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Agricultural Engineering

WINDMILLS FOR WATER LIFTING
AND THE
GENERATION OF ELECTRICITY ON THE FARM

by

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FOREWORD

This Informal Working Bulletin issued in our Agricultural Engineering Series, reviews the developments that have been taking place in the utilization of wind power for agricultural purposes.

Although much has been written on the subject of wind power, especially during the last few years, the emphasis has mostly been on large scale production of electricity by wind power, rather than its possibilities for the purposes of water pumping and the generation of electricity on a domestic scale.

The purpose of this Bulletin is to provide information, mainly of a practical nature, for the benefit of those agricultural workers responsible for power supplies on farms which have little immediate prospect of connection to main power networks, or where the difficulty in transporting fuel may render oil produced power expensive. The Bulletin concentrates on wind power for agricultural use.

In the introduction the Bulletin describes research and development work that has been made towards several new experimental machines. Where these are of a small capacity of up to 20 H.P. there is a prospect of their being used in the future for large farms, or for rural communities, and there is little doubt that they would be of great benefit if they are proved to be satisfactory in service and economical in cost. However, the use of wind power on farms does not depend upon such developments. Already there are satisfactory, though somewhat small, machines on the market, and sufficient experience has been gained during the last two to three decades to justify recommendation of them.

The Bulletin further points out that wind power utilization, if it is to be economical, is not merely a question of buying a machine and installing it anywhere, for subsequent operation. The Bulletin indicates the many factors, such as the climatic, topographical, economical, and social, that should be taken into account if a wind power project of any significant size is to be carried out successfully.

These subjects are dealt with fully in the various chapters, and the text is illustrated with photographs and diagrams which assist in clarifying the points made in the text. It is hoped this Bulletin will assist all those associated with, and interested in, the use of wind power, both for water lifting and the generation of electricity on the farm.

The material in this Bulletin has been assembled and prepared by Mr. E.W. Golding, who, since 1945, has been Assistant Director, Head of Rural Electrification and Wind Power Department and Overseas Liaison Officer of the Electrical Research Association of the United Kingdom.

Mr. Golding is a well-known international authority in the field of wind power research and development and is a member of the Arid Zone Panel of the United Nations Educational, Scientific and Cultural Organization. He has undertaken a number of missions for the UN and its specialized agencies to advise governments on the use of wind power and the development of local energy resources to supply power for isolated areas. These missions have taken him, among other countries, to Israel, India, Somalia, Haiti, Uruguay and the United Arab Republic.

Mr. Golding is the author of a number of technical books, including "The Generation of Electricity by Wind Power".

A comprehensive list of selected references are cited to enable those readers who desire further information on the subject to obtain appropriate publications. In addition, a list of some manufacturers of windmills, with their addresses, is appended. The very nature of such a list, however, renders it impossible to include all windmills that are on the market in the various countries, and it must also be understood that those manufacturers mentioned are not necessarily recommended in preference to others who are not.

This Informal Working Bulletin will be revised and later published in FAO's Agricultural Development Series. Therefore suggestions for the expansion and improvement of the text are invited from those readers who receive copies. All comments and suggestions should be addressed to:

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CONTENTS

INTRODUCTION

Long ago man became conscious of his own very limited capacity as a power unit - as an "engine" - and sought some assistance to enable him to increase his productivity and so to improve his standard of living. First he used animals, and found, for example, that a horse could exert 7 to 10 times as much power as he could himself. But domestic working animals need food and, although they have given good service to agriculture for centuries, it is undeniable that their food consumption can be a serious drain on the resources of small farmers.

The next step in power development was the exploitation of natural sources of energy* and those having motive form were the most obvious. They were the wind and flowing water, both of which possess energy (or capacity for doing work) because of their mass and their velocity. Unfortunately, wind, which for power purposes is to be considered as a column of air in motion, possesses much less energy than that of a similar column of water moving at the same speed: this is because its mass, per unit of volume, is some 800 times less than that of water.

Windmills and water mills, at first very simply built and later being developed into more complicated, and more efficient, machines, were installed wherever the wind was sufficiently strong or flowing water was available. Obviously the choice of sites for windmills was not so restricted as for those for water mills which had, of course, to be built on the banks of streams. This comparative freedom in choosing the locations of windmills was an advantage - and, indeed, remains an advantage - over water mills and counterbalances, in some small degree, the disadvantage of their relatively large size for a given power capacity.

The subsequent histories of these two power sources, first introduced many centuries ago, were very similar until the latter half of the nineteenth century. Windmills, particularly the large ones used for corn grinding and for drainage, then declined in numbers while water mills, developed into turbines built in large sizes for hydro-electric purposes, went ahead rapidly: at the present time, there are water turbines having individual capacities of several hundred thousand h.p. The main reason for this difference in progress during the last few decades is the unpredictability of the wind: even in very windy places there is no absolute certainty that the wind will blow sufficiently strongly for power production, at any particular time. Wind-driven machines, therefore, are not well suited to the supply of power for

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* It is very important to understand clearly the relationship between the terms "energy" and "power". <u>Energy</u> is defined scientifically as "the capacity for doing work" where "work" is understood to be the result of applying a force through a distance, the direction of the force being the same as that of the movement. <u>Power</u> is "the rate of doing work or of expending energy".

Energy, or work, is measured in units which take into account both the force exerted and the distance moved. Common units are the "foot-pound", or the "kilogram-metre". The corresponding units of power are the foot-pound per second or the kilogram-metre per second. These power units are, however, rather small for practical purposes and one horse power (equal to 550 foot-pounds per second) or, in the metric system, one cheval-vapeur (75 kilogram-metres per second) are used more commonly. There is very little difference in magnitude between these two units: 1 C.V. = 0.986 H.P.

general purposes unless arrangements can be made to store energy as a source of power during periods of calm weather. The windmills were displaced by steam- or oil-engines, or by electric motors, capable of giving power at any time. There was also, in the more industrialized countries, a strong tendency towards concentrating power production in large, efficient, power stations instead of using a large number of small, scattered units such as the windmills represented.

The Power in the Wind

Wind is, of course, a free and inexhaustible source of energy but its economy and practical potentialities depend - as indeed they do with any other natural energy resource - upon the cost of harnessing it. To gain an impression of the problem involved, we can consider the wind as a horizontal stream of air moving at a speed which is, in fact, continually varying in both magnitude and direction but which remains steady enough, over significant periods of time, for it to exert a usuable pressure on any object placed in its path. This pressure is proportional to the square of the wind speed while the power in the wind stream is proportional to the cube of this speed. The formula for this power P, is $P = k.A.V^3$ where A is the cross-sectional area of the wind stream and V is the wind speed. The factor k is a constant the value of which depends upon the density of the air and on the units used for the measurement of P, A and V. If P is expressed in horse power, A in square feet and V in miles per hour, k has the value 0.0000071. Other values for this constant, with different units for P, A and V, are given in Table 1 (see also Ref. 14).

Table 1

Values of coefficient k for different systems of units

Unit of power P	Unit of area A	Unit of velocity V	Value of k
Kilowatts	Square feet	Miles per hour	0.0000053
Kilowatts	Square feet	Knots	0.0000081
Horse-power	Square feet	Miles per hour	0.0000071
Watts	Square feet	Feet per second	0.00168
Kilowatts	Square metres	Metres per second	0.00064
Kilowatts	Square metres	Kilometres per hour	0.0000137

As an example of the power contained in a wind stream, consider a horizontal stream 10 metres (33 feet) square, moving with a speed of 10 metres per second (22.4 miles an hour). The power is

$$0.00064 \times 10^2 \times 10^3 \text{ or } 0.0000053 \times 33^2 \times 22.4^3 = 64 \text{ kilowatts or } 48 \text{ h.p.}$$

But this power has to be extracted from the wind to put it to practical use.

Historical Notes

Probably the earliest application of wind for practical purposes was to propel ships with sails. The wind presses on the **sails** and does useful work as the ship moves in a straight line but, even so, only a fraction of the power in the wind is extracted in this way. For the production of power in a stationary power plant the movement produced cannot be along a straight line but must be rotational. The essential part of a "windmill" is **thus** a "rotor" which is driven round by the wind, the useful power being transmitted from the shaft of the rotor to some other machine driven by the windmill. This machine might be a corn-grinding mill, a water pump, an electric generator or perhaps some other type of machine for agricultural purposes.

The number of different designs for wind-driven machines - conveniently called windmills although they may not, in fact, be "mills" - is very large. Some of the more important of these will be discussed later. It will suffice now, to say that they fall into two categories - those with a vertical-axis rotor and those with a horizontal-axis rotor.

The earliest windmills of which there is any reliable record were those used by the Persians for corn grinding. They had a vertical axis carrying several large sails and enclosed within a circular wall with openings to admit the winds from different directions. A machine of this type obviously must have some arrangement whereby the wind is allowed to press on the sails on one side of the vertical axis while those on the other side - which move against the wind - must be screened from this pressure. Fig. 1 shows a simple - even crude - form of windmill of this type used in more recent times in China for pumping brine. In this, the sails which are moving counter to the wind are allowed to flap so that they move up in an edgewise position only turning flat as they begin to move in the same direction as the wind.

The type of windmill with a horizontal axis, of which the well-known Dutch windmills are an example, was introduced much later - probably in Europe in the twelfth century. It is this type which was developed, through the centuries, until it became a very effective power unit and, although there may be exceptional circumstances which may favour the construction of a machine with a vertical axis, future machines, for all purposes, are likely to have horizontal shafts.

Though vertical-axis windmills have the advantage that they can accept wind from any direction, while those with a horizontal axis have to be turned into the wind, they have the disadvantage of low rotational speed and low efficiency. The word "efficiency" is here used to express the fraction, of the available power in the wind, that is extracted by the windmill

Om te [illegible] : 10 m^2 in 10 m/sec [illegible] 10 pk

It can be shown theoretically that no windmill can extract more than 59.3 per cent of the power in the wind. In practice, 40 per cent extraction would be considered very good and may be approached in the best horizontal axis machines. Vertical-axis machines, on the other hand, cannot be expected to extract more than about 20 per cent and probably their efficiency would be lower than that.

To express this conception in another way, referring to the calculation made above, for the power in a wind stream, a windmill whose rotor swept the stream 10 metres square, moving at 10 metres per second, would extract not 48 h.p. but something between 9.6 h.p. and 19.2 h.p., according to its type and detailed design.

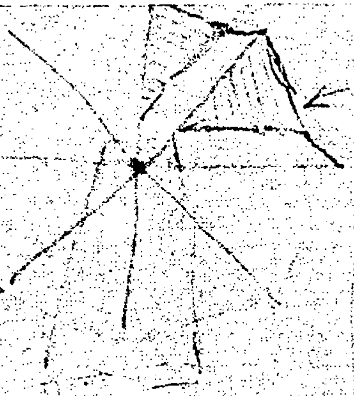
The windmills developed in European countries through the centuries following their introduction had horizontal shafts carrying four or more sails, on a wooden framework, constituting the rotor. The sails were of canvas, or some other strong cloth, which could be furled or spread according to the strength of the wind, or, later, they took the form of wooden slats hinged so that, in very strong winds, the slats could open to allow the wind to pass through the sail.

