshing, oil extraction, etc.; design studies for development of small and medium capacity wind electric generators specially intended for wind turbines and auxiliary equipment; research and development relating to indigenous materials for construction of windmills and design of low cost towers using locally available materials; indigenous development of windmill pumps and research on improving their efficiency; conduct of extensive wind velocity surveys for economic utilization of wind energy; research on the characteristics of winds affecting the economic operation of windmills and development of simple methods of estimation of availability of power from the wind; study and analysis of statistical data on wind velocities obtained from wind velocity surveys and meteorological observations and establishment of correlations between geographical, topographical and other features with the characteristics of wind regimes in different areas.

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Summary

The paper states briefly the economic, climatic and human factors peculiar to India on which the use of wind power depends. It is shown that the urgent need of power in the widely distributed villages of India is for water, for drinking and minor irrigation purposes. Considering the various sources of energy and the rapid technical developments now taking place, any programme in the employment of wind as a source of power may also undergo rapid changes, and a vast country like India, with its technological development, can afford only simple and cheap equipment. The conventional multi-bladed windmill is therefore considered most suitable at present and it has been designed to operate at low wind speeds of 5-6 miles per hour; it is also capable of being constructed indigenously. The paper discusses briefly the future developments in windmill design to suit Indian conditions. Since India is not a place of very high winds, such as Northern Europe or the North of England, it is felt that a rational approach would be to experiment with small wind electric generators of about 1-5 kW capacity and develop their use in rural areas, the primary need being pumping water. The paper also states some of the special problems of windmill design in connection with the occurrences of cyclonic storms and squalls associated with thunderstorms. The programmes of research and development proposed to be undertaken in connection with wind power are stated.

MODÈLES D'AÉROMOTEURS JUGÉS APPROPRIÉS POUR ÊTRE EMPLOYÉS EN INDE SUR UNE GRANDE ÉCHELLE

Résumé

On passe brièvement en revue, dans le mémoire, les éléments économiques, climatologiques et humains qui sont propres à l'Inde, lesquels conditionnent l'emploi de l'énergie éolienne. On démontre que la demande urgente d'énergie, dans les villages très disséminés de par tout le pays, est dictée par les besoins d'eau potable et des petits systèmes d'irrigation. En passant en revue diverses sources de force motrice et les progrès techniques rapides qui se manifestent actuellement, on notera que tout programme d'utilisation du vent comme source d'énergie peut également faire l'objet de modifications importantes et, dans un vaste pays tel que l'Inde, compte tenu de son degré actuel de développement technologique, on ne peut envisager que du matériel simple et peu coûteux. On estime donc que l'éolienne classique à plusieurs pales est actuellement la plus indiquée et on l'a étudiée pour fonctionner avec des vitesses de vent ne dépassant pas 5 ou 6 milles à l'heure (8 ou 10 km). On peut, en outre, la réaliser sur place. On passe brièvement en revue les progrès possibles dans la construction des moulins à vent, pour les adapter aux conditions propres à l'Inde. Pour autant que l'Inde n'est pas un pays où dominent des vents intenses tels que ceux que l'on trouve en Europe du Nord et en Angleterre septentrionale, on estime qu'une manière rationnelle de s'attaquer au problème consisterait à faire des expériences avec de petits groupes électrogènes à énergie éolienne d'une capacité allant de 1 à 5 kW, puis à en développer l'emploi dans les zones rurales, où le pompage de l'eau est le premier besoin. On pose également, dans le mémoire, certains des problèmes spéciaux ayant trait à la réalisation des moulins à vent pour tenir compte des tempêtes cycloniques et des rafales dont s'accompagnent les orages. On examine le programme de recherches et de mises au point que l'on se propose d'entreprendre dans le cadre de la mise en œuvre de l'énergie éolienne.

PROBLÈMES CONCERNANT LE COUPLAGE AUTOMATIQUE D'UN AÉROGÉNÉRATEUR SUR UN RÉSEAU

F. H. Delafond *

Lorsque l'aérogénérateur expérimental de 100 kW (figure 1) Andreau-Enfield fut installé à Grand Vent, près d'Alger (novembre 1957), le couplage sur le réseau s'effectuait de la manière suivante.

Un contact commandé manuellement provoquait la fermeture du contacteur reliant l'alternateur au réseau, le rotor étant branché sur résistances de démarrage, avec le rotor de l'excitatrice intercalé sur l'une des phases.

Au bout de quelques secondes, un contact auxiliaire temporisé provoquait le court-circuitage des résistances de démarrage.

Quelques secondes plus tard, un autre contact auxiliaire temporisé provoquait le branchement du stator de l'excitatrice, et du servo-moteur ouvrant le passage de l'air à la turbine et fermant le by-pass.

L'alternateur, accouplé à la turbine, démarrait donc en moteur asynchrone sur résistances, puis en court-circuit, puis se synchronisait, et devenait enfin générateur, si la dépression produite par l'hélice était suffisante pour que la turbine entraîne l'alternateur.

L'énergie nécessaire au démarrage, assez considérable, était empruntée au réseau, et l'opération demandait environ deux minutes, l'ouverture du volet d'air étant, de beaucoup, la plus longue de ces opérations.

Le démarrage de l'hélice était entièrement indépendant de celui de l'alternateur : une électrovalve commandée par bouton-poussoir envoyait l'huile d'un accumulateur alimenté par une électropompe au servomoteur de mise au petit pas, et l'hélice démarrait d'elle-même (si le vent était suffisant).

La mise en drapeau se commandait d'une manière analogue, par une autre électrovalve.

On voit que l'ensemble de ces opérations, bien que commandé électriquement à distance, avec une certaine part d'automatisme, ne pouvait être déclenché que par une intervention manuelle.

C'est dans ces conditions qu'ont été effectués les premiers essais.

Premiers résultats

Lors des premiers essais, on ne parvenait pas à synchroniser l'alternateur sur le réseau, le fort appel de courant provoquant une baisse de tension, ce qui faisait lâcher l'un des relais, et le cycle de démarrage recommençait indéfiniment. On y remédia provisoirement en réduisant la force du ressort de relais.

On put alors faire les observations suivantes.

Par vent moyen

La puissance produite (figure 2) varie constamment dans d'importantes proportions : par exemple en une minute, la puissance produite descend de 60 kW à 30, puis remonte à 70 kW après deux ou trois pointes intermédiaires. Les périodes stables sont rares, et ne dépassent pas une dizaine de secondes.

Il semble que ceci soit dû uniquement aux variations de la vitesse du vent, et non pas à un phénomène d'auto-oscillation de la machine, comme certains expérimentateurs en ont observé [1].

Nous n'avons jamais observé pour notre part de phénomène d'auto-oscillations dangereuses, mais nous avons toutefois noté, aux environs de 70 kW, une oscillation de puissance ne dépassant pas $\pm$ 4 kW et de fréquence sensiblement double de la vitesse de rotation de l'hélice. Il semble qu'elle soit due au passage des pales dans le sillage de la tour, et sa lecture se trouve peut-être amplifiée par une résonance du wattmètre à cette fréquence.

Le régulateur automatique de tension suit très bien les variations de puissance, et le facteur de puissance se maintient sensiblement à la valeur choisie, soit 1.

Enfin, le réseau de distribution de 10 kV sur lequel est branchée la machine ne s'est jamais trouvé perturbé par ces variations de puissance, beaucoup trop faibles par rapport à la puissance globale du réseau.

Par vent faible

La puissance produite (figure 3) passe des valeurs positives aux valeurs négatives à une cadence moyenne qui peut être d'une minute environ. Avec le système de couplage décrit ci-dessus, il était impossible de coupler et découpler l'alternateur à une telle cadence, car, en plus de la puissance consommée pour chaque couplage et de la fatigue des contacteurs, on risquait toujours de tomber sur une puissance négative en fin de couplage. On pouvait évidemment arrêter la machine sans grosse perte d'énergie. Mais

* Électricité et gaz d'Algérie, Alger.

[1] Voir « Effet de la résistance de ligne sur la stabilité des machines synchrones, avec application particulière à la génératrice éolienne 100 kW Enfield Cables » par J. A. Fox dans *The English Electric Co. Ltd.*, décembre 1955.

alors, quand devait-on la remettre en marche? Le vent est si capricieux qu'il est bien malaisé de prévoir, même une minute à l'avance, s'il va augmenter, et pendant combien de temps.

On en conclut qu'il fallait rendre plus rapide cette opération de couplage, éviter qu'elle fasse appel à l'énergie du réseau, et la rendre automatique.

Par vent fort

La puissance produite (figure 4), liée à la vitesse de rotation de l'hélice, est limitée par variation du calage des pales, elle-même commandée par un régulateur de régime, du même principe que ceux employés sur les hélices d'avions. Ce régulateur se contente d'augmenter le calage si la vitesse de rotation dépasse le régime choisi — 100 t/m — et de le réduire jusqu'à la butée lorsque le régime est inférieur à 100 t/m.

Ainsi qu'on pouvait l'imaginer, il en résulte un « pompage », c'est-à-dire une oscillation auto-entretenue autour du régime d'équilibre. La puissance baisse en ½ seconde de 130 à 80 kW, en moyenne, pour remonter en 2 secondes aux environs de sa première valeur. Ce phénomène est difficilement mesurable, car il dépend autant des rafales que des variations propres à la machine. L'amplitude et la fréquence sont donc assez variables.

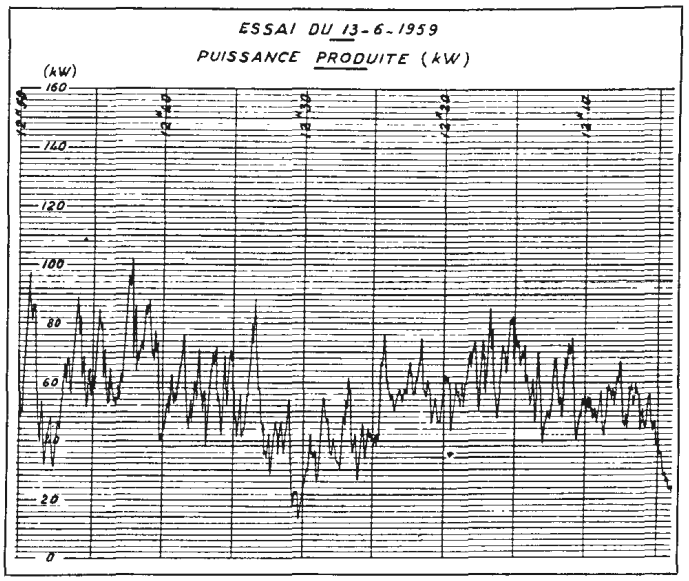

Figure 2

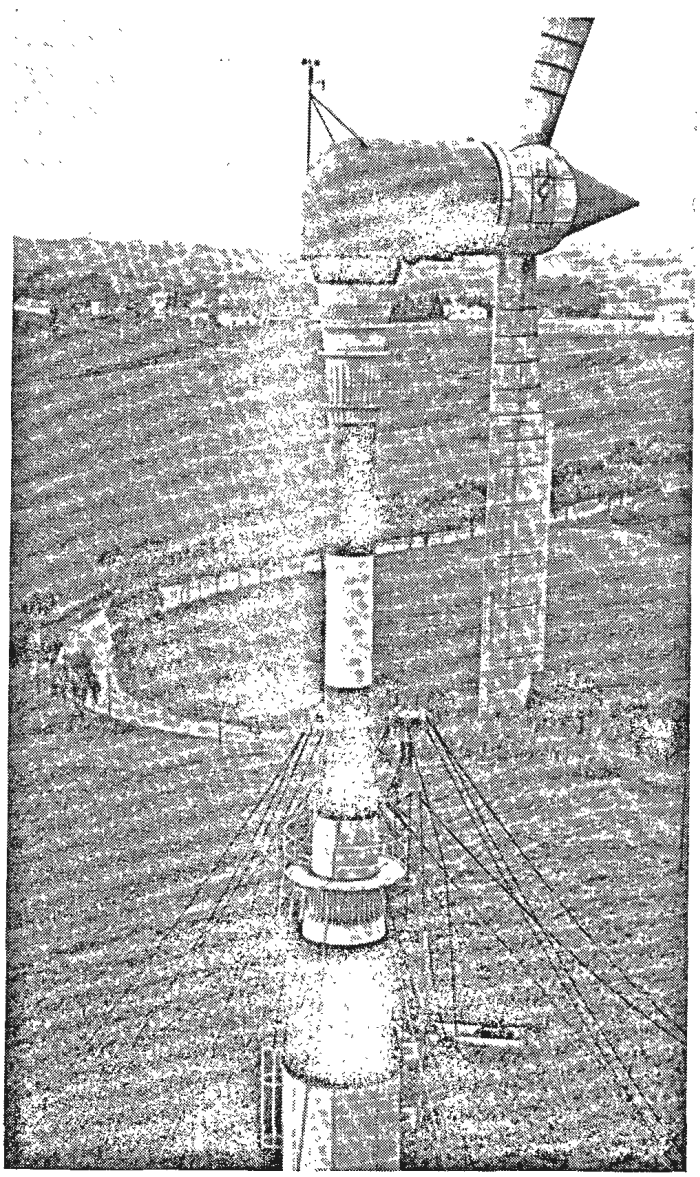

Figure 1

Ce pompage présente les inconvénients suivants :

a) Il oblige à réduire le régime de réglage du régulateur pour ne pas dépasser le régime admissible. L'énergie produite s'en trouve réduite.

b) Il est préjudiciable à la machine et à la bonne régulation du réseau.

c) S'ajoutant parfois aux rafales, il risque de devenir dangereux par vent de tempête.

Ces différentes observations nous ont amenés à effectuer, ou à prévoir, les réglages et modifications qui suivent.

Réglages et modifications effectués ou à effectuer

Couplage de l'alternateur

Cette modification a été effectuée la première, car c'est l'opération qui doit se produire le plus fréquemment.

Pour supprimer l'appel de courant sur le réseau, on a séparé la commande d'ouverture du volet d'air de la turbine, qui se fait maintenant dès la mise sous tension de la machine.

Le groupe turbo-alternateur est alors lancé par la dépression produite par l'hélice. Lorsqu'il dépasse légèrement le synchronisme, l'alternateur est couplé sur le réseau, rotor en court-circuit, par un relais tachymétrique. L'intensité est encore importante, mais la puissance demandée est à peu près nulle. Au bout de 3 secondes environ, un contact auxiliaire temporisé provoque l'excitation de l'excitatrice, donc la synchronisation, comme auparavant.

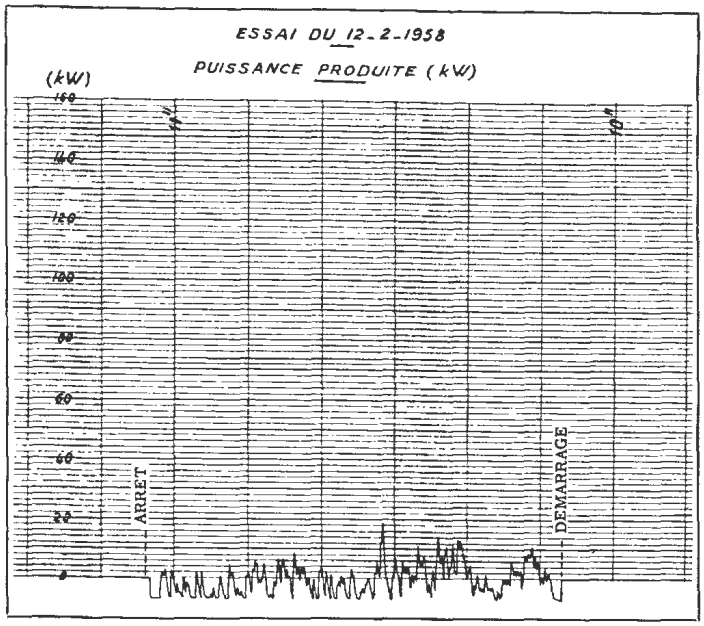

Figure 3

Dès que l'alternateur est couplé, un contact auxiliaire maintient ce couplage, car le relais tachymétrique ne maintient pas son contact, le régime étant descendu au synchronisme. Ceci est indispensable, surtout pour éviter des découplages et recouplages plusieurs fois par seconde.

Le découplage pourrait se faire par un relais à retour d'énergie, quand la puissance est devenue légèrement négative, pour éviter un fonctionnement trop fréquent. Nous avons trouvé plus simple d'employer un manocontact à dépression, qui coupe le contact de maintien du contacteur dès que la dépression, trop faible, correspond à une puissance légèrement négative. Sitôt l'alternateur découplé, il ne peut donc se recoupler que s'il est monté légèrement au-dessus du synchronisme, ce qui évite les couplages trop fréquents, d'autant plus que, même à puissance nulle de l'alternateur, l'excitatrice consomme une certaine énergie si elle est branchée.

Ce dispositif fonctionne depuis deux ans, et il nous est arrivé, démarrant l'hélice par fort vent, de voir l'alternateur monter en régime en moins de 5 secondes, et s'accrocher au réseau sans le moindre incident.

Le découplage s'effectuant à intensité presque nulle, le contacteur ne se fatigue pas, malgré son fonctionnement fréquent.

Mise en marche de l'hélice

Détection du vent

La mise en marche de l'hélice doit être commandée par un dispositif anémométrique. Nous avons utilisé le moulinet classique à coupelles, entraînant un petit alternateur à aimant permanent. Mais, tout d'abord, où placer ce moulinet pour qu'il reçoive le même vent que l'hélice, sans toutefois subir son influence, quelle que soit la direction du vent?

Nous l'avons placé au sommet de la tour, aussi en amont que possible, c'est-à-dire 5 m environ en avant du centre de l'hélice. Mais quand l'hélice se met en marche, le vent se trouve ralenti en ce point d'environ $\frac{1}{3}$ de sa valeur, et, à moins de conserver une très large marge entre la vitesse provoquant la mise en marche de l'hélice et la vitesse provoquant son arrêt, on verra fréquemment l'hélice s'arrêter dès qu'elle commence à tourner.

Nous avons évité ce défaut en ajoutant un contact auxiliaire au relais qui commande la mise en marche de l'hélice, ce contact court-circuitant une partie de la résistance d'ajustage placée dans le circuit alimentant le relais galvanométrique. Cette résistance est calculée pour que, en supposant le vent constant, le courant traversant le relais soit le même si l'hélice tourne que si elle ne tournait pas, malgré le ralentissement du vent local provoqué par cette rotation.

Phase préparatoire

La mise en marche de l'hélice suppose que les accumulateurs d'huile sont sous pression, et que la tête de la machine se trouve orientée dans le vent.

Quand les accumulateurs d'huile sont vides, il faut à la pompe dix minutes pour les remplir, et ensuite la pompe fonctionne environ 2 minutes par heure pour compenser les fuites.

D'autre part, quand la machine est complètement arrêtée, elle ne s'oriente dans le vent que s'il est fort. Un servo-moteur commandé par girouette assure l'orientation dès que la tête de la machine est alimentée en courant.

Nous aurions pu laisser ces deux dispositifs marcher en permanence, pour que la machine soit toujours prête à démarrer. Mais alors, en plus de la consommation inutile de courant, et de la fatigue inutile des mécanismes par longue période de vent nul, on risquait surtout de voir la tête de la machine tourner indéfiniment si la girouette de commande d'orientation se trouvait en dehors de l'axe de la tête

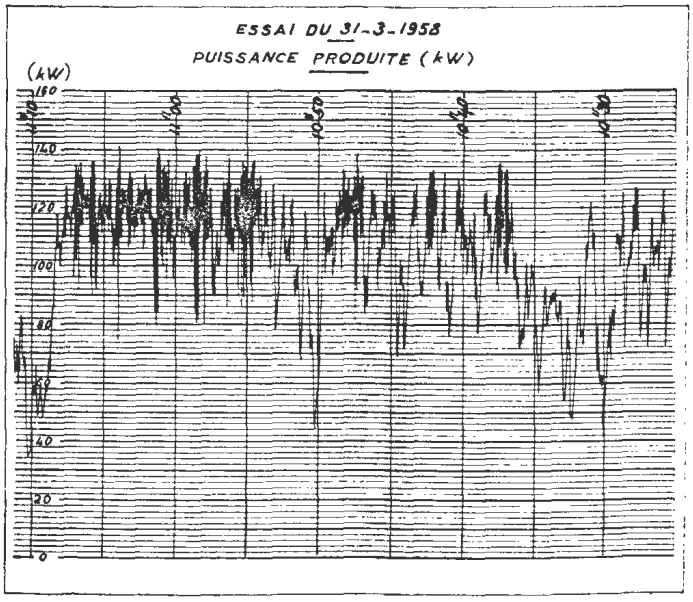

Figure 4

lorsque le vent est nul. Nous avons donc jugé nécessaire de prévoir :

a) Une phase d'arrêt total, où le courant de la tête est coupé, quand le vent est inférieur à 5 m/s environ;

b) Une phase préparatoire, où le courant est envoyé dans la tête, quand le vent est supérieur à 5 m/s environ;

c) La mise en marche de l'hélice, quand le vent est supérieur à 8 m/s environ.

Pour commander le passage de la phase d'arrêt à la phase préparatoire, et réciproquement, un relais galvanométrique à deux contacts (maximum et minimum) est alimenté par le circuit anémométrique, et commande le contacteur assurant l'alimentation de la tête de la machine, par l'intermédiaire d'un relais restant dans la dernière position commandée.

En réglant le contact maximum aux environs de 5 m/s et le contact minimum aux environs de 4 m/s, on conserve une marge d'inertie suffisante pour éviter un passage trop fréquent d'une phase à l'autre. Cette inertie est d'ailleurs augmentée par un fort condensateur placé entre les bornes du relais galvanométrique pour réduire l'effet des brèves rafales.

Mise en marche et arrêt de l'hélice

Un relais galvanométrique analogue au précédent, alimenté par le même circuit anémométrique, provoque simultanément l'ouverture de l'électrovalve de mise au petit pas et la fermeture de l'électrovalve de mise en drapeau, ou inversement pour l'arrêt, toujours par l'intermédiaire d'un relais restant dans la dernière position commandée.

Le contact maximum étant réglé pour 8 m/s environ et le contact minimum pour 6 m/s environ, on conserve, ici encore, une marge d'indifférence suffisante pour éviter des mises en route et arrêts trop fréquents.

Une petite précaution supplémentaire est encore nécessaire : si le vent monte de zéro à plus de 8 m/s en quelques minutes, on risque de provoquer la mise en marche de l'hélice avant que les accumulateurs d'huile ne soient à pression suffisante. Pour éviter cela, un relais intermédiaire est alimenté par le manostat, seulement si la pompe est arrêtée. Puis, dès que l'hélice est mise en marche, il est alimenté également par un contact auxiliaire de maintien, pour ne pas provoquer la mise en drapeau de l'hélice quand la pompe à huile se remet à fonctionner.