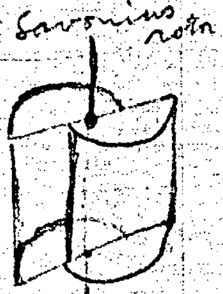
The sails had to be turned into the wind and this was done either by mounting the whole windmill on a turn-table (in the "post-type" mills) (Fig. 2) or by using a rotatable head at the top of a stationary tower (in the "tower-type" mill) (Fig. 3). The latest form of the latter is that developed in Denmark following the work of Professor P. La Cour at the State Windmill Station at Askov founded in 1890. An example, made by the Danish firm of Lykkegaard, is shown in Fig. 4. It has slatted sails and the rotor drives, through bevel gears, a shaft passing vertically down through the lattice-steel tower at the foot of which is located the machine to be driven by the windmill. Another set of bevel gears converts the power from the shaft to driving power for a horizontal-axis machine which is usually an electric generator supplying power for farm purposes.

Wind Power for Agriculture

La Cour was not only concerned with wind power per se but was anxious, by this means, to introduce electric power for use on Danish farms. In this he was very successful and he can be considered as one of the pioneers of agricultural electrification.

From 1890 onwards wind power development has received almost continuous attention in Denmark (Ref. 18) where other natural resources of energy are scarce. Many Lykkegaard machines, of up to 30 kilowatts in capacity, were installed in the first three decades of this century and proved very useful, during World War II, in supplementing the village diesel-power plants when fuel was difficult to obtain. During this war, another type of wind-driven machine, for electricity production, was also developed in Denmark by the firm of F.L. Smidth of Copenhagen. Their machines (see Fig. 5) had propeller-type rotors with either 2 or 3 wooden blades driving direct-current generators, through gearing, at the top of the tower. They varied in capacity from 50 to 70 kilowatts and had rotors of 18 or 24 metres diameter. Some of these





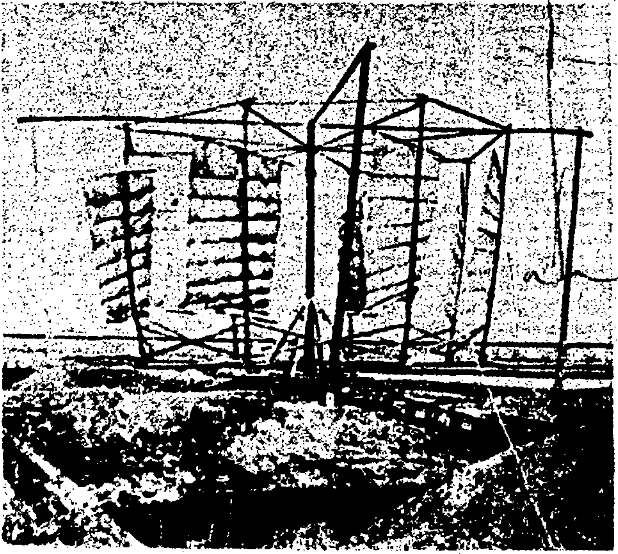


Fig. 1 - Primitive Chinese windmill for brine pumping. (From "Farmers of 40 Centuries" by F.H. King - By courtesy of Jonathan Cape Ltd. London)

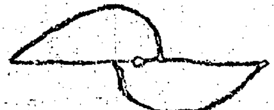


Fig. 2 - Old-fashioned post-type windmill.

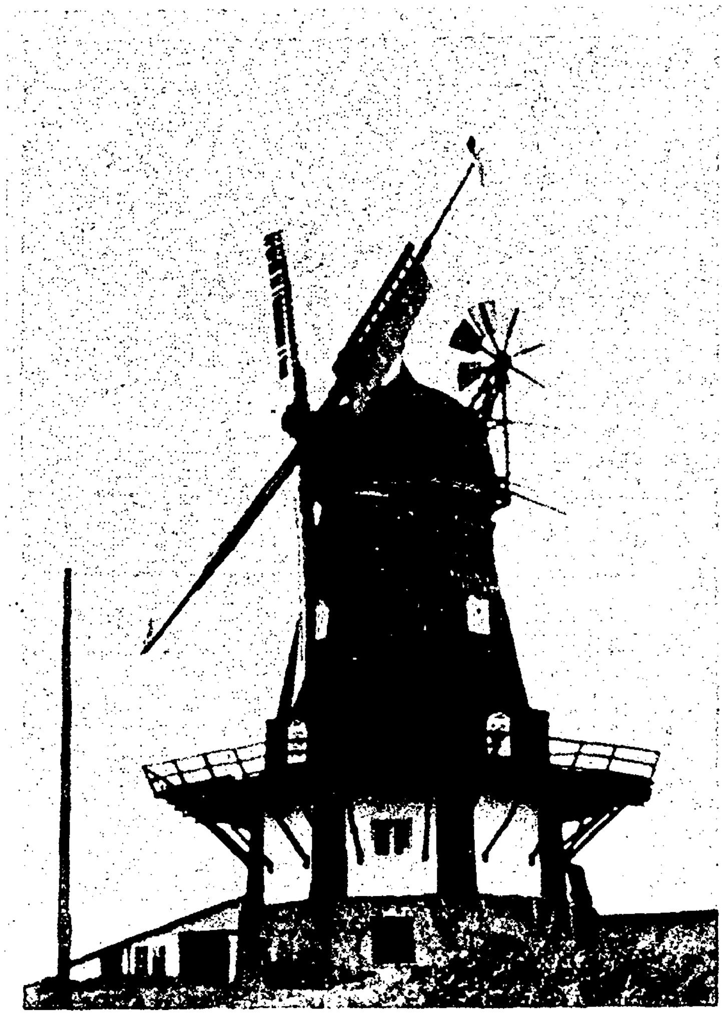


Fig. 3 - Old-fashioned tower-type windmill.

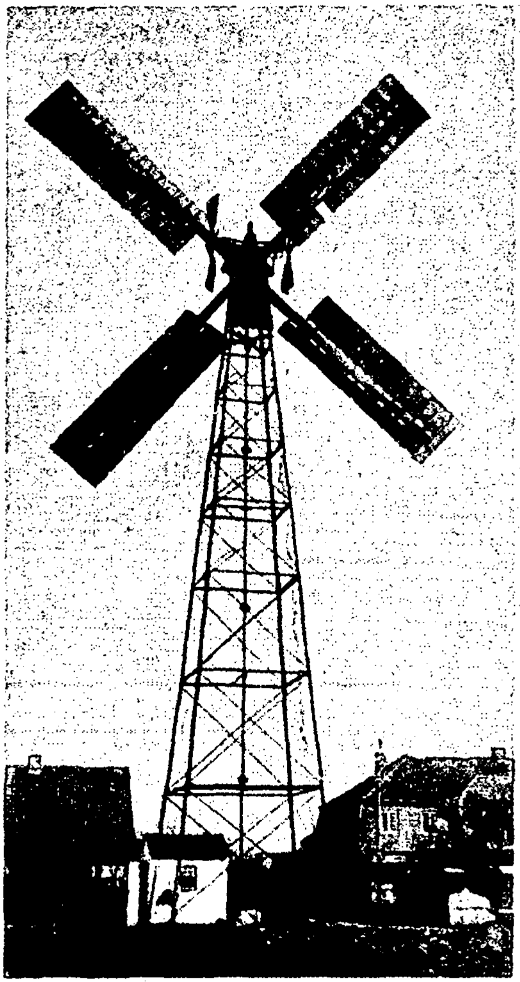


Fig. 4 - Lykkegaard 30 kW windmill.

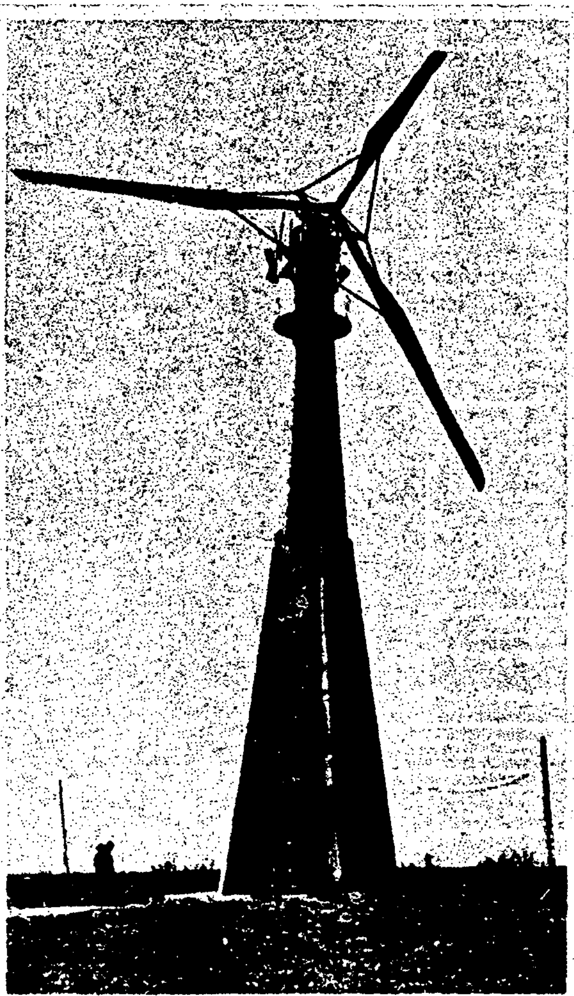


Fig. 5 - 70 kW windmill with rotor 24 m diameter (F.L. Smidth).

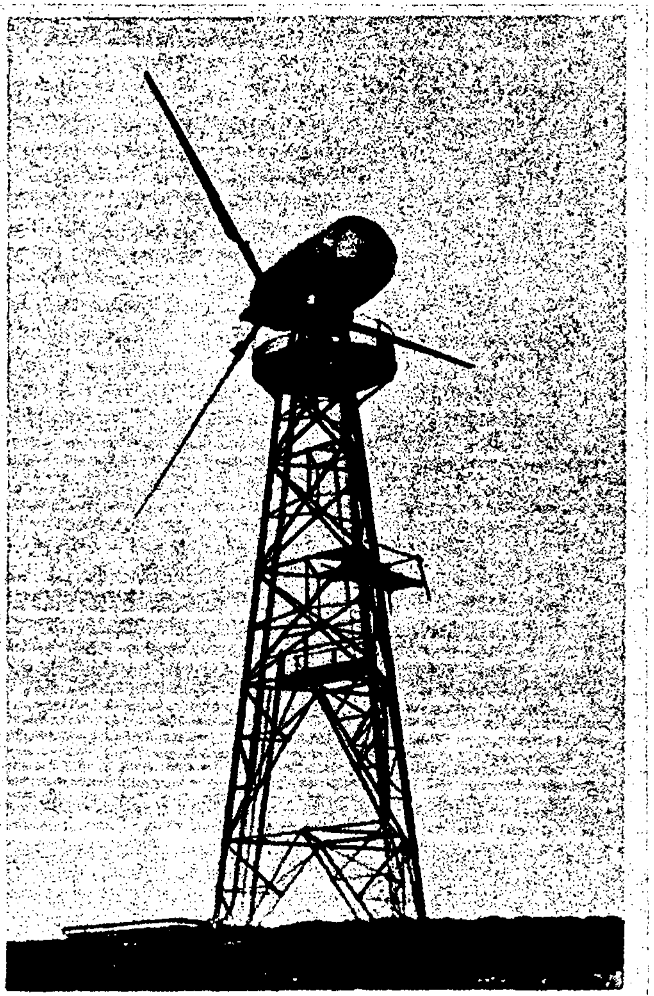


Fig. 6 - 100 kW windmill (John Brown and Co. Ltd).