L'ensemble de ces dispositifs a fonctionné une trentaine d'heures au moment où nous écrivons ces lignes. Au début, nous avons eu quelques mises en drapeau intempestives. Elles étaient dues à des baisses de tension trop importantes dans les circuits d'alimentation de certains relais. Il y a été aisément remédié, et actuellement le dispositif donne entière satisfaction.

Nous ne reproduisons pas le schéma électrique de notre installation, très compliqué du fait de dispositifs de sécurité et de servitudes auxiliaires particuliers à la machine. Le schéma peut d'ailleurs varier notablement selon les éléments constitutifs dont on dispose. Nous avons seulement cherché à exposer les principes généraux qui permettent à une machine de fonctionner automatiquement et correctement malgré les caprices du vent.

Régulation de la puissance

Comme nous l'avons vu, la limitation de puissance est assurée sur cette machine en limitant la vitesse de rotation de l'hélice, par variation de l'angle de calage des pales, variation commandée par un simple régulateur centrifuge et un servo-moteur à huile pour chaque pale, les deux mouvements étant solidarisés mécaniquement; c'est donc un régulateur du type flottant.

En fait, il existe aussi un relais de distribution d'huile entre le régulateur et les servo-moteurs, les sections de passage du régulateur étant insuffisantes pour l'alimentation des servo-moteurs. Ce relais, provoquant un retard dans l'action des servo-moteurs, augmente nécessairement la tendance au pompage.

Ceci étant, quand nous avons constaté le pompage avec baisse de régime très rapide, et avec rabattement des pales — articulées — vers l'amont, nous avons diaphragmé les canalisations d'huile, pour réduire la vitesse d'action des servo-moteurs. Nous avons constaté qu'il fallait se limiter dans cette voie, car si la régulation se fait trop lentement, on risque des pointes de vitesse exagérées lors des rafales.

La période de pompage est ainsi passée de 2,5 à 6 secondes environ, la baisse de régime se faisant alors à peu près à la même vitesse que la montée. L'amplitude moyenne de pompage est nettement réduite, mais il arrive que des rafales provoquent des amplitudes aussi grandes qu'auparavant.

Un système de régulation apériodique est en cours de réalisation pour remédier à ce défaut.

Ce problème de régulation se traite évidemment de différentes manières selon le moyen envisagé pour limiter la puissance. Mais les problèmes de régulation sont suffisamment connus maintenant pour qu'on puisse dans tous les cas remédier à l'instabilité.

Arrêt par vent de tempête

Sur notre machine, le constructeur avait avancé qu'il faudrait prévoir un dispositif d'arrêt automatique si le vent dépasse 29 m/s. En fait, la machine a fonctionné jusqu'à 31 m/s malgré une mauvaise régulation, et son fonctionnement n'a pas semblé plus inquiétant que par 15 m/s.

Mais il semble bien difficile de déterminer à partir de quelle vitesse de vent il faut l'arrêter, car, le vent étant toujours variable, ce ne sont que des rafales, plus ou moins nombreuses, fortes et fréquentes, qui dépassent la vitesse choisie.

La mise en drapeau doit être assez progressive pour éviter que les pales, agissant en ventilateur, aient tendance à se rabattre en avant, ce qui rendrait

l'opération dangereuse. Et, une fois la machine arrêtée, quand doit-on la remettre en marche? La mise en marche par vent fort, bien que nous l'ayons également pratiquée, présente aussi des risques. Et si l'on doit attendre l'arrêt complet du vent, on risque de perdre de nombreuses heures de marche à pleine puissance.

Or un calcul simple montre que la poussée du vent sur l'hélice croît avec la vitesse du vent, tant que le calage des pales reste fixe, puis décroît à partir du moment où la régulation « à régime constant » agit en faisant varier ce calage. Si cette régulation fonctionne bien, il semble qu'il y ait moins à craindre du fonctionnement que de l'arrêt de l'hélice par vent de tempête.

A notre avis, la seule chose à prévoir est un détecteur de vibrations, ou un accéléromètre, placé en haut de la tour, et commandant la mise en drapeau en cas de vibrations excessives, quelle qu'en soit la cause.

Conclusions

Nous avons vu que dans notre cas, malgré le vent assez turbulent qui règne dans le site où est placée la machine, il ne s'est jamais posé de problème d'instabilité de l'alternateur par rapport au réseau.

Toutefois, sur un très petit réseau, il est probable que les variations rapides de puissance du vent poseraient un problème de régulation difficile à résoudre, surtout à cause des baisses rapides de puissance, qui devraient fréquemment provoquer la mise en marche d'une machine de secours pour des durées souvent très brèves.

Dans le cas d'un très petit réseau, il est donc conseillé de prévoir au moins trois machines situées à des distances d'au moins 1 km, pour réduire les variations relatives de la puissance produite. Encore faut-il assurer l'écoulement de l'excédent de puissance. Mais ceci semble plus facile, par exemple en débitant sur des résistances liquides, qui peuvent elles-mêmes servir à la distillation d'eau saumâtre.

Pour les vents faibles, les problèmes d'automatisme de mise en marche de l'hélice et de couplage de l'alternateur semblent résolus de manière simple et satisfaisante.

Pour les vents forts, la régulation doit être étudiée pour éviter le pompage, ce qui est notre but actuel.

Une fois ce résultat atteint, il ne semble pas souhaitable d'arrêter systématiquement la machine au-dessus d'une certaine vitesse de vent, car la poussée du vent est alors fonction décroissante de la vitesse lorsque la régulation de puissance s'effectue par variation du calage des pales.

Résumé

Les essais effectués sur l'aérogénérateur expérimental 100 kW Andreau-Enfield, conçu pour débiter sur un réseau triphasé, nous ont permis de faire les observations suivantes.

Par vent moyen, la puissance produite varie constamment dans d'importantes proportions. Le réseau ne s'en est jamais trouvé perturbé, et le régulateur automatique de tension maintient un excellent facteur de puissance.

Par vent faible, ces variations de puissance obligent à effectuer des couplages et découplages très fréquents, si l'on veut éviter tout gaspillage d'énergie.

Par vent fort, le régulateur de puissance, par son « pompage », augmente la fréquence des variations de puissance.

D'où les réglages et modifications effectués ou à effectuer :

a) Pour le couplage, le dispositif initial, à commande manuelle, d'action lente provoquant un fort appel de courant sur le réseau, a été modifié pour être rendu automatique, presque instantané, et pour s'effectuer à puissance presque nulle. De même pour le découplage.

b) La mise en route et l'arrêt de l'hélice ont été également rendus automatiques. Ces différents mécanismes donnent entière satisfaction.

c) Par vent fort, l'amplitude du pompage a pu être réduite en agissant sur la vitesse de changement de pas de l'hélice.

Pour un fonctionnement parfait, il faudrait un régulateur tenant compte non seulement de la vitesse de rotation de l'hélice, mais de sa dérivée.

Ce problème peut se présenter différemment pour d'autres types de machines.

Conclusions

Il ne s'est pas posé pour nous de problème d'instabilité de puissance par vent moyen.

Pour les petits réseaux, les variations rapides et importantes de puissance produite peuvent amener des perturbations dans la tension et la fréquence. Ces perturbations peuvent être réduites par l'emploi de plusieurs aérogénérateurs de puissance moyenne, au lieu d'une seule machine de forte puissance.

Pour les vents faibles, les couplages et découplages très fréquents exigent un automatisme complet, rapide et sûr. Il a été réalisé par des moyens simples et fonctionne correctement.

Pour les vents forts, le régulateur automatique de puissance par variation de pas de l'hélice nous a permis de fonctionner sans incident jusqu'à des vents dépassant 30 m/s.

Lorsque le pompage du régulateur sera éliminé, il semble qu'il n'y ait plus rien à craindre du fonctionnement par vent de tempête.

PROBLEMS OF AUTOMATIC COUPLING OF A WIND-DRIVEN GENERATOR TO A NETWORK

Summary

Tests on the experimental 100 kW Andreau-Enfield wind-driven generator, designed to feed a three-phase network, have permitted us to make the following observations.

In a moderate wind, the power output is always varying over a great range. The network is never disturbed, and the automatic voltage regulator maintains an excellent power factor.

On relatively calm days, these power variations require very frequent coupling and uncoupling if all waste of energy is to be avoided.

In a high wind, the power regulator, by its " pumping " action, increases the frequency of the variations in power.

Hence the adjustments and modifications that have been or will be made :

(*a*) The original manual coupler was slow and drew a large amount of current from the network; it has now been made automatic, almost instantaneous, and operates at close to zero power. The same has been done with the decoupling.

(*b*) Propeller starting and stopping are now automatic. These mechanisms give complete satisfaction.

(*c*) In a high wind, the amplitude of the pumping action could be reduced by modifying the rate of change of the propeller pitch.

Perfect operation requires a regulator taking account not only of the propeller speed but also of its derivative.

This problem may present itself otherwise for different types of machines.

Conclusions

We had no problem of power-output instability in a moderate wind.

For small networks, the rapid and great variations in power may disturb both voltage and frequency. These disturbances may be reduced by using several medium-power wind-driven generators instead of a single high-power machine.

For gentle winds, the very frequent coupling and uncoupling demands complete, rapid and reliable automatic action. It was achieved by simple means and shows satisfactory operation.

For high winds, the automatic power regulator, which operates by changing the propeller pitch, permitted trouble-free operation at wind speeds up to over 30 m/sec.

When the pumping of the regulator has been eliminated, there will apparently be no reason to fear trouble, even when operating at gale force.

RECENT DEVELOPMENTS AND POTENTIAL IMPROVEMENTS IN WIND POWER UTILIZATION FOR USE IN CONNECTION WITH ELECTRICAL NETWORKS IN DENMARK

J. Juul *

The information given below regarding operating results of electric wind mills in connection with electrical networks refers to the plants described under item II B.2. (*a*), i.e., the Bogø mill with a swept area of 132 m² and a maximum capacity of 45 kW and the Gedser mill with a swept area 450 m² and maximum capacity 200 kW. The Bogø mill is erected on the island of Bogø, situated in the waters between the islands of Zealand and Falster.

The Bogø mill was put into operation in the autumn of 1952 and has, virtually without interruption, been connected to the grid system of Sydøstsjællands Elektricitets Aktieselskab (SEAS), and producing electricity whenever the wind velocity was above 5 m/s. The same applies to the Gedser mill since the summer of 1958.

The day and night production of the Gedser and Bogø mills has been worked out daily at 9 am per (24 hour) day, per month and per year.

In table 1 the output in the period from 1/11/1959 to 31/10/1960 is recorded.

The proportional of the swept areas of the two mills is $\frac{450}{132} = 3.4$, but the annual average proportional of the production is 5.1. This is first and foremost due to the wind conditions at Gedser being the more favourable, the Gedser mill being situated near the west coast of the south point of Falster, whereas Bogø is situated in a narrow sound between Zealand and Falster, thus having about the same wind conditions as any inland site.

In table 2, the annual output of the Bogø mill since 1952 is recorded.

By multiplying the figures of table 2 by the proportional 5.1, a figure is found, indicating what the Gedser mill may be supposed to have produced under the same conditions, namely an average, during 8 years, of 410 400 kWh or 12 per cent more than in 1960. The causes of the relatively small production of 1959-1960 were the meteorological conditions, the wind being for an abnormally great number of days easterly and of low velocity with dry weather which made itself felt through lack of rain and consequent drought, especially during the summer of 1959.

Calculations show that the Gedser mill will produce annually about 300 kWh more per m² swept area than the Bogø mill, which shows how important it is to find the most favourable sites for the erection of electric wind mills.

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Table 1

		Gedser mill swept area 450 m² kWh	*Bogo mill swept area 132 m²*	*Proportional* $\frac{450}{132} = 3.4$
1959	November	25 710	6 324	4.06
	December	52 840	11 000	4.80
1960	January	31 460	8 165	3.86
	February	44 640	8 487	5.27
	March	34 180	5 431	6.30
	April	38 340	6 757	5.68
	May	27 390	4 425	6.17
	June	23 980	3 588	6.66
	July[a]	22 000	4 324	5.10
	August	18 920	3 798	5.00
	September	20 840	4 165	5.00
	October	30 740	6 195	5.00
	TOTAL	371 040	72 659	5.1

[a] In July 1960, a defect arose in a relay of the Gedser Mill. Hence, the actual output in this month was only 7 880 kWh, but computed in accordance with the proportional of the two mills (stated in the heading of the third column of the table) the output would have been 22 000 kWh, which figure has been entered in the table as the Gedser mill July output to make a comparison of the annual outputs of the two mills feasible.

Table 2

	Bogo mill output kWh	*Per m² swept area kWh*	*Gedser mill output computed according to proportional kWh*	*Per m² swept area kWh*
1953	87 170	660	445 000	985
1953	90 967	690	464 000	1 030
1953	68 680	520	350 000	780
1953	91 133	690	465 000	1 030
1953	78 191	590	399 000	890
1953	78 502	590	400 000	890
1953	76 363	575	389 000	865
1960	72 659	550	371 040	825
TOTAL	643 665		3 283 040	

Computed average annual output of Gedser mill during 8 years

$$\frac{3\ 283\ 040}{8} = 410\ 400 \text{ kWh}$$

Computed output per m² swept area of Gedser mill

$$\frac{410\ 400}{450} = 910 \text{ kWh}$$

Actual average annual output of Bogo mill during 8 years

$$\frac{643\ 665}{8} = 80\ 457 \text{ kWh}$$

Actual output per m² swept area of Bogo mill

$$\frac{80\ 457}{132} = 610 \text{ kWh}$$

Average proportional

$$\frac{3\ 283\ 040}{643\ 665} = 5.1$$

Experiences — in the technical field — from the Bogø mill are, however, to some extent, the basis of an improved efficiency of the Gedser mill, just as experience has been gained from the Gedser mill which will make it possible to build future electric wind mills of greater efficiency than the Gedser mill.

Both on Bogø and at Gedser, electric wind mills had existed since 1942, producing D.C. in connection with local D.C. power stations with Diesel engines. The Bogø works was taken over by SEAS in 1952, the local electric wind mill being reconstructed for A.C. production and provided with 3 blades with swept area 132 m² instead of 2 blades with swept area 240 m².

The Gedser mill as built in 1942 had 3 blades and 450 m² swept area and produced D.C. in connection with the local works that was taken over by SEAS in 1955 and likewise reconstructed for A.C. production.

Both of these D.C. mills were of modern design with streamlined blades, and, for the purpose of keeping the voltage of the D.C. system constant, were provided with mechanical regulation of the capacity. The mills during the war were exploited to the utmost extent there being a serious shortage of diesel oil.

In table 3 the output of these mills is recorded for the years 1943-46 inclusive.

The table shows the average production per m² swept area to have been 272 and 114 kWh annually; it shows also that under existing local wind conditions an amount of energy of from 3.4 to 5.4 times more per unit area can be turned to account, when electric wind mills are feeding extensive A.C. grid

Table 3

	Gedser mill		*Bogo mill*	
	kWh per annum	*kWh per m² swept area*	*kWh per annum*	*kWh per m² swept area*
1943	135 671	300	29 220	122
1944	125 800	280	28 000	117
1945	117 100	260	31 889	132
1946	113 640	252	20 882	83
TOTAL	492 211	—	109 991	—
Annual average. . .	123 000	272	27 500	114

systems instead of supplying local D.C. works. The reason for this is that the extensive A.C. systems are able to take delivery of a far greater part of the possible output of the mills without its influencing the tension of the local grid system.

The Gedser mill has proved to have a yearly production of 400 000 kWh. By building a large number of this type of mill, the cost of erection for each plant will presumably be about 250 000 D. cr. (about US $38 000).

Summary

During the years from 1947 to 1957 the Sydøstsjœllands Elektricitets Aktieselskab (SEAS) made investigations regarding the possibility of using wind power for supplementing the electricity produced by means of coal, oil and hydraulic power, it being realized that extensive networks for the distribution of electric energy might equally be used for collecting energy produced by many, relatively small wind power plants.

Since 1952, the SEAS has had the " Bogø mill " in continual operation. The said wind power plant, which can render 45 kW, is coupled to the SEAS grid and thus supplements the production of the thermal power works.

Since the month of June 1959 the Danish Wind Power Committee has had the " Gedser mill " (described in detail under item II B. 2 (*a*)) in continual operation. This plant, which can render 200 kW, is also coupled to the SEAS grid.

The Gedser mill has proved to have a yearly production of 400 000 kWh. By building of a large number of this type of mill the cost of erection for each plant will presumably be about 250 000 D. cr. (about US $38 000).

PROGRÈS RÉCENTS ET AMÉLIORATION POSSIBLE DANS LE DOMAINE DE L'UTILISATION DE L'ÉNERGIE ÉOLIENNE CONCERNANT LES RÉSEAUX DE DISTRIBUTION ÉLECTRIQUE DANOIS

Résumé

Au cours des années allant de 1947 à 1957, la société électrique du sud-est de la Zélande (SEAS) a procédé à des travaux de recherches visant à juger de la possibilité d'utiliser l'énergie éolienne comme appoint à la production d'électricité par le charbon, le pétrole et la houille blanche, consciente qu'elle était du fait que d'importants réseaux de distribution d'énergie pourraient également être utilisés pour recueillir l'énergie produite par nombre de centrales éoliennes relativement petites.

La centrale dite « Centrale de Bogø » est en service continu depuis 1952, exploitée par la SEAS. Cette centrale éolienne, qui peut débiter 45 kW, est branchée sur le réseau de la SEAS et son apport s'ajoute à la production des centrales thermiques.

La centrale de Gedser, décrite en détail dans les mémoires se rapportant au point II. B. 2 *a*) de l'ordre du jour, est en fonctionnement continu depuis le mois de juin 1959. Cette installation, capable de débiter 200 kW, est également branchée sur le réseau de la SEAS.

La capacité annuelle de production de courant de la centrale de Gedser est de 400 000 kW/h. Les frais d'établissement de chaque usine s'établiront aux environs de 250 000 couronnes danoises, soit quelque 38 000 dollars des États-Unis, si on construit un grand nombre de centrales de ce type.

ECONOMY AND OPERATION OF WIND POWER PLANTS

J. Juul *

Whether or not it will pay to build electric wind mills for producing in connection with large size A.C. power plants depends on what it costs to supply the energy from a large size power station or, more commonly, from several such power stations. In Denmark the big power stations may be classified in two groups :

1. Modern big power stations, costing about D. cr. 1 000 (£50) per kW to build and producing at a fuel consumption of about 2 800 cal. per kWh.

2. Earlier plants, having cost about D. cr. 600 (£30) per kWh to build and using about 4 000 cal. per kWh produced.

The power produced by these stations generally has to be transformed into 120-150 kV by a main transformer, being then carried through a 120-150 kV network of mains and on through intermediary transformers to a secondary network of 50 kV mains. The 50 kV tension is then transformed down to a 10 kV grid system into which the wind energy can presumably be fed.

The whole of the power for consumption not being

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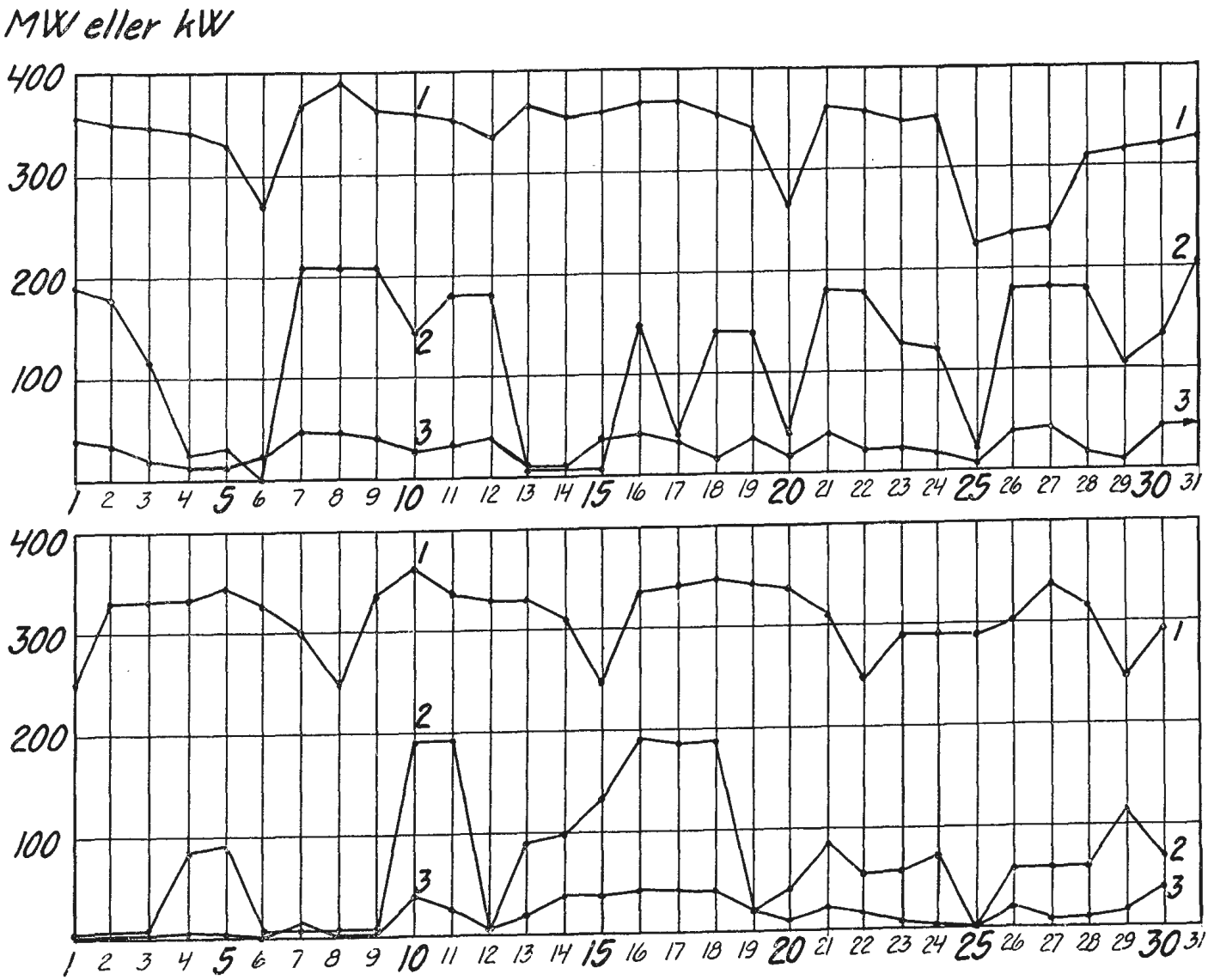


Figure 1. Curve 1. Load curve (indicating MW) of co-operating main power stations on Zealand, in November-December 1959; curve 2. Daily maximum effect in kW of Gedser mill; curve 3. Daily maximum effect in kW of Bogø mill

produced by the most modern power stations and a loss of energy occurring in transformer and mains, and a fuel consumption of about 3 100 cal. per kWh supplied to the 10 kV grid has to be reckoned with.