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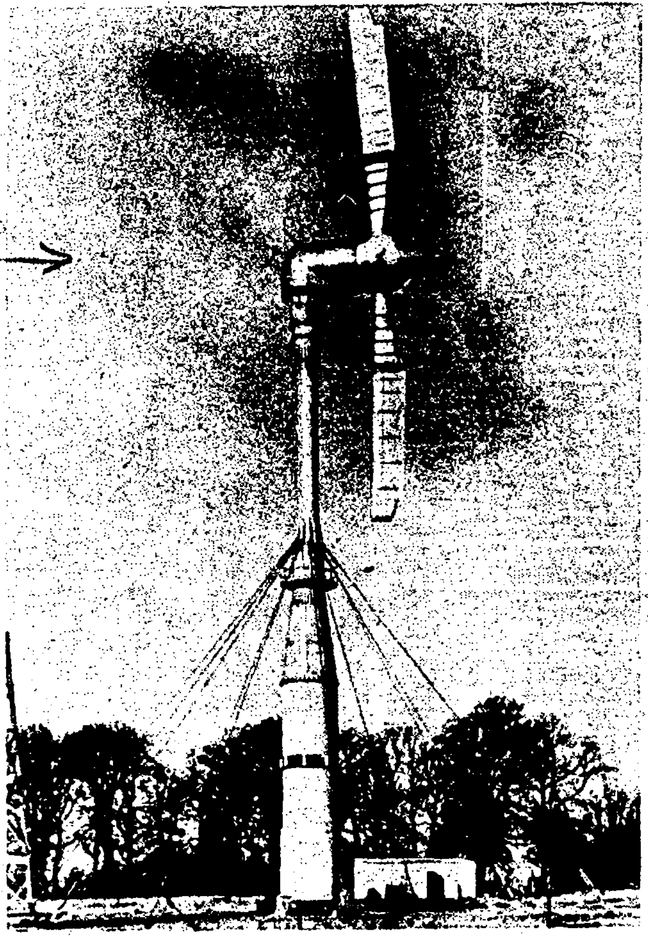


Fig. 7 - 100 kW Enfield/Andreau windmill.

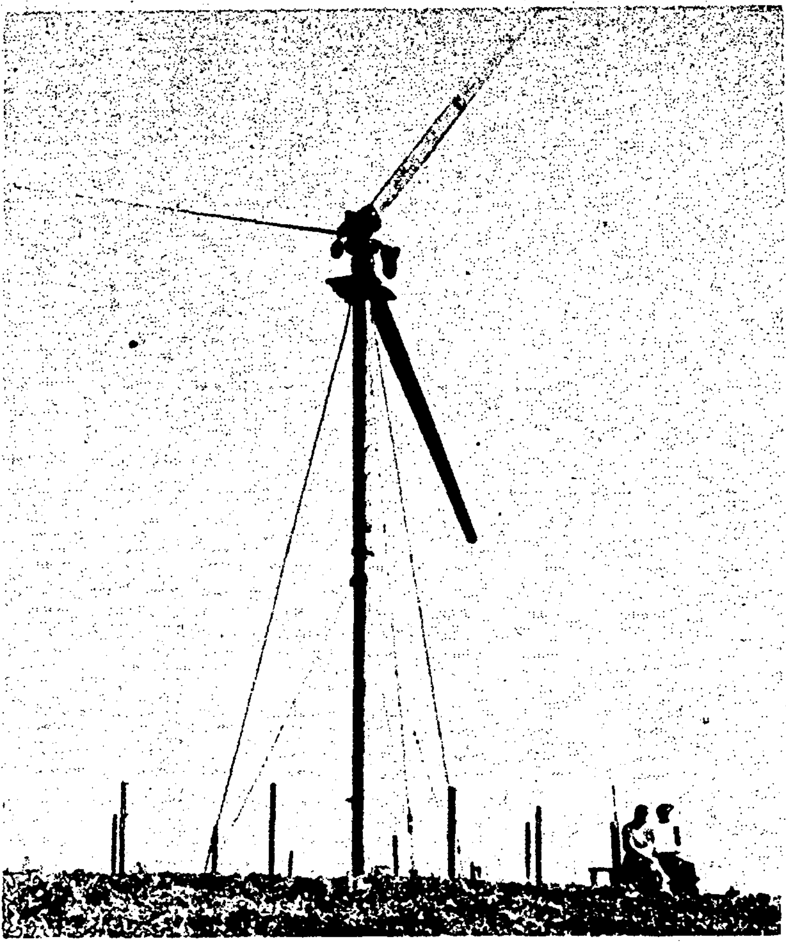


Fig. 8 - Allgaier 8 kW windmill.

Danish wind power plants, both by Lykkegaard and Smidth, are still running successfully in connection with local electrical networks.

To complete the story of Danish wind power developments, in recent years a national wind power committee, working on similar lines to those established in Great Britain and in Germany, has been responsible for the building of several experimental machines of up to 200 kilowatts capacity. This work has been done under the direction of Mr. J. Juul (Refs. 25, 26, 27 and 28) (of the South East Zealand Electricity Company) who was, in fact, a pupil of La Cour at Askov.

Other countries, as well as Denmark, have not entirely neglected wind power during the last few decades. Although the old-fashioned type of windmill, with wooden or cloth sails, has laregely disappeared - except in the Netherlands where their attraction for tourists has been an important factor in maintaining them in operation - two more modern types of machines have been developed and widely used in many parts of the world.

Both are for use on farms and, in remote areas, for dwelling houses. One is a non-electric machine, with a multi-bladed rotor, used for the sole purpose of water pumping, while the other is a small wind-electric plant, with a propellor-type rotor, running at high speed and driving an electric generator. This generator usually produces direct current and charges an electric battery which stores enough energy to provide a supply during calm weather. These machines will be discussed more fully later.

Large and Medium-Scale Wind Power

Encouraged by the building of a 1,250 kW aero-generator in the United States of America during World War II, much research and development work on relatively large wind-driven machines has been done in several European countries since the war. The major part of this work has been devoted to investigating the possibilities of using wind-driven electric generators in conjunction with, and in electrical connection to, main electric power networks. Nevertheless, it has a definite bearing on the question of wind power plant for farm use because, at the lower end of the scale of capacity of these machines, there are some which could be used on large farms or for farming communities in isolated areas.

For clarity, it should be explained that a rough classification of wind power machines, on a basis of their capacity, has been made. Thus, machines with a power capacity of up to 10 h.p. are called "small", those with a capacity between 10 h.p. and about 100 h.p. are of "medium" size and those with greater capacities are called "large". Both small and medium size machines, if of the right design, might be used on farms but the large machines are only for use with main power networks.

The work done in different countries (other than Denmark) can be summarized briefly as follows:-

Great Britain: The Electrical Research Association, advised by a wind power committee, and with additional financial support from the Ministries of Power and of Agriculture, Fisheries and Food, has done research on both theoretical and practical aspects of the problem during the last 12 years (see Refs. 11, 12, 13, 16, 17, 18, 19, 32, 34, 35, 36, 51 and 52). Wind surveys covering Great Britain and Ireland have been made and the survey methods used have been followed in other countries including British Somaliland, Burma, UAR (Southern Region), Haiti, India, Israel, South Australia, Trinidad and Uruguay. Instruments for the detailed study of wind structure and wind régimes have been developed and methods of testing the performance of wind-driven machines have been evolved. A number of prototypes, of different designs made by British manufacturers, have been tested. These include machines of 10 and 25 kW capacity and three of 100 kW capacity. A successful experimental study of the operation of an 8 kW machine, supplying power for an isolated house, has also been made.

France: Electricité de France, after making an extensive survey of potentially favourable sites in France, using anovel form of anemometer (Ref. 1), have continued to work on the wind power problem with large-scale plant especially in mind. Much experimental work has been done and detailed studies of all possible forms of wind-driven machines have been made. Experimental plants of 130 kW and 640 kW are under test. Two French manufacturing firms have also been responsible for the development of different types of windmills in the small-power range.

L. Vadot (Refs. 47, 48 and 49) has made very comprehensive studies of the various possible designs of windmills and of their applications.

Germany: Therehas been continued interest in wind power in Germany during the past three decades. A number of ambitious projects, using novel designs of very large machines, were put forward before the war. These did not materialize but accompanying studies of the aerodynamics of wind-driven rotors, particularly by A. Betz of Göttingen, made a valuable contribution to knowledge of the subject.

Since the war Dr. U. Hütter, working first with the manufacturing firm of Allgaier and later at the University of Stuttgart, has done much to develop modern types of wind-driven electric generators. Allgaier made an 8 kW machine (Fig. 8) which has given good service in several installations in Germany and elsewhere (Refs. 21, 22 and 23).

During the last few years the Studiengesellschaft Windkraft e.V., Stuttgart, supported by a number of large German electricity supply undertakings, has developed a 100 kW prototype machine for use in connection with electrical networks and Dr. Hütter has been closely associated with its design.

Holland: A society for the preservation of Dutch windmills (De Hollandsche Molen) was formed in 1923 and has since worked to improve the performance of these mills as well as to ensure their more effective use.

In 1936 another organization, the Prinsenmolen Commissie, was set up to study methods of improving the performance of Dutch windmills and this has done valuable work (see Ref. 31) which has included experiments on the use of the mills for electricity generation when they are not needed for water pumping.

Union of the Soviet Socialist Republics: A central wind power institute was established in Russia after 1918 and this has been responsible for the development of a number of wind-driven machines, of capacity up to about 20 h.p. for both water pumping and the generation of electricity (Refs. 2, 3 and 8). Its work still continues quite actively and at the experimental station at Istra, near Moscow, 6 or 7 different types of machines are being tested with the special purpose of deciding which type is likely to be best suited for water pumping in the dry areas of the USSR where a main electricity supply for power purposes is not available. The possibility of installing, in remote areas, groups of wind-driven generators for electricity supplies is also being studied.

Spain: A government-sponsored wind power study group, with headquarters in Madrid, has been investigating the economy of wind power both for the Spanish mainland and for the Canary Islands. Wind data for a considerable number of apparently favourable sites has been collected and a testing station, at a well-exposed site near Madrid, has been set up to test different types of wind-driven electric generators.

India: The government of India established a wind power research committee in 1952 and this has made wind surveys to determine the most favourable areas for wind power. In some of the most windy coastal areas medium or large capacity machines might be used to supplement electricity networks and, in many dry areas, windmills for water pumping would be very useful. These questions are being studied at the Indian National Aeronautical Laboratory at Bangalore (Ref. 30).