To the price of fuel should be added expenses for interest and amortization of investments in power stations, transformers and networks sufficient for managing the supply at peak consumption. Further, the overhead charges have to be considered. In Denmark they are generally reckoned to be about D. cr. 100 per kW supplied at maximum load which appears to set in during the month of December when the weather is cold and windy. Consumers then use electricity for heating, the consumption for lighting, use of power and other purposes being high at the same time also.

In figure 1 curve 1 shows how the MW-load of the network of mains of the co-operating Zealand power works was in November-December 1959.

Curves 2 and 3 show the coincident output in kWh from the mills of Gedser and Bogø respectively. On December 8th there was a blizzard and about 8°C below zero. Both mills were then rendering their full effect which coincided with the maximum load of the year. Heavy load may also occur in a calm but it will always be heavier when the weather is cold and windy. Under such conditions the electric wind mills will, of course, also render great effect, relieving power stations as well as network and assisting in maintaining the voltage when the load is heavy on account of heating.

The influence of the 200 kW generator on the operating voltage at Gedser is shown in figure 2. The left side of the diagram shows conditions as they are when the machine is working as a generator and on the right side is shown conditions as they would be if it worked as a motor. In the latter case the loss of voltage will be about twice the amount of the voltage increase when it works as a generator; this is due to its using exciting current from the grid simultaneously with feeding energy into it. Thus, voltage conditions in the grid system near the mill are favourably equalized.

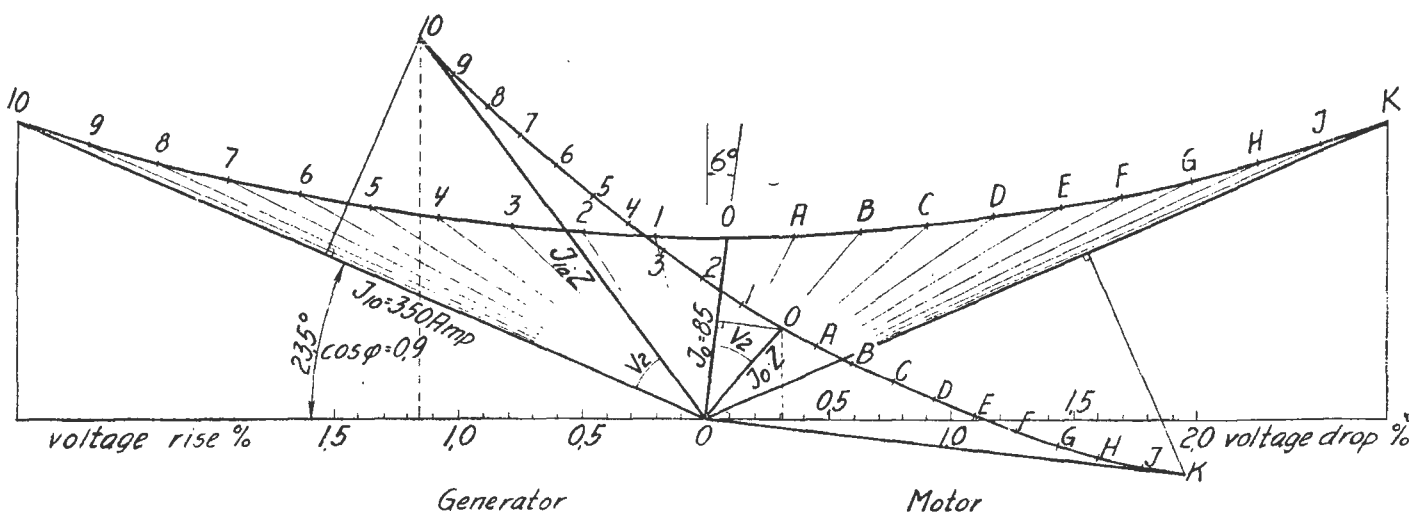
In figure 3 is shown the daily output of the 3 mills in kWh per m² swept area during 84 days at the end of 1958; curve 4 shows the output in kWh per m² swept area of a fourth mill (if erected), as it would be if based on the daily wind velocity measurements of the Danish Meteorological Institute.

Curve 1 refers to the Gedser mill, curve 2 refers to the Bogø mill, curve 3 refers to the Vester Egesborg mill, curve 4 is based on Meteorological Institute measurements, curve 5 shows average of curves 1-4.

It appears from figure 3 that a considerable equalization of the produced energy takes place during the daily operation when the mills are situated within a distance from each other of 150 km — or more, as in the case of the above mentioned mills.

Wind power does not only occur seasonably with regard to relieving thermal power stations and networks under peak load but is also available during the period of the year when it is most needed; this appears in figure 4.

Figure 4 shows average monthly production over 3 years of the Vester Egesborg and Bogø mills,



Loadcurrent and voltage drop at different loads of an asynchronous machine connected to the grid by a 10kV overhead line of 10km length.

Specification for the asynchronous machine: 3×380 volt, 350 amp, 50 cycles
J_0=85 amp, J_k=2200 amp, 8 pole

Specification for the overhead line: Resistance R = 7 ohm
Reactance X = 4 "

Figure 2. Diagram showing current and voltage of the Gedser mill asynchronous generator. 200 kW — 3 × 380 V — 350 amp. — 50 periods — J_0 (idling) = 85 amp. — J_k (short circuit) = 2 200 amp. 8-polar — connected to transformer 380/10 000 V. Network resistance r = 7 ohm. Reactance x = 4 ohm — the diagram shows voltage rise and fall when the machine is working as generator and motor, respectively

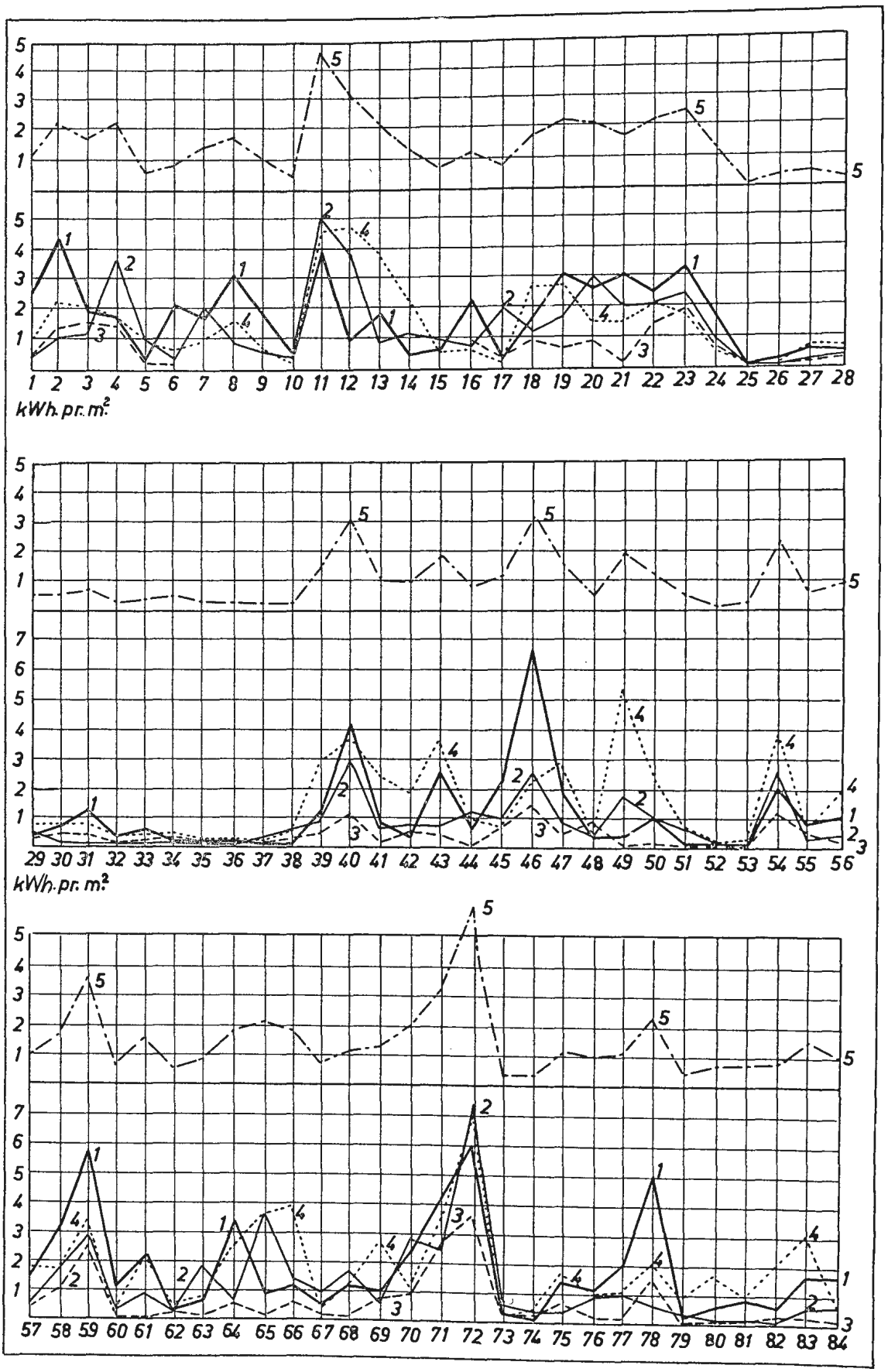


Figure 3. Daily output of the three experimental mills during 84 days of the autumn of 1958 shown in per cent of max. load : curve 1, Gedser mill; curve 2, Bogø mill; curve 3, Vester Egesborg mill; curve 4, output of a mill (if erected) as based on wind measurements of Meteorological Institute, Copenhagen; curve 5, average output in per cent of max. output

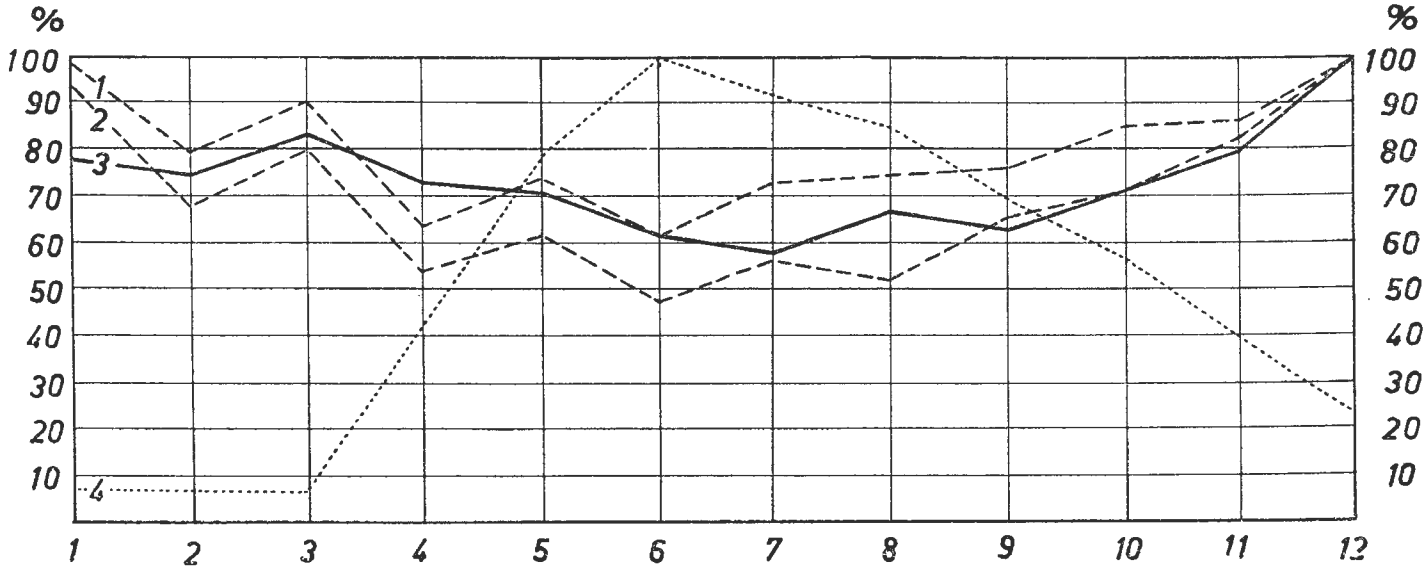


Figure 4. Average monthly output and consumption over 3 years, shown in per cent of maximum : curve 1, Gedser mill; curve 2, Bogø mill; curve 3, total consumption from SEAS network; curve 4, annual rate of water flow of Scandinavian river

expressed in per cent of the maximal monthly production which occurs in December, as does the peak of SEAS's curve of power sold to consumers, as mentioned above. The three curves in the figure appear to have a tendency to run parallel. This does not apply to curve 4 representing the occurrence in Scandinavia of hydraulic power, which has its minimum in the winter months, contrary to consumption and wind power. The latter therefore is of great value when utilized in parallel operation with hydraulic power, especially when there is a possibility of damming the water for some days, so that the hydraulic power can take over the production during a calm. In Denmark, where coal and oil do not occur naturally and hydraulic power is available to an insignificant extent only, great difficulties with satisfying the power demand were met with during the two world wars. Supplies from abroad almost came to a stop and available fuel was very expensive.

It therefore became necessary to have recourse to local lignite and peat. Another important power reserve available at that time was the great number of wind motors found on farms all over the country. About 3 000 big industrial mills with swept areas of about 20 m diameter were also at disposal and partly managed the grinding.

By now, the mills have almost entirely disappeared and the same to a considerable extent is true of lignite and peat, so that a stopping of the supply from abroad of coal and oil would be a catastrophe.

A critical situation like this can partly be alleviated by a suitable number of electric wind mills which will satisfy part of the demand and eke out the scant amounts of fuel.

All things considered, I should think electric wind mills have the greatest value where conditions are like those prevailing in Denmark.

Coal and oil prices have always been strongly fluctuating and during the two world wars prices were very high. It would therefore seem natural to calculate with the average of prices during the last 10 years as shown by figure 5 and table 1.

From this it appears that prices at present (i.e., spring of 1961) are very low and that they have varied by more than 100 per cent during the last decade.

It appears also that average prices of coal and oil are, by and large, equal, namely 4 281 and 4 218 øre

Cost of fuel per kWh produced and delivered into 10 kV grid

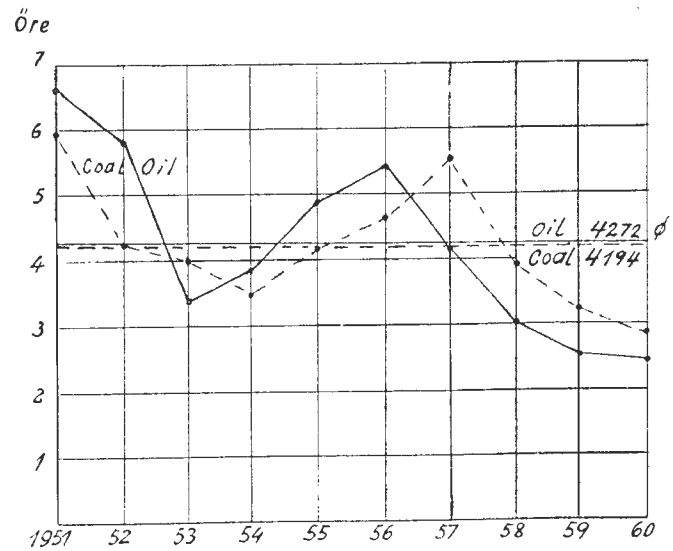


Figure 5. Fuel prices for the period 1951-1961 : curve 1, prices in Danish øre of 3 400 cal., coal; curve 2, prices in Danish øre 3 400 cal., oil

Table 1

	Danish crowns per 10^6 cal		Danish "ore" per 3 100 cal	
	Coal	Oil	Coal	Oil
1951 . .	19.00	21.00	5.89	6.51
1952 . .	13.80	19.00	4.27	5.89
1953 . .	12.80	11.00	3.97	3.41
1954 . .	11.17	12.36	3.46	3.83
1955 . .	13.32	15.70	4.13	4.86
1956 . .	14.95	17.55	4.52	5.44
1957 . .	17.85	13.40	5.53	4.15
1958 . .	12.70	9.80	3.93	3.03
1959 . .	10.50	8.50	3.26	2.65
1960 . .	9.30	7.90	2.88	2.50
	13.35	13.61	4.184	4.227

for a quantity rendering the 3 100 cal necessary for supplying 1 kWh to the 10 kV grid system.

When — for comparison with the cost of power produced in the conventional way as mentioned above — I calculate the value of annual production of the Gedser mill as supplied to a 10 kV grid, I arrive at the following figures :

	D. cr.
200 kW effect at D. cr. 100 a kW	20 000
410 000 kWh at 4.2 øre a kWh	17 220
	37 220

The expenses connected with supplying power produced by electric wind mills depend upon various factors, especially payment of interest and amortization of the plants.

Supposing that electric wind mills will normally be built when rate of interest is low and employment lacking, capital should presumably be obtainable at 6 per cent per annum. The life of electric wind mills as compared with other kinds of machinery is long. By way of examples, I may mention that in Denmark wind mills are to be found made of wood, and of old-fashioned design, that are more than 100 years old but still in operation, and that plants of more recent design exist, made of steel and over 30 years old, are also still operating.

A period of amortization of 25 years, according to my judgement, should be warrantable, and a cost of construction of D. cr. 250 000 per 200 kW unit is probable, in view of the experience gained during the erection and mounting of the Gedser mill which it cost D. cr. 270 000 to make by craftsmanlike methods.

Supposing a battery consisting of 100 units is built in a locality with good wind conditions and within an area having about 50 km maximum distance from its centre. It will presumably be possible for a team of eight workmen — two of them in each of four tool wagons — and a managing technician to inspect, maintain and repair the battery. The economic synopsis will then be the following:

Cost of erection 100 × 250 000 = D. cr. 25 000 000

Annual expenses :

	D. cr.
25 000 000 at 6 per cent interest and 2 per cent repayment	200 000
Wages of team for maintenance etc. 8 × 15 000	120 000
Management and office expenses	50 000
Travelling (tool wagons etc.) 100 000 km annually, D. cr. 0.50 a km.	50 000
Maintenance, insurance and repairs	200 000
	2 420 000

As mentioned above, the value of the annual output of an electric wind mill — for comparison with energy and effect from ordinary main power stations — will be D. cr. 37 220, i.e.,

	D. cr.
For 100 units	3 722 000
Estimated expenses deducted	2 420 000
Annual excess of income over expenditure . .	1 302 000

The surplus obviously should be used for consolidation and, on the consolidation attaining suitable proportions, for reducing the prices of the 20 MW and the 41 000 000 kWh.

A battery of 100 units will have a total swept area equalling 4.5 ha (just over 11 acres) in the vertical plane. From this it will appear that, in a country like Denmark, there is much more energy in the power of the wind than the country will ever need.

The extent to which it is warrantable to utilize wind power is a question that may be left open for the present, but according to my own judgement, I should say that about 20 per cent of the annual consumption of this country ought to be produced by wind power and that the experimental work has shown it to be warrantable to start the erection of wind mills in Denmark, as it offers the following advantages:

A home source of energy of almost unlimited extent can be utilized and ward off a state of catastrophe in case the fuel supply from abroad fails or prices rise materially.

Payments in foreign exchange can be saved.

The energy of the wind can be fed into the ubiquitous networks in an economically sound way by means of plants of the Gedser mill type, the experiments having proved the technical difficulties to be surmountable.

Possibilities of improving this type of plant, constructionally and economically.

The plants can be built by using local labour and locally available materials to the extent of about 80 per cent of every plant.

It appears that future plants can be built so that considerably greater amounts of effect and energy can be obtained by mounting several sets of blades together on one common higher frame.

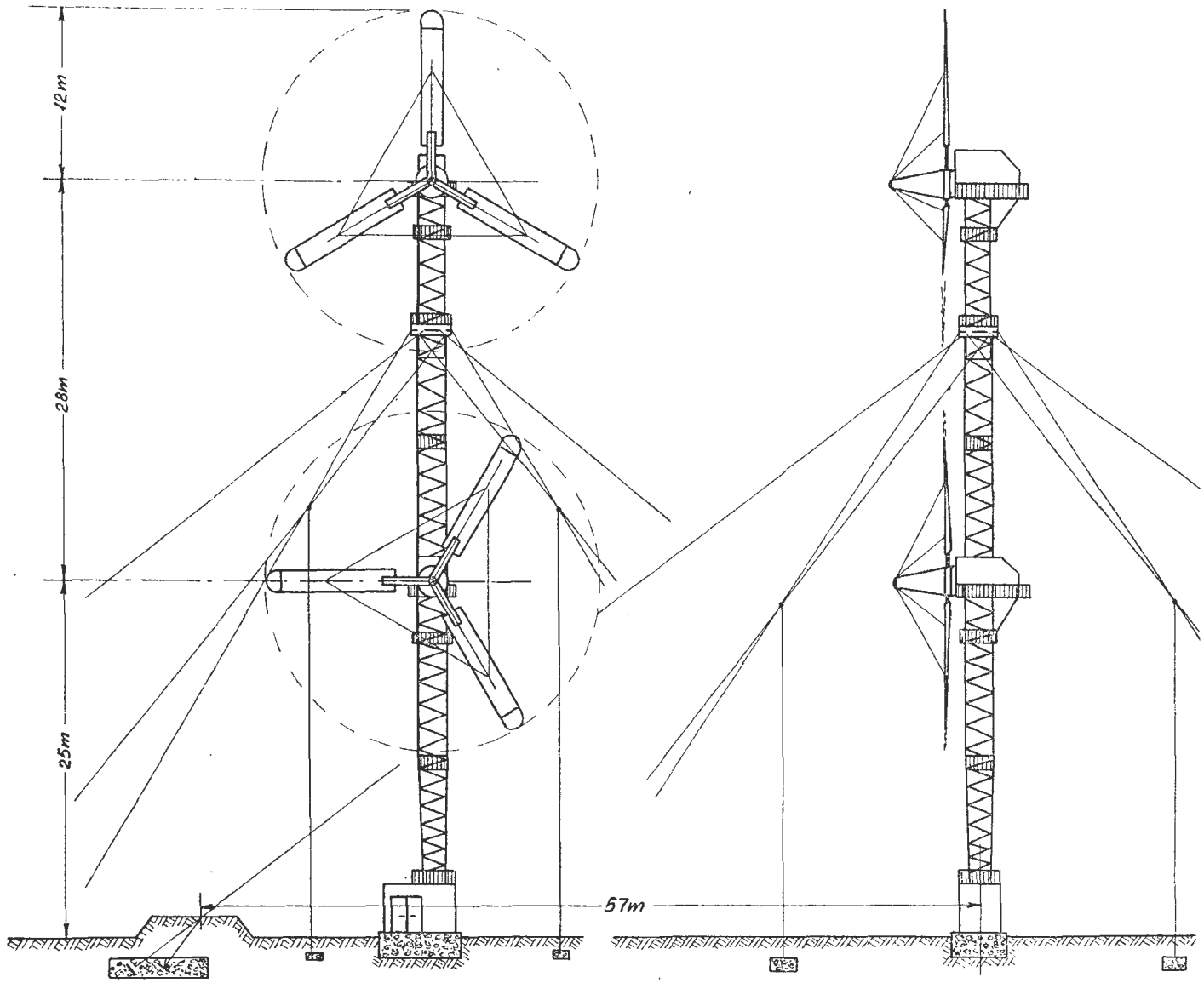


Figure 6. Duplex mill 2 × 200 kW at 38 m/s blade tip velocity; duplex mill 2 × 300 kW at 50 m/s blade tip velocity Annual output in either case 1 000 000 kWh