Algeria: There are strong winds on the coast of Algeria and the national electricity authority, Electricité et Gaz d'Algérie, has been interested in wind power possibilities for some years (Ref. 20). One aspect studied has been the combination of wind power with water power with the object of supplementing the latter in dry periods. Some four years ago one of the British made 100 kW experimental aerogenerators (of the Andreau type) was sent to Algiers for the use of the electricity authority and this has been installed on a hill a few miles from Algiers. A full testing program has given some valuable data on the performance of the machine.

Israel: A wind power committee was established in 1951 and instituted a wind survey to discover favourable wind power sites. Studies of wind behaviour have been made and these are still continuing at the Israel Institute of Technology at Haifa. Small windmills of different types have been installed to test their performance: one of the testing stations was at Eilat on the Gulf of Aqaba (Ref. 9).

I. GEOGRAPHICAL DISTRIBUTION OF WINDS AND CHARACTERISTICS OF WIND FLOW

Natural winds are movements of air - air streams - caused by differences in atmospheric pressure which, in turn, are the result of differences in temperature causing corresponding variations in air density. The air flows from an area of high pressure to one of lower pressure and the wind speed depends upon the magnitude of this pressure difference. The actual velocity of the wind, in magnitude and direction, comes from a combination of the pressure-induced speed and that due to rotation of the earth's surface which carries air, adjacent to the surface, round with it. This surface speed changes from about 1,000 miles per hour at the equator to zero at the poles and, therefore, its influence on the resultant wind velocity varies greatly with latitude.

Although both the speed and direction of the wind at any given place vary greatly throughout any lengthy period of time, e.g. one year, the direction, at least, is not entirely random. For average conditions, two belts of high pressure continuously exist, round the earth, one between 30°N and 40°N and the other between 30°S and 40°S and there is a low pressure belt in the equatorial zone between them. These high pressure belts produce persistent winds from the north, in the northern hemisphere, and from the south in the southern hemisphere. The effect of the earth's high surface velocity in the tropical zones is to convert these persistent "trade" winds into north easterly winds, north of the equator, and south easterly winds, south of the equator. Associated with this system of winds are persistent westerly winds, in the belts 40° to 60° latitude in both hemispheres.

In spite of the disturbance caused by storms which, for a time, obscure the prevailing wind direction, there are thus certain well-defined tendencies in wind direction for the belts mentioned. Cyclonic depressions are superposed on the general system of atmospheric pressure. These depressions may move in any direction but, nevertheless, they have certain established tendencies in direction which assist in making predictions of wind direction in the areas affected.

The meteorological services all over the world make continuous measurements of atmospheric pressure and the data so collected provide the basis for the construction of "isobars" for any particular time. These are lines joining points having the same atmospheric pressure, at sea level, and corrected for temperature and latitude. From the isobars the "gradient wind", i.e. the wind speed due to pressure difference, can be calculated but, due to frictional and local temperature effects at low altitudes, this calculated speed is not, in general, actually attained below an altitude of about 1,500 feet (500 metres).

When considering power production by the wind we are, of course, interested not in the winds at high altitude, but in those up to one or two hundred feet (30 to 60 metres) above ground level. These surface winds, in which windmills operate, are greatly affected by the topography of the area in which the windmill is to be located and also by very local obstructions in the form of rocks, trees, buildings and, in fact, anything which will disturb the wind flow.

Thus, the idea of putting a windmill on a raft [illegible] in 1594!! was not so bad; it has a good flow of [illegible] all around plus easy, automatic [illegible] around towards the wind

The speed of the wind is responsible for its power content and factors affecting this speed will be dealt with later in some detail. Wind direction is not so important except in so far as it may influence the choice of a site for a windmill: if, viewed from a proposed site, there are serious obstructions in the general direction of the prevailing wind these will be especially detrimental and may lead to the choice of another site.

Wind Speed

Before discussing the geographical distribution of winds it is important to define what we are to understand by "wind" from the point of view of its power potentialities.

By far the most important characteristic of the wind is its variability in speed. At any specified point on the earth's surface the wind, at a given instant of time, can have a speed ranging from zero to as much as 125 miles per hour (56 m/sec) or more. Even the windiest places have their clam spells while the least windy are occasionally subjected to storms which bring high winds. One cannot, therefore, rely absolutely on power from the wind at a given moment however windy the chosen site may be and, on the other hand, one cannot safely reduce the mechanical strength of a windmill, destined for a relatively calm area, to any great degree. Nevertheless, the probability of there being power available at a particular time is much greater at the windy site as is the probablity of a machine, erected there, having to withstand severe mechanical stresses fairly frequently.

If, instead of taking the wind speed at any instant, we consider its value over various time scales, it is possible to state some important, and generally applicable, facts:-

1. The nature of wind in the open (See also Ref. 14)

In a natural wind the speed is never strictly constant: even on a scale of seconds it varies continuously, though the variations may not be large enough to be troublesome for a wind power plant. The conception of a "steady" wind speed is true only within certain limits. Much depends upon the instrument used to measure the wind speed: if it is slow in response its indication may appear quite steady although, had a quick-response instrument been used instead, this would have shown rapid variations in speed. The magnitude of these variations, as well as their frequency, would depend on the "gustiness" of the wind at the time of measurement. Under stable weather conditions, and at a site free from any obstructions near enough to interfere with the wind flow, the speed fluctuations are usually of low frequency and small in magnitude, but, during a storm, they are often violent.

2. Rapid variations

The rapid variations in wind speed referred to in (1) are more likely to be important from the point of view of the mechanical design of a windmill than in their influence upon the power output. The mean, or average, wind speed - on which these rapid fluctuations are super-imposed - does not usually change quickly. Although it is certainly possible for this mean speed to rise or fall by, say, 50 per cent within a few minutes the more general experience is that the time is longer than this so that hourly mean wind speeds can be used with some confidence in assessing power potentialities.

3. Diurnal variations

Considering now the scale of hours, in many tropical and sub-tropical areas, diurnal variations in hourly wind speed are clearly marked: during a stated season of the year it is often possible to predict the daily wind régime with some degree of certainty. Thus, for example, in a coastal area the wind speed may be almost zero throughout the night, beginning to rise as daylight comes and increasing to a maximum value soon after mid-day with a subsequent fall to zero in the early evening. In the temperate zones, however, especially in those areas lying in the tracks of storms, diurnal variations are usually masked by storm disturbances and no predictions of daily wind régimes are of much value.

In certain special geographical conditions the diurnal variations in wind speed are very small. Thus, for example, at Longwood, St. Helena, which is subjected to what is virtually an ocean wind régime, without any land masses of sufficient size near enough to cause daily temperature variations, the wind speeds throughout the day are as shown in Table 2 (Ref. 14).

Table 2

Diurnal Variations in Wind Speed at Longwood, St. Helena

Hour of day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January mean	20	21	21	22	22	22	22	22	23	23	22	21	20	19	19	19	19	19	19	19	19	20	21	21
July mean	17	17	16	17	16	18	18	18	19	19	20	18	18	17	17	17	17	17	17	17	17	17	17	17
Yearly mean	18	18	18	19	19	20	20	20	20	20	21	19	18	18	18	18	18	18	18	18	18	18	18	18

4. Seasonal variations

Seasonal variations, i.e. on the scale of months, are often clearly definable. Taking monthly mean wind speeds, these rise to peak values in a season of the year which, of course, varies according to the part of the world considered: sometimes a second, subsidiary, peak occurs during the year. As an example of the changes in these monthly values, in Great Britain the months May, June, July and August are always relatively calm while

December, January and February are usually the windiest months. In some years, however, the autumn or spring months are as windy as the winter and, indeed, throughout the period September to April, high monthly mean speeds can be expected. Some monthly mean wind speeds, measured at meteorological stations in different parts of the world, are shown in Table 3 as an indication of the variability pattern to be expected (see also Ref. 35).

Table 3

Monthly Mean Wind Speeds at Meteorological Stations

Station	Mean wind speed (miles per hour)												
	J	F	M	A	M	J	J	A	S	O	N	D	Year
England and Wales (average of 20 stations)	14.4	13.8	12.5	12.3	10.8	10.7	10.6	9.9	10.8	12.8	13.1	13.5	12.
U.S.A. (average of 20 stations in New England)	11.0	11.2	11.4	11.0	9.8	9.0	8.6	8.4	8.8	9.6	10.5	10.6	10.0
Madras (India)	11.0	9.5	9.6	11.1	11.8	11.9	10.8	10.7	10.0	8.7	12.3	12.5	10.[illegible]
Ramallah (Jordan)	16.2	13.2	15.3	12.6	11.3	11.9	12.6	10.7	10.0	9.5	10.0	11.3	12.
Perth (W. Australia)	13.8	13.5	12.8	10.7	10.6	10.6	11.2	11.8	11.8	12.6	13.4	13.9	12.2
Beaufort West (U. of S. Africa)	9.9	8.8	8.3	8.4	9.8	10.6	10.3	10.4	10.2	11.1	10.6	10.2	9.9
St. Helena	17.0	15.8	15.5	15.1	14.2	15.3	15.7	18.2	21.2	19.1	19.7	18.8	17.2
Victoria Point (Burma)	5.6	5.5	5.3	4.9	4.7	5.4	6.5	6.4	5.0	4.1	4.6	5.5	5.3

An examination of the figures in Table 3 shows that, although the months with the highest winds vary from place to place, there is a uniform trend with a fairly gradual building up to the highest monthly speed and a gradual falling away again. For the stations with yearly mean speeds in the range 9.9 to 12.2 m.p.h., the monthly variation from the yearly mean is usually within ± 2 m.p.h., the exception being Ramallah where the variation is +4.1 to -2.6. At the very windy St. Helena station the monthly means vary from the yearly mean over the range +4 to -3 m.p.h., while at Victoria Point, Burma, the fluctuation is little more than ± 1 m.p.h.

5. Long-term variations

At most places where long-term records of wind speed are kept it is found that the annual mean speed for the station changes little from year to year. The actual value of this mean speed varies from about 1 m.p.h. (for Dibrugarh, Assam) (Ref. 24) to 27 m.p.h., or even more, at specially selected windy sites in coastal areas of Great Britain and other countries in the high latitudes, but it appears to remain constant, within fairly narrow limits. Examples, for long periods of time, are those for Southport (England) and for a group of 50 stations in the United States of America. The periods of the records were 42 years and 31 years respectively. The annual variation, in terms of the long-period mean, was from 84 per cent to 118 per cent for Southport: in only three of the 42 years did the variation lie outside the range ± 10 per cent. The annual wind speed at the American stations did not fall by more than 18 per cent below the 31-year mean value.

The Importance of Wind Variations

It may be useful, here, to point out the significance of the general facts stated above.

First, short-period mean wind speeds, i.e. for times of the order of seconds or minutes, may be important for the designer of wind power plant because their extreme values influence the calculations on the mechanical strength of the machine or on the required characteristics of control gear.

For estimation of the energy to be obtained from a wind-driven machine at a given site, hourly wind speeds over a period of a year are most useful. If the hourly mean wind speed is measured continuously, throughout the year, the records will enable an investigator to determine the following:-

(a) The maximum and minimum values of the hourly mean speed and the total numbers of hours, during the year, for which the speed lies outside - above or below - the operating range of a windmill with specified design characteristics;

(b) The diurnal variations in wind speed and the chances of power being available at any given hour of the day;

(c) The maximum number of hours of continuous calm weather - this influences the question of the provision of energy storage facilities or of stand-by plant;

(d) The seasonal variations in windiness and the time relationship between the occurrence of wind and other climatic factors such as rainfall. Clearly this is especially important when considering the use of wind power for water pumping for irrigation;

(e) The probable total energy which could be obtained, in a year, from a wind-driven machine of a given size and with known operating characteristics.