The simplest form of a device of this kind is the one shown in figure 6 having 2 sets of blades on a 55 m high tower, supported by stays fixed to a collar inside which the tower will turn when yawing. This construction is cheaper than two separate towers and creates no technical difficulties with regard to construction. The topmost set of blades is thus elevated to a height of 55 m — at which height the wind energy considerably exceeds that of 25 m. — Figure 7 shows wind measurements from 1959. Curve 1 is measured at 45 m height at the Gedser mill, curve 2 is measured in the same place at 25 m height, curve 3 is computed on the basis of the Meteorological Institute daily records as measured at 20 m height, while curve 4 is measured at 12 m height near the Vester Egesborg mill. Curve 5 shows the efficiency of the Gedser mill at a blade tip velocity of 38 m/s. If this velocity is increased to 50 m/s by using a generator of 1 000 rpm instead of 750 rpm, the mill will not begin to render any energy till at 7 m/s wind velocity, but then, on the other hand, it will render more at the higher wind velocity, so that the annual amount of energy will be at least as great as if it operates at 38 m/s blade tip velocity only. As shown by curves 5 and 6, the efficiency of the mill at 38 m/s blade tip velocity is somewhat greater than at 50 m/s blade tip velocity, which is due to the greater frictional loss of energy of the blades in the air. The topmost set of blades, according to the wind measurements taken, should render about 40 per cent more than the lower set.

At 50 m/s blade tip velocity the axial pressure will also be increased and this necessitates the use of somewhat heavier material for tower and blades. But as the increased amount of energy is attained through an increase of blade tip velocity, the transmission parts and the generator become only slightly more expensive in spite of a 50 per cent increase of the effect. The value of the annual output of

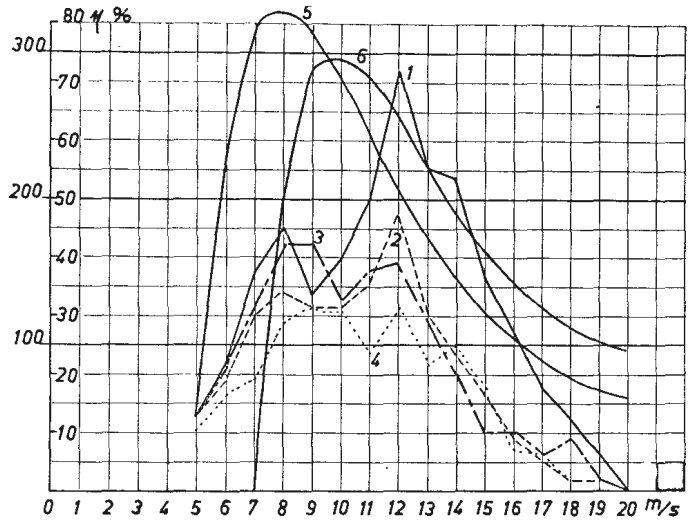


Figure 7. Efficiency of Gedser mill at blade tip velocities 38 m/s and 50 m/s and wind measurements : curve 1, proportional of wind energy at 50 m height at Gedser; curve 2, proportional of wind energy at 25 m height at Gedser; curve 3, proportional of wind energy at 20 m height at Meteor. Inst. Copenhagen; curve 4, proportional of wind energy at 12 m height at V. Egesborg; curve 5, efficiency of Gedser mill at 38 m/s blade tip velocity; curve 6, efficiency of Gedser mill at 50 m/s blade tip velocity

this kind of plant at Gedser can be estimated thus :

The lower blade set will render 300 kW effect and	410 000 kWh
The topmost blade set will render 300 kW effect and	550 000 kWh
TOTAL YIELD 600 kW effect and	960 000 kWh
	D. cr.
The value of 600 kW effect is	60 000
The value of 960 000 kWh at 4.2 øre is . .	40 320
	100 320
2 mills of the Gedser mill type will render . .	74 440
Difference	25 880

which means a 35 per cent increase of annual output value as compared with that of the Gedser mill.

Along the west coast of Jutland and especially the northern part of it, there is considerably more wind energy and more effect to be had during a considerably greater number of hours annually.

During the testing of the Gedser mill in co-operation with the Electrical Research Association engineers, pulsations, by means of an automatically recording wattmeter with fast travelling recording tape, were found to appear in the effect rendered by the mill. The pulsations were of an amplitude of about plus and minus 25 kW and an average frequency of about 1.35 times the rpm. The pulsations appeared when even a gentle breeze was blowing and were present as a superposition or upper layer on the effect surges due to variations of the wind velocity. The cause of the pulsations could not immediately be identified and as it was to be feared that they might be due to mechanical conditions in the construction, an expert theorist on mechanical vibrations in building constructions, Højlund Rasmussen of Copenhagen, was approached and requested to investigate the matter. He did not find the cause of the pulsations, but was able to ascertain that the variations of the mill effect, of the order of magnitude measured, offered no danger to the constructional parts of the mill. However, I started investigating the phenomenon at the Gedser mill at various wind velocities and various angles of attack of the wind on the swept area, supposing the pulsations to be due to aerodynamic causes. By means of an automatically recording wattmeter, with a recording tape travelling 25 mm/s, the pulsations could be measured, although with less sensitivity than that of the English instrument. In the same manner, conditions were investigated at the Vester Egesborg and Bogø mills as well as at a 4-blade Lykkegaard mill with a swept area of 18 m diameter. In all the mills investigated, pulsations could be stated to a greater or less extent, differing in frequency from the rpm of the mills, i.e., from about 0.8 in the two smaller experimental mills to 1.35 in the Gedser mill and this frequency could be altered to 1.26 and 1.57 by yawing the mill 10° to the right and left of the position of the swept area when perpendicular to the wind. The Lykkegaard mill was driving a differentially compound wound D.C. dynamo, which has a very soft characteristic and consequently gives very slight pulsations only, but when the dynamo was coupled for working as an ordinary compound wound machine, thereby getting a hard characteristic, it gave pulsations to a marked degree. On another occasion, a Lykkegaard mill was found to give very strong pulsation on being coupled to an A.C. generator with a small slip.

The Vester Egesborg and Bogø mills have generators with 5 per cent and 4 per cent slip respectively, whereas the Gedser mill generator has 1 per cent slip only. Hence it has a considerably stiffer characteristic than the other two generators and has a relatively much stronger pulsation of the effect than where the generator has greater slip and more flexibility in the mechanical transmission of effect from the main shaft of the blades to the generator shaft.

Generators, coupled to electric wind mills, should therefore be constructed so as to have a suitably greater slip. The efficiency, to be true, is thereby reduced, almost in proportion to the increase of generator slip. But, as an offset, the mill will render its effect at greater variations of its blade tip velocity. At Gedser the pulsations are not perceptible in the network tension, but where the grid system is of smaller dimensions, it is conceivable that they will be so. Pulsations of the kind described above can be rendered harmless by using generators with 3-4 per cent slip; thereby the further advantage is gained of obtaining an increased selectivity between centrifugal relay and return current relay, so that a damping of the latter can be avoided.

The occurrence of the pulsations can be explained by the fact that the wind does not attack the swept

area perpendicularly. This is partly because the Gedser mill swept area has an inclination of 10°, as shown in figure 8, in order that a sufficient distance of the blade tips (when in bottom position) from the tower can be obtained and partly because the wind, on account of its turbulence, hardly ever attacks the blades perpendicularly. The wind, besides, has greater velocity at the top part of the swept area than at the bottom part.

It appears from figure 7 that the blades, when moving from their bottom to their top position, have moved relatively 4 m down wind thus making a negative component to the wind velocity. When moving from top to bottom position they make a corresponding positive component, the instantaneous value of which is expressed by the formula

$$4 \times \frac{\pi}{2} \times \sin \phi$$

In horizontal position of a blade the component has its maximum value, $\sin \phi$ then being equal to 1 and the component is then computed to be equal to

$$1 \times \frac{4\ \pi}{2} = 6.3 \text{ m/s}$$

When the blade, for instance, in a wind velocity of 8 m/s is passing the horizontal position on its way upwards, it is attacked by a wind of velocity (8 — 6.3) m/s = 1.7 m/s, thus rendering a negative effect; whereas on its downward path it is attacked by a wind of velocity (8 + 6.3) m/s = 14.3 m/s. At this relative wind velocity it will already have started stalling, thus rendering reduced effect.

To the constant component deriving from the inclination, however, are added sub-components all the time, the direction of the attacking wind varying on account of turbulence. Consequently, amplitude and frequency of the pulsations vary as well. This, to a great extent, is due to another influence also; each blade forming a channel, a wake, of retarded and turbulent wind. The wake starts at a little distance in front of the blade and on its sides; behind the mill it is shaped spirally.

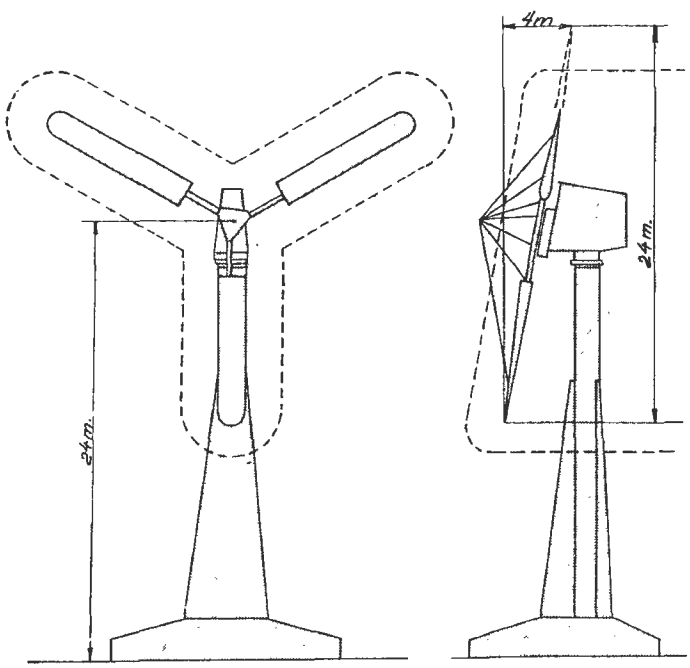


Figure 8. Profile of Gedser mill. Inclination of blades 10°

At the Gedser mill, in wind velocities up to 12-15 m/s, a mutual interference of the wakes is the rule, mostly, one blade running into the wake of the one ahead of it, thus having its effect reduced.

On the face of it, the blades might be supposed to share the wind equally, but generally this is not so, apparently because a gust from either side may displace the wake of a blade, causing the following blade either to run into it altogether or to run clear of it, depending on whether the gust comes from one side or the other. In the latter case, i.e., when running clear, the blade will render great effect, forming a wide wake which, however, influences the other blades thus causing them to render less effect. This is easily ascertained by a person standing near the blade, the difference of the swishing sounds of the blades being plainly audible. It appears, also, that a blade, once having taken the lead, will keep it for a lengthy period until a gust alters the situation once more.

From this it is evident that each blade acts as an independent source of energy, pulsating with a frequency corresponding to the rpm of the mill.

The indication of the wattmeter is thus a summation of energy from 3 sources of energy, pulsating with varying amplitude and frequency and forming another pulsation pattern with a different amplitude and frequency.

These conditions are recorded in figure 9 which shows registered curves of the Gedser mill effect in fairly high wind of 10-14 m/s velocity. On curves 1 and 2 are a few places where pulsations cease, the wind being momentarily sufficient for all of the three blades, which cause pulsations of the same extent which are levelled out in the 3-phase system of the blades.

Curves 2 and 3 were registered under the same wind conditions as curve 1, the mill being yawed 10° to the left and right respectively of the wind direction at the time. It appears from the curves that the pulsations materially alter in these circumstances according to whether the slanting gusts attack a blade on its upward or downward path.

Curve 4 is recorded at 6-8 m/s wind velocity and shows more regular pulsations, there being constant interference of the blades, one blade continually pulling more than the two others.

This goes to show that a mill should have its blades mounted either very nearly vertically or else completely vertically on a lattice tower and that there should be either a mechanically resilient coupling to the generator or else the latter should have a slip fixed empirically at 3-4 per cent. The pulsations will then be without practical significance and the efficiency be increased.

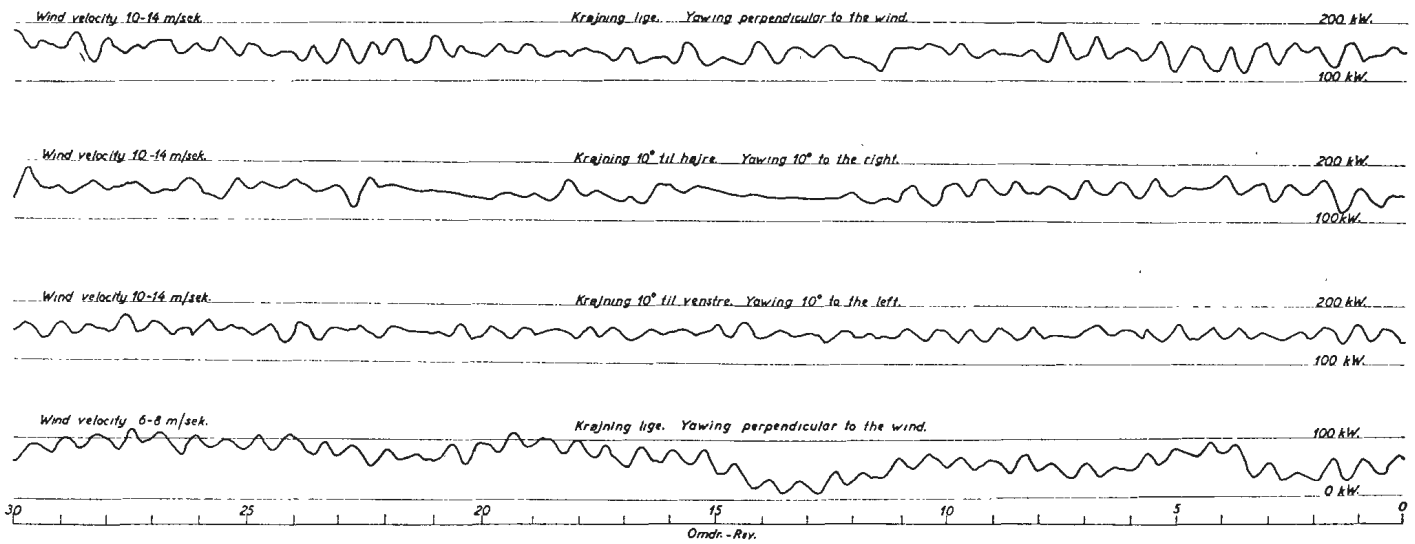


Figure 9. Recording tape diagrams, Gedser mill : curve 1, effect of Gedser mill with swept area perpendicular on wind direction and at 10-14 m/s wind velocity; curve 2, effect of Gedser mill when yawed 10° to the right of perpendicular; curve 3, effect of Gedser mill when yawed 10° to the left of perpendicular; curve 4, effect of Gedser mill perpendicular on wind direction at 6-8 m/s wind velocity

Organization and financing of wind power plants

The existence of modern society is dependent upon the electricity supply being in good order and being distributed in the cheapest possible manner.

Research and practical experience have shown that wind power can be used for taking over a material part of the energy production in an economically sound way, where wind conditions are like those prevailing in Denmark.

By the erection of electric wind mills, the advantage is gained of being able to obtain the strictly needful amount of power by means of a locally available source of power; this may become of inestimable importance in such critical cases as have been experienced during the last 47 years.

How best to solve the problems of supplying wind power is presumably rather a political question, but one of the following solutions may be used:

1. The existing power supply companies take it upon themselves to have the necessary number of electric wind mills built under their own technical and administrative auspices, financing the undertaking in the usual way.

2. A nation-wide company is formed for the sole purposes of having the necessary number of electric wind mills erected and of selling the output and the effect to existing power works and supply companies. A company of this nature should obviously be a limited liability company with existing power works and possibly the state as main shareholders and with possibilities of floating loans guaranteed by the state.

3. The state takes the entire task in hand, decreeing that existing power works must take delivery of a suitable proportion of the wind electricity produced.

Summary

In the papers on Danish wind power plants, (agenda items II.B.2 (*a*) and II.B.3 (*c*)), it is stated that no technical difficulties are connected with the transmission of wind energy to extensive electrical networks and that about 1 000 kWh per m² swept area can be transmitted wherever the mean annual wind velocity is about 6 m/s.

Whether or not it will pay, on this basis, to build wind power plants on a large scale depends, first and foremost, upon the price at which the plants can be erected as well as on the price at which electricity can be produced by the conventional power works.

It has often been alleged that the practical value of wind power plants corresponds only to the value of fuel saved and that no value, as regards effect, can be ascribed to wind power plants, due to the fact that the wind is not always blowing and also because, to secure a continual supply of electricity, it is necessary at all times to have the full effect available from other machinery.

In the following paper it is explained that wind power plants, with regard to effect, are of value also, seeing that wind power is available especially when most needed, namely in the month of December. In the said month, the power works carry a heavy load partly because of electrical heating of dwellings which is used not only when the weather is cold, but particularly so when it is windy as well.

Under these circumstances wind power works attain their maximum value which should not be under-rated. Above all, wind power plants will be

able to function as a substitute for fuel from abroad, which experience has shown may run short in Denmark, and the price of which may vary very strongly.

The building of wind power plants may, besides, serve as a means of adjustment of the Danish labour market, about 80 per cent of the building costs being workers' wages.

It is of course difficult to render in plain figures the value of the two last-mentioned advantages of wind power plants and in any case it will be a question of judgement.

On the basis of such operating experience as has been gained from the Danish experimental plants, I should think that wind power plants, in circumstances such as those prevailing in Denmark, may be considered to have the same value as conventional thermal power stations, in view of the fact that the latter have not, at all times, full effect either, because defects may occur which have to be remedied and because of periodical inspections and repairs.

When operating, the Gedser mill is found to render its effect in pulsations, in surges not in phase with the rpm of the mill, and the pulsations are found to be superimposed on such variations of the effect as are due to variations of the wind velocity. Some doubt has been felt as to whether the pulsations are due to vibrations of the blades of the mill or to aerodynamic causes or perhaps to both. In the paper I have given an explanation of the aerodynamic conditions which I believe to be the cause of the pulsations.

ÉCONOMIE ET EXPLOITATION DES CENTRALES ÉLECTRIQUES ÉOLIENNES

Résumé

On fait observer, dans les mémoires portant sur les centrales danoises à énergie éolienne, (points II.B.2 *a*) et II.B.3 *c*) de l'ordre du jour), qu'il n'existe pas de difficultés techniques ayant trait à la transmission d'énergie éolienne à des réseaux électriques importants et qu'il est possible de leur fournir environ 1 000 kW/h par mètre carré de surface balayée partout où la vitesse du vent est de l'ordre de 6 m/s.

La question de savoir s'il sera économiquement indiqué de construire des centrales éoliennes à grande échelle, compte tenu de ce qui précède, est conditionnée au premier chef par le coût de construction des centrales, ainsi que par le prix auquel l'électricité peut être débitée par les installations classiques.

On a souvent allégué que la valeur pratique des centrales éoliennes ne correspond qu'à la valeur du combustible économisé et que l'on ne saurait attribuer aucune valeur à de telles centrales quant à ce qu'elles débitent, car le vent ne souffle pas toujours et, dans la mesure où l'on veut assurer une fourniture continue d'électricité, il est toujours nécessaire de disposer du plein débit des autres centrales.

On explique, dans le mémoire ci-joint, pourquoi les centrales éoliennes ont également leur valeur dans ce domaine, car l'énergie du vent est disponible particulièrement au moment où elle présente son maximum d'utilité, c'est-à-dire au mois de décembre. Au cours de ce mois, toutes les centrales doivent faire face à une lourde charge, particulièrement en raison du chauffage des locaux que l'on met en œuvre chaque fois qu'il fait froid, mais plus spécialement quand le vent vient aggraver ce froid.

Compte tenu de ces considérations, on peut voir que la valeur des centrales éoliennes est alors à son maximum, avantage qu'il faut pleinement reconnaître. Avant toute chose, ces centrales pourront éviter la consommation d'une certaine quantité du combustible qui doit être importé de l'étranger, dont une insuffisance peut se présenter au Danemark, ainsi qu'on le sait par expérience, et dont le prix peut subir de très grosses variations.

Par ailleurs, la construction de centrales éoliennes pourrait servir de « volant » au marché du travail du Danemark, pour autant que 80 p. 100 environ de son coût représentent la main-d'œuvre.

Il est évidemment très difficile d'exprimer clairement par des chiffres la valeur des deux derniers avantages que nous avons signalés pour les centrales éoliennes et, en tout état de cause, il s'agira en fin de compte de faire un choix.

En se fondant sur l'expérience de l'exploitation acquise avec les centrales expérimentales danoises, on peut dire que les installations éoliennes, dans des circonstances telles que celles qui se présentent au Danemark, peuvent être considérées comme ayant la même utilité que les centrales thermiques classiques, pour autant que ces dernières ne donnent pas toujours au maximum, elles non plus, si on se rappelle qu'elles peuvent se heurter à des difficultés de fonctionnement auxquelles il faut remédier et qu'elles doivent faire l'objet d'inspections et de réparations périodiques.

On a observé que la centrale de Gedser, quand elle fonctionne, débite par impulsions, par poussées qui ne sont pas synchrones avec le régime de rotation des pales, et que les pulsations se superposent aux variations de débit qui s'expliquent par celles de la vitesse du vent. On s'est demandé si les pulsations doivent être attribuées à des vibrations des pales de l'aéromoteur, à des causes aérodynamiques ou, le cas échéant, à ces deux phénomènes. Dans le texte du mémoire, on présente une explication des conditions aérodynamiques que l'on croit être la cause des pulsations.

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