Some or all of the data so determined must be taken into account in deciding upon the economic possibilities for wind power at the site where the wind measurements were made.

Assessment of Wind Power Economy

There is so much misconception of the question of economy in using wind power that the position must now be clarified. The relative costs of energy, from different sources, as applied to agricultural purposes will be discussed later but the basic facts should be clearly understood at the outset.

In the preceeding paragraphs the importance of a knowledge of the wind speed, hour by hour, throughout the year has been mentioned while, earlier, the dependence of wind power on the cube of the wind speed was illustrated. To estimate (with fair precision) the cost per unit of energy to be produced by the wind, three facts must be known - or assumed. These are (i) the capital cost per unit of capacity (i.e. per horse-power or per kilowatt) of the wind power plant; (ii) the percentage to be applied in calculating the annual capital charges for interest, depreciation and maintenance; and (iii) the annual output of energy per unit of power capacity (expressed in kilowatt-hours per kilowatt or in horse-power hours per horse-power and referred to as the "specific output").

Let these be denoted by

C = capital cost per unit of power capacity

p = percentage of annual charges

T = the "specific output".

The calculation of energy cost is simple: the annual costs for the machine are $\frac{pC}{100}$ and, for this cost, the annual output produced is T units of energy. The cost per unit of energy is, therefore, $\frac{pC}{100T}$. As an example, suppose the capital cost C is £80 per horse-power of the machine's capacity and the annual charges are at the rate of 12 per cent. If the annual output is 3,000 h.p.-hours per h.p. of capacity, the cost per h.p.-hour is £ $\frac{12 \times 80}{100 \times 3000}$ = £0.0032 or 0.768 pence. The calculation is, of course, exactly the same if C is the cost per kilowatt and T is in kWh per kW.

The potentialities of wind power, as a method of producing energy in competition with other methods, are judged by comparing the energy cost, calculated in this way, with that for the alternatives.

The values of C and p are dependent on the manufacturer of the wind power plant and on the person, or organization, responsible for financing the installation. The initial cost C is entirely in the hands of the manufacturer while the "life" of the machine (i.e. the number of years over which its cost can be depreciated) is also greatly influenced by the quality of the plant and, particularly, on its resistance to deterioration under the climatic conditions to which it is subjected in use. The cost component included for maintenance is also affected by the details of construction though this component is likely to be small, e.g. between 1 and 2 per cent of C. The percentage p is governed by interest rates and by the method of amortization.

The third factor, T, can be determined only from wind data and must be provided by the potential user of the plant - or by some organization working on his behalf. To understand how T is obtained, suppose that the hourly mean wind speeds for the site concerned are available for a complete year. These are first classified and a graph (called the "velocity-duration curve") is plotted as in Fig. 9. This gives the number of hours, in the year, for which the wind speed is equal to, or greater than, any given value. To illustrate the point, on the curve shown in the figure, the wind speed is equal to or exceeds 20 m.p.h. for 5,500 hours in the year.

Because the power in the wind is proportional to the cube of the speed, we then cube the ordinates of the velocity-duration curve and obtain a "power-duration curve" as shown in Fig. 9.

The next procedure is to introduce the main operating characteristics of the wind power plant itself, particularly its "rated wind speed", i.e. the wind speed at which it generates its full rated power. It must be emphasized, at this point, that no windmill can be made to operate economically over the whole range of wind speeds that may occur at the site where it is to be used. Although there is, indeed, a large amount of power available when the wind speed is high, the length of time, during the year, for which the speed has such high values is usually so small that a machine made to utilize this high power would be badly underproductive for most of the year. Again, because of the power losses, in the machine - which are inevitable - a certain minimum wind speed is necessary before the plant begins to generate any power output. An operating range is thus chosen, by the designer, to suit the wind régime at the site and this may include a "shut down" value of wind speed at which the operation of the machine is stopped to avoid damage. We thus have an annual operating schedule which may be shown by the broken lines in Fig. 10 which indicate that the machine being considered generates its full power capacity at a wind speed of 30 m.p.h. after beginning to give effective output at 17 mp.h. (called the "cut-in" point): it is shut down when the wind speed reaches a value of (say) 60 m.p.h. Note that, for allwind speeds above 30 m.p.h., the machine generates full power output but no more than that. An important feature of its construction must be a controlling mechanism which prevents its power output from rising with the power in the wind itself.

Referring again to Fig. 10, the shaded area represents, therefore, the annual output of energy by the wind power plant with the assumed operating characteristics, while the rectangular area represents the energy which would be produced if it were possible to obtain full power from it throughout the entire year.

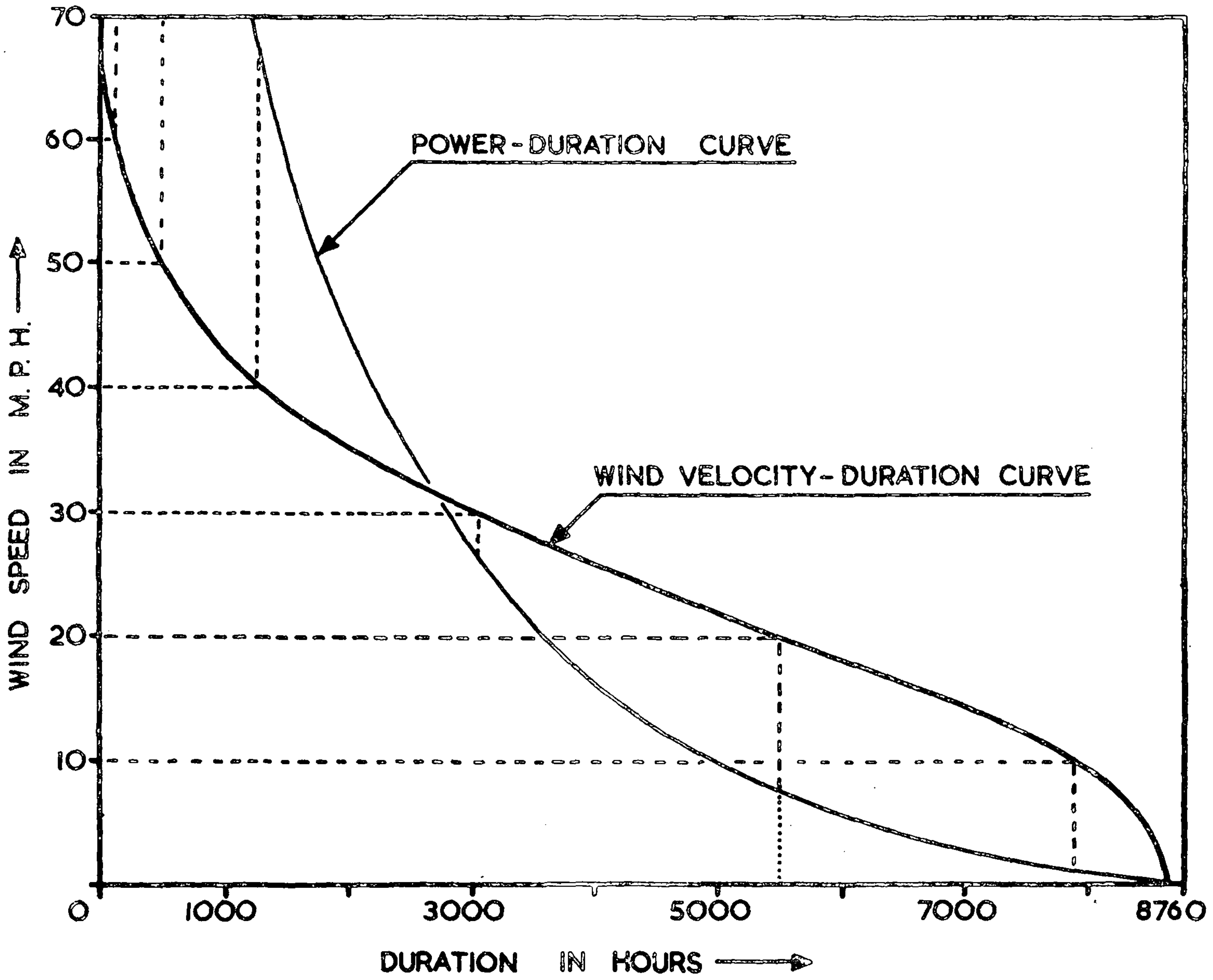


Fig. 9 - Velocity- and power-duration curves.

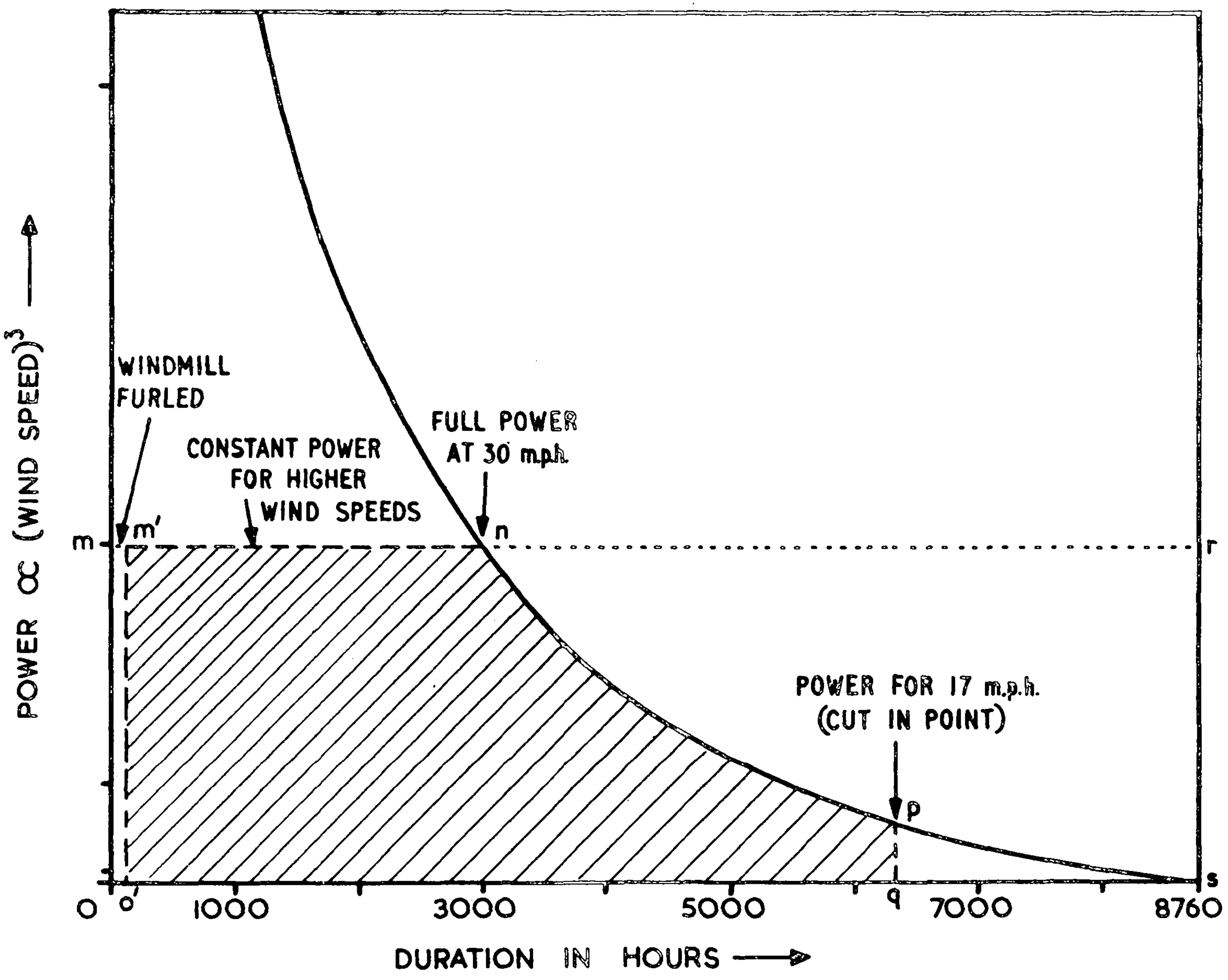


Fig. 10 - Determination of specific output.

The specific output T is then given by multiplying by 8,760 (the total number of hours in the year) the ratio of the two areas just mentioned, i.e.

$$T = \frac{\text{shaded area ommpq}}{\text{rectangular area omrs}} \times 8{,}760$$

If, for example, the shaded area happens to be one third of the rectangular area, $T = \frac{1}{3} \times 8760 = 2920$. This figure T is, in fact, the equivalent number of hours in the year which, if the machine were running at full power, would produce the same energy as it actually produces in the varying wind régime.

It will be shown later that it may not always be necessary to follow the whole of the graphical process outlined above in order to obtain the value T, but a proper understanding of the operation of a wind power plant in a given régime can be gained only by this method.

The cost of the wind-produced energy, determined as just indicated, is an important factor when considering the economy of wind power but it cannot be taken as the sole criterion. The fact that power from the wind is random, and cannot be relied upon at any particular time, introduces a further consideration, namely, the degree to which random energy can be accepted by the user and its actual value. Thus, if there are times when the user <u>must</u> have power for essential purposes some provision must be made for the storage of some of the energy to cover periods of calm weather or, alternatively, a stand-by plant must be installed. Devices for storing energy are always costly and it may be more economical to install a fuel-driven stand-by plant. When such a plant is used the wind power plant acts as a "fuel saver", each unit of energy produced by the wind saving an equivalent amount of fuel which would otherwise have been used by the engine. Nevertheless, although the wind-produced energy may be cheap, as random energy, it must be recognized that the provision of either a storage device or a stand-by plant adds to this cost and should be avoided if possible.

It should be noted carefully that the need for storage or stand-by plant arises only when essential power loads are to be met at particular times. If the load can be met satisfactorily by random power, no specified times being involved, we revert to the cheap rate of wind power production. Fortunately, there are a number of important agricultural loads which can be met in this way and water pumping is one of them: within fairly broad limits the time when the water is pumped is not critical provided, of course, that the time intervals between the spells of pumping are not so long that the supply of water fails when it is needed. The assumption, here, is that pumped water can be stored and this, in fact, represents stored energy but it is storage which is inherent in the pumping process: it does not call for the provision of any device, such as an electric battery, for the sole purpose of storing energy.

We can summarize this discussion on the economy of wind power as follows:-

Being given, by the prospective user of the plant, data on the wind régime at the site where it would be used, the manufacturer can design it for optimum operation. He, alone, can decide on the cost of the plant itself although the user can influence the cost of its installation on the site. The rate of the annual charges on the expenditure for the completed installation is also a matter which must be decided by the user. Knowledge of the wind régime at the site enables the total annual output of energy to be calculated as explained above and this figure is used to calculate the cost per unit of energy generated.

It is then a question of comparing this cost per unit with that which would apply to power generation by any feasible alternative means but, at this point, it is important to consider the purposes for which the energy is to be used in order to plan for full utilization of the random power with little or no storage.

Although, therefore, the designer and manufacturer of the plant have, of course, an important part to play on the technical side, it can be seen that the main responsibility for ensuring the economic success of a wind power project lies with the user.

II. WIND DATA AND THE SELECTION OF SITES

It has already been stated that the power in a moving stream of air is given by the formula $P = kAV^3$ where V is the speed of its movement, i.e. the wind speed. When we are considering a windmill located so that it is acted upon by this stream, the cross-sectional area of the stream is approximately that of the area swept out by the windmill rotor as it rotates in a plane at right angles to the direction of the wind. In fact, some of the air which passes round the extremities of the rotor also has an effect upon the machine's performance but, for the moment at least, we can neglect this.

If it were possible to create, in a very large wind tunnel, or to find in nature, a column of air every part of which was moving at the same, constant, speed and to place a windmill rotor in this stream, it would be quite easy to determine the performance of the machine for this particular value of wind speed. In practice this is not feasible. Except for very small wind-driven machines, a wind-tunnel test would be out of the question because of the large size and, therefore, very heavy cost, involved. On the other hand, it is virtually impossible to find a natural wind fulfilling this ideal condition. The filaments of air which make up the air stream do not usually move at exactly the same speed nor is the speed of the stream precisely constant for any appreciable length of time. We have already discussed the nature of the variations which take place in a natural wind.

What, then, must we measure to obtain useful wind data and how should we measure it?

The answers to these questions depend very largely on the purpose we have in mind and the use which is to be made of the data obtained. The most important aspects of the question will be dealt with under separate headings below.

Wind Measurements to Determine Site Characteristics

Measurements placed under this heading are not made with any intention of discovering the detailed, moment-to-moment, behaviour of the wind at a chosen site but are for the purpose of obtaining information on the wind régime, i.e. the long-term behaviour of the wind over a period of months or even of years They are often concerned with the windiness of one site relative to that of another and form, therefore, an essential part of wind surveys. It is clearly desirable that they should be made according to some standard pattern so that the results can be accepted, perhaps, on an international basis, not only as a guide to the degrees of windiness of different areas, but as a basis for windmill designs which ensure suitable constructions for the sites concerned.

The methods already established for wind measurements deserve mention before discussing the question in further detail.

The meteorological services of the world, as is well known, have networks of observation stations where wind measurements are made together with those of rainfall, solar radiation and other climatic factors. The World Meterological Organization is much concerned with such work and internationally acceptable standards for measuring methods have been formulated. Thus, for example, the standard height, above ground, for wind measurements is 10 metres. For various reasons, however, other heights are often used in erecting anemometers and the measured values are then corrected to conform to the 10 metre standard. This correction has to be made by using a formula, for the increase in wind speed with height above ground, which has a statistical basis but which may not be strictly applicable under all conditions so that there may be errors in wind data presented from such measurements.

Again, the sites of meteorological stations are seldom chosen with regard to any especially high degree of windiness. Indeed, there may be good reasons against such a choice because the climatic data obtained are to be taken as averages for the area surrounding the station rather than as extreme values.

Another difficulty in accepting, for wind power purposes, wind speed values from meteorological observation stations arises from the different methods of measurement used. The most complete information on wind speeds and directions is gained from recording anemometers - an example of which is the Dines anemometer - commonly used in Great Britain and some other countries. These give continuous records of speeds and directions and analyses of their charts provide data on hourly wind speeds and on the gustiness of the wind as well as on the directions from which the winds come.

Instruments of this kind are, however, expensive to purchase and to install and need skilled maintenance. They are not, therefore, universally used. This is especially so at the minor observation stations of which there are large numbers all over the world, including those at airports where information is needed on the wind speeds at particular moments rather than on a long term.

Frequently anemometers which give "instantaneous" wind speeds are used: they are indicating instruments, not recorders, and their readings are noted at certain specified times in the day. The wind speed values thus measured are certainly useful as a general guide but do not form an accurate basis for a statement of hourly speeds.

Another method of wind measurement used at some stations is that using a cup-counter type of anemometer which does not record wind speed but which integrates the run-of-wind, in miles, or in kilometres, during any given period. These anemometers have a cyclometer type of indicator and the difference between any two readings gives the miles (or kilometres) of wind which have passed during the time interval between them. The average wind speed over this time is then easily calculated by dividing this wind movement by the time.

Obviously, if this time interval is one hour, the run-of-wind in the period between successive readings is numerically the same as the hourly average wind speed. This fact leads naturally to a variant of the simple cup-counter anemometer, namely the electric cup-contact anemometer. In this instrument the rotating system of cups drives, through gearing, a device which makes a contact, in an electric circuit, once for some selected value of wind run, e.g. for a run of 2 miles of wind. If the circuit includes a coil-operated pen, or marker, which makes a mark on a recorder chart at each contact, it is possible to take a record of the run of wind per hour, the chart running at a constant speed and receiving also a mark at the end of each hour (Fig. 11).

Another type of recorder is shown in Fig. 12. In this instrument narrow paper tape is moved forward by a short distance for each contact produced by the anemometer. A time switch is used to operate a pen or marker so that a dot is made on the tape at hourly intervals. The distance between successive dots represents the run-of-wind. This type of instrument is designed particularly for economy and for simplicity in operation and in the subsequent chart analysis.

Several types of anemometers and recorders are illustrated in Figs. 12, 13, 14, 15, 16 and 17.

At some less important stations local observers may keep records of wind speeds obtained by "judicious guesses" taking into account visual signs such as the bending of trees, movement of leaves, etc.

It should be clearly understood that none of the foregoing remarks is intended as any form of criticism of the very fine work of the world's meteorological services. The fact is that both the locations of observation stations and the methods used are doubtless suitable for general climatic studies, or for special purposes such as aerial navigation, but, unfortunately, they are not very useful for the assessment of wind power possibilities. They do, however, give reliable guidance on the general question of the relative windiness in different areas and, particularly when measurements are made by recording anemometers located at well-exposed places in level country, they may give all the information needed.

Let us now consider the methods to be followed in site selection and the determination of the wind régimes at selected places. In the first place it must be clearly understood that the object of such work is the discovery of especially windy sites which will be suitable for wind-driven plants. It must be borne in mind that, because of the cube law for wind power, an increase in average wind speed of even 1 mile an hour, when this average is (say) 10 m.p.h., may mean an increase of 20 per cent in the annual energy to be obtained from a windmill so that it is vitally important that the most favourable sites should be found.

Suppose, then, that wind power possibilities for an area of considerable size - perhaps several hundred square miles - are to be studied. The first step is to obtain information on wind speeds, and prevailing wind directions, from such meteorological stations as already exist. Long-term records will give reliable guidance on which are the windiest districts and on the choice of site from the point of view of exposure to prevailing winds: one should not choose a site which is shielded, by high ground, trees or other obstructions, particularly those in the prevailing wind direction.

The next step in the survey is a study of the topography of these windiest districts. In general, wind speed increases with altitude so that high ground - if such exists in the area - is to be sought. But this is not all. When the wind flows over a hill its speed, in the lower layer, undergoes a considerable change and, if it is of a favourable shape, with fairly steep but smooth slopes, the wind speed over its summit is accelerated due to compression of the streamlines by the upper layers of air: there is a Venturi effect. To illustrate this phenomenon, the results of some measurements on the summits of suitably shaped hills are given in Table 4 which includes also the annual average wind speeds (obtained from the nearest meteorological stations) for the areas in which the hills are situated and the heights of the hills.

An examination of the altitudes of the hills and of the gains in average wind speed shows that these gains are not simply the result of altitude: the exposures and shapes of the hills have important influences.

Figures 18 and 19 show photographs of two of the hills (sites 1 and 3) for which data are given in Table 4. They are both almost ideally shaped for wind acceleration. If one were to attempt to specify the ideal it would probably be a hill of approximately conical shape, though with a smoothly rounded top, so that winds from all directions would be similarly accelerated. It would be an isolated hill lying in a coastal plain with no other high ground within perhaps 2 or 3 miles. (Wind speeds are higher near the coast than inland because of the ground friction which retards the passage of the wind). It has been suggested that a ridge lying athwart the prevailing wind will give the best results but, although this may be true if the wind direction remains constant for a large part of the year, it is found that, for variable wind directions, the gain when the wind blows directly across the ridge is offset by the losses when it blows in other directions. Hence the above suggestion for the choice of a conical type of hill.

Table 4

Influence of hill shapes on average wind speed

Site No.	Altitude of hill summit (feet)	Annual average wind speed (m.p.h.)	Annual average wind speed for the surrounding area (m.p.h.)	Percentage gain in wind speed at hill summit
1	500	25	15	67
2	657	22	16	38
3	1,203	27	17.5	54
4	1,358	25	14	80
5	1,894	25	12.5	100

After selecting the sites at which measurements are to be made, the next consideration is the form of the measuring installation. It might be supposed that an elaborate equipment giving a continuous record of wind speed and direction should be installed, but this is not necessary. Only hourly average wind speeds are needed - to provide information from which the velocity-duration curve can be drawn - while the wind directions are not likely to differ greatly from those prevailing, at the same times, at the local meteorological stations. Complicated instruments are not only expensive but are an embarrassment when installed on a remote hilltop because they need skilled maintenance. Further, a continuous record calls for much time and effort in analysing it to provide the hourly speeds which are required.

The best procedure is, therefore, to install on the summits of the hills or, if there are no hills, at the chosen, well-exposed, sites, anemometers of the cup-contact type with some form of recorder giving information from which the hourly average wind speeds can be obtained easily. It is highly desirable that the process of changing the recorder chart at, say, weekly intervals, should be simple so that it can be done by unskilled people who can also provide any small amount of maintenance which the installation may

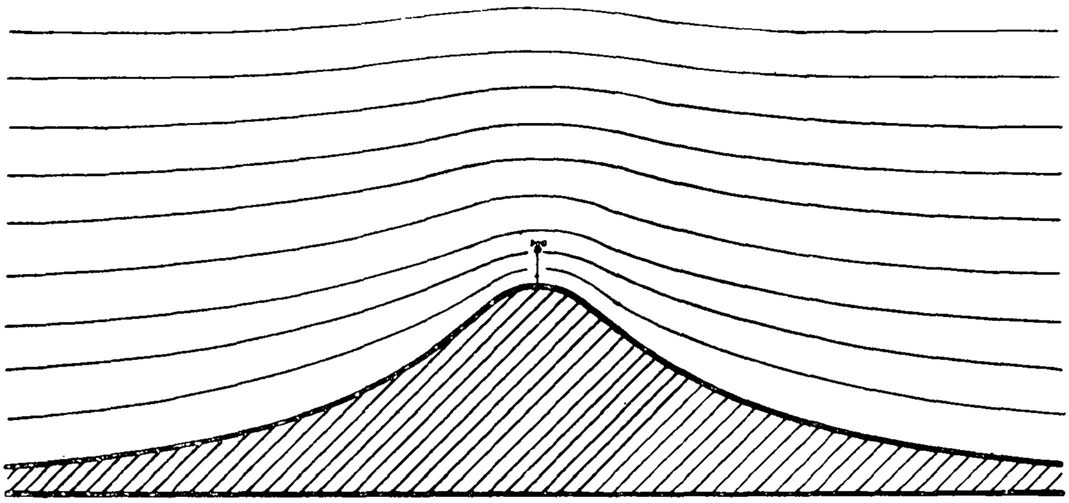


Fig. 21 - Air flow over pointed hill.

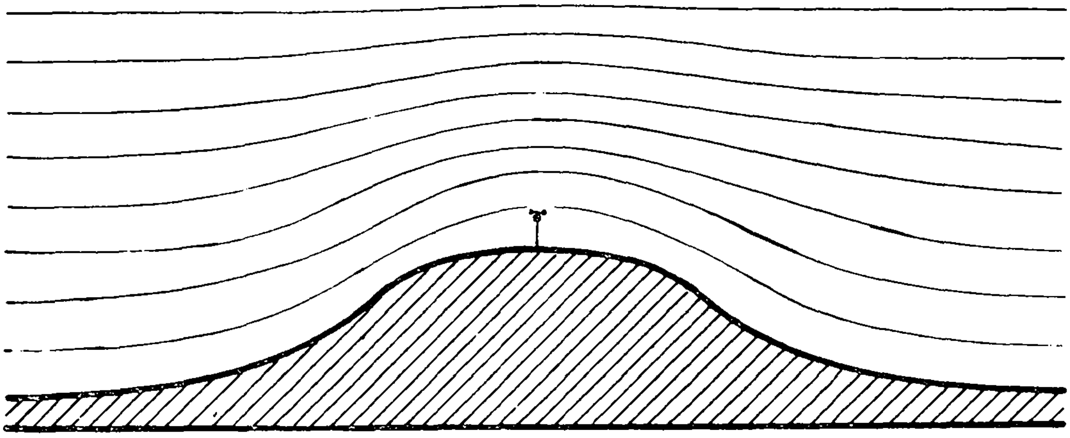


Fig. 22 - Air flow over hill with flattened top.

need. The anemometer itself should, preferably, be mounted on a pole, or light tower, 10 metres high (Fig. 20). This height of 10 metres is suggested because it is the standard used by the meteorological services and it is sometimes desirable to use the same height so that wind records can be compared without the introduction of corrections. There is, however, an important point to be noted in this connection. It can most easily be appreciated by reference to Fig. 21, which shows the probable air flow over a hill, of aerofoil shape, with a fairly sharply pointed summit: the wind stream follows the ground surface and the accelerated wind speed will be measured by the anemometer on a 10 metres-high tower. In Fig. 22 the hill has a flattened top with steeply sloping sides and there is a likelihood, in that case, that the main, accelerated, wind stream will pass over the hilltop at a height greater than that of the anemometer so that the wind speed measured will be less than might be expected and much less than would be measured by an instrument placed on a tower high enough to "tap" the accelerated wind. This shows that the height of the anemometer above ground might have to be related to the contours of the hilltop site. Remembering that the equipment will be subjected to high wind pressures and generally difficult climatic conditions, precautions should be taken to ensure that all parts of the installation are robust and are protected from the weather as far as possible. Especially if the sites are distant from usable roads and man-handling of the equipment over difficult ground is involved, portability and low weight are important. The pole or supporting tower for the anemometer can well be sectionalized to ease the transport problem, and it is useful to devise methods of making foundations, or anchoring guy ropes, which do not call for the carriage of heavy loads or involve complicated procedures.

As a power supply for electrically-operated recorders, batteries of accumulators, or of dry cells, are needed and thought should be given to the question of replacement of these when they become exhausted. If the recharging of accumulators introduces a difficulty, it may be found cheaper to use dry cells or even, perhaps, wet Leclanché cells.

Some protection for the recording equipment - placed near the foot of the anemometer tower - is desirable. This can take the form of a wooden or metal box, properly tied down to prevent the wind from blowing it away, or it may be possible to use local material to build a small hut: this can be done if there is a plentiful supply of flat stones at the site or if the ground is soft so that a turf hut can be built.

In analysing the records obtained from an installation of this kind it is useful to devise a tabular system which can be used in a semi-automatic way by unskilled workers who can make the analyses regularly and so maintain a continuous check upon the wind régime at the different sites. This is important because sometimes it is found that an apparently good site has an unexpectedly low wind speed: a continuous and regular analysis will call attention to this fact and will thus save waste of time in continuing observations at a useless site.

From the wind speed records for a complete year the velocity-duration curve for the site can be plotted and the value of the specific output T can be found as explained earlier. It is this value, T, which characterizes the site - in relation, of course, to a suitably designed windmill which might be erected on it - and which provides the necessary information from which the possibility of an economic wind power installation there can be judged.

Although priority must certainly be given to the question of obtaining reliable data from a wind survey, it is usually necessary to undertake such work at the minimum cost. **For this** reason the use of the simpler cup-counter anemometer, already mentioned earlier, is suggested. This instrument can be mounted on a light pole (guyed to give it increased strength to withstand wind pressures) of only 3 metres height so that its dials can be read by an observer standing on the ground (see Fig. 23). In suggesting this low height it is assumed that there are no local obstructions to interfere with the wind flow at that height and that the question of shape of the hilltop - sharply pointed and not flattened - has been considered.

An installation of this kind is cheap, is easy to erect and can be used by a completely unskilled observer: it is only necessary that the observer shall be able to read the dials and write down the readings.

A cup-counter instrument when read at lengthy intervals, e.g. weekly, does not give hourly wind speeds; it integrates only run-of-wind from which an annual average wind speed can eventually be obtained. Nevertheless, if the weekly readings are plotted on a graph as in Fig. 24 it is possible to distinguish the relative windiness of a number of sites very easily. Indeed, sites can be placed in order of windiness after an observation period of a few months.

Fortunately, as has been shown by analysis of wind records at sites in different parts of the world, there is a close relationship between the specific output T and the annual average wind speed at a site. This is shown on the curves of Fig. 25 which relate to different values of "rated wind speed" for windmills which might be installed at the sites.

This means that a fairly good approximation to the value of T for a site can be obtained from measurements by the cup-counter anemometers - which give data for the calculation of annual average wind speeds.

An anemometer measuring hourly wind speeds is still necessary, in a survey area, to provide information on the full wind régime, on periods of calm weather, and on maximum hourly wind speeds but, out of (say) six installations in the area being studied, only one such installation is essential, the rest being the cheaper and simpler cup-counter instruments. The result of the survey would then be that at five sites the annual average wind speed will be measured while, at the sixth, full wind data will be obtained. Unless the survey area is very extensive and includes very different terrains and exposures to prevailing winds, it is, to say the least, very unlikely that the wind régimes at the first-mentioned five sites will be very different from that measured at the sixth.

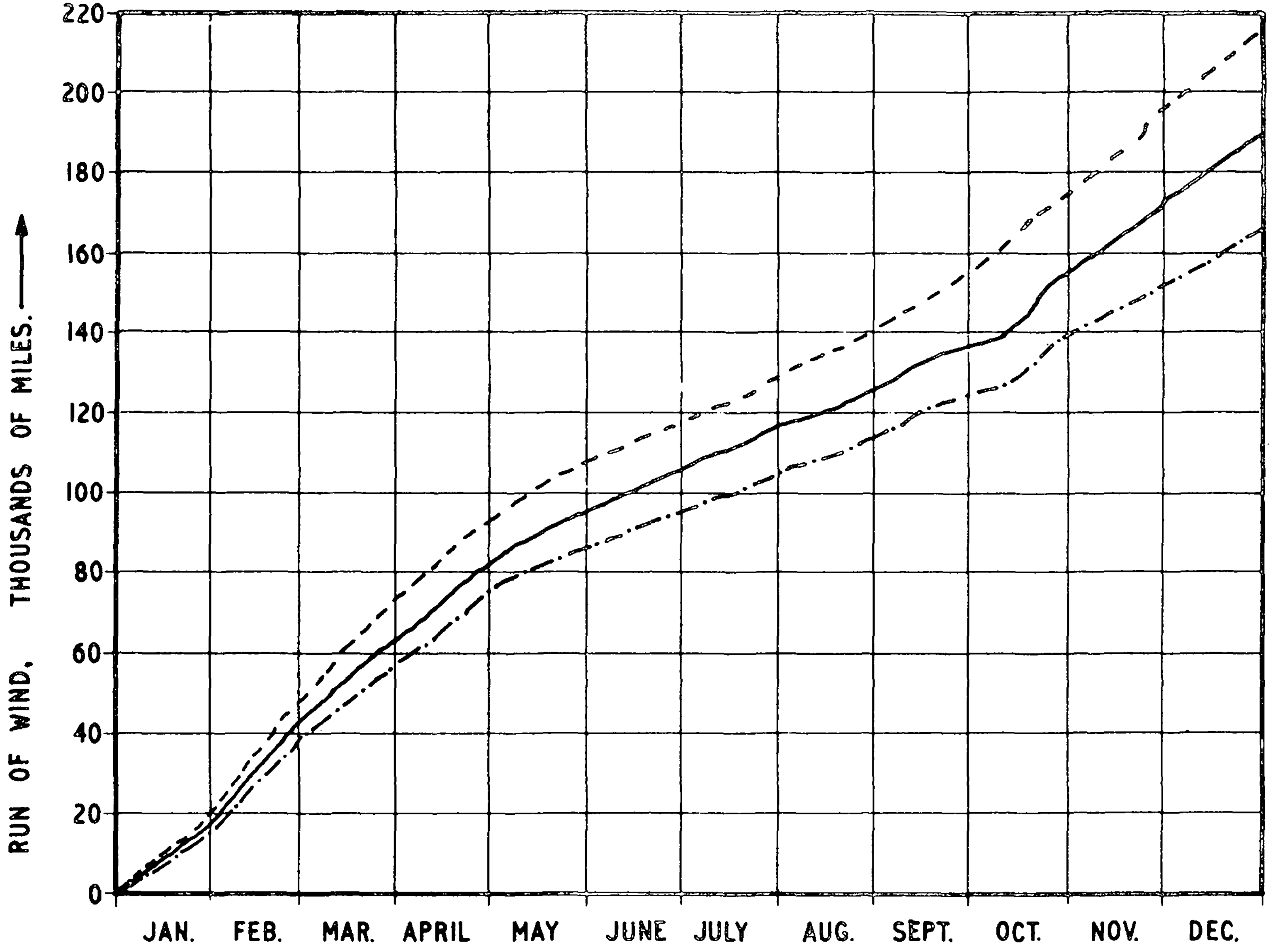
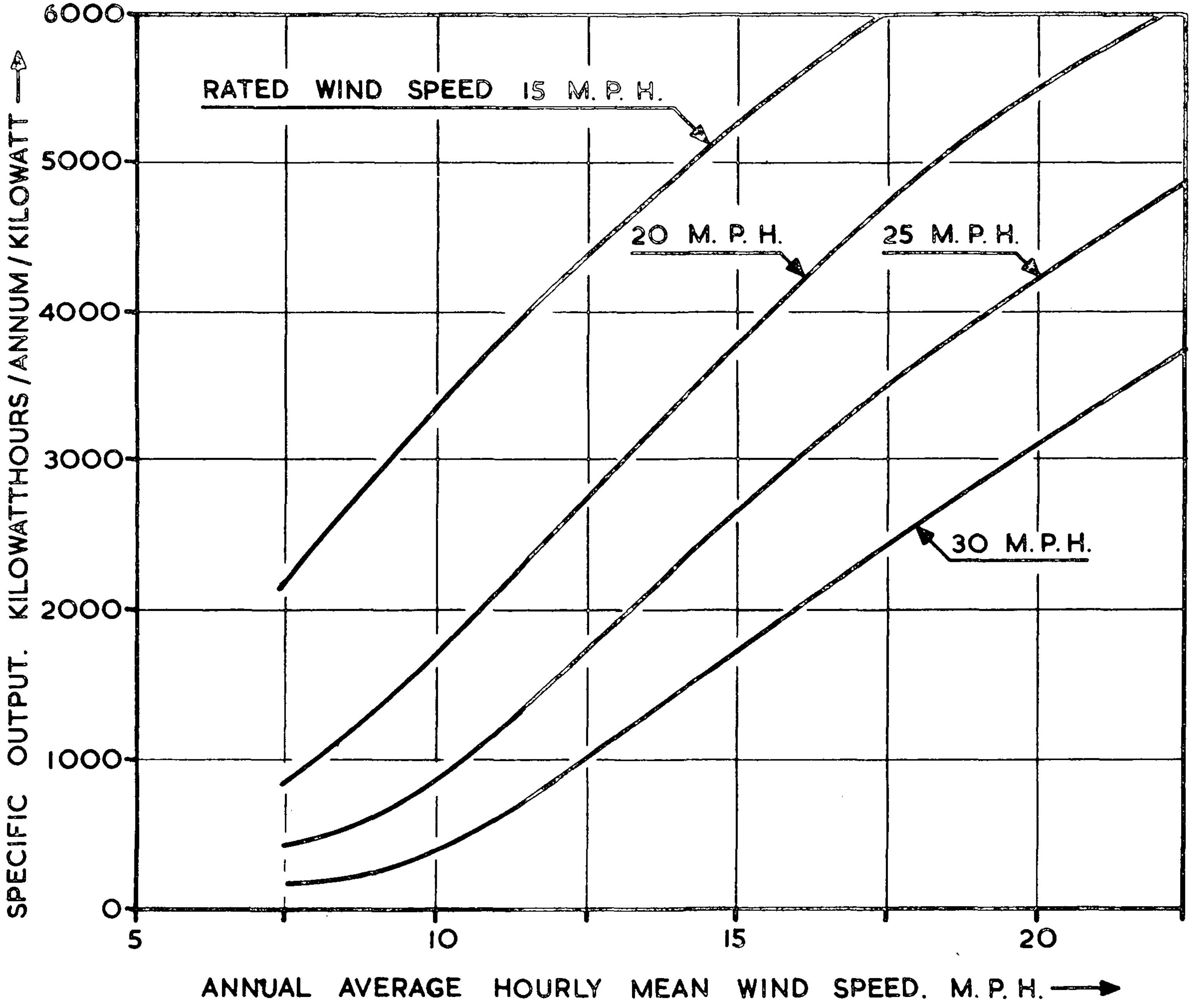


Fig. 24 - Run-of-wind curves.

Fig. 25 - Specific output/average wind speed curves.



A novel type of anemometer, specially designed for wind power purposes, has been used successfully by the research department of Electricité de France in the French preliminary wind surveys in which a large number of sites were classified in order of windiness (Ref. 1). The rotor of this instrument has four long cylindrical cups, with quarter-sphere ends and sufficient power is generated by it to drive a small alternator the permanent-magnet rotor of which is mounted at the bottom of the anemometer spindle. Both the voltage and frequency of this small alternator are proportional to wind speed and its output is fed into a modified form of kilowatt-hour meter. The electrical constants of the circuit are so adjusted that the speed of revolution of the meter disc is proportional to the cube of the wind speed and the meter registers the integration of the cubes as the wind speed changes. By using a multiplying constant which takes into account the air density and the theoretical maximum efficiency of a windmill (59.3 per cent) the dials of the meter are marked in kilowatt-hours per square metre (of area swept by the rotor of a theoretical windmill).

This equipment begins to operate in a wind speed of about 3 metres per second (6.7 miles per hour) and its registrations follow the cube law closely up to a wind speed of about 13 metres per second (29 m.p.h) after which the error increases until, at 25 m/sec., it is some 30 per cent low.

In spite of the large errors at high wind speeds the instrument is useful, particularly for the comparison of sites, because it can be left running for a long period without its registrations being destroyed: it thus needs only infrequent attention and, in fact, readings spaced at exactly one year apart would show the theoretical annual total of energy (per square metre of swept area) which would be produced at the site by a windmill. It should be emphasized, however, that these readings cannot be taken as true indications of the possible energy obtainable: their value lies in their relationship to readings from other sites. Again, no indication of the distribution of power production in the time interval between readings is given so that the durations of calm spells, and of particularly windy periods, cannot be distinguished. The equipment, which is made by the Compagnie pour la Fabrication des Compteurs, of Montrouge,, is inevitably somewhat expensive in initial cost but is, of course, cheap to operate owing to the infrequency with which it needs to be read.

The Increase of Wind Speed with Height

For many years meteorologists have taken a considerable interest in this question and much experimental work has been done to establish the law governing wind speed and height above ground. The underlying facts are that, while the wind at great heights (say several thousand feet) takes up a speed dependent mainly on atmospheric pressure differences, wind near the ground is impeded by frictional drag caused by the ground surface. We have, therefore, fast-moving upper air "sliding" over slower-moving lower air and, if we think of the air stream as consisting of layers, the influence of one layer on the speed of another depends on the degree to which there is intermixing of the air in the layers. This intermixing is caused by the eddies which are discussed more fully under the next heading and is, of course, increased by temperature differences at different heights.

Weather conditions vary so much, from place to place and from time to time, that it is impossible to state any law, for the vertical wind gradient, which can be accepted as precise under any specified conditions. Nevertheless, a statistical law for the average wind speed over level ground has been formulated as the result of the work of many investigators (see Ref. 14). This is that the average wind speed V_h, at height h, is proportional to the height raised to some power α which is of the order of 0.17 but which, unfortunately, itself varies according to the time of day, the climatic conditions, the actual value of the wind speed and other factors. If, however, we accept this law we find (as an example) that, over level country, the ratio of the average wind speed at 150 feet (45 metres), to that at 50 feet (15 metres), is $\frac{150^{0.17}}{50^{0.17}} = 1.2$. The speed increases by 20 per cent as we ascend from 50 feet to 150 feet and this is useful information if we are considering the question of the height of the tower for a windmill. Assuming that the tower is to be at least 50 feet high, is it worthwhile to build it higher to obtain the benefit of increased wind speed? To answer this question we need to know more about the annual wind régime at the site, the purpose of the windmill and, especially, about the variation in the cost of the tower with height, but a knowledge of the vertical wind gradient is certainly a basic requirement for any such calculations.

It should be noted that at coastal sites the effect of altitude is reduced so that when a site is almost surrounded by the sea - as it will be on a promontory - the ratio of wind speeds at different heights must be multiplied by a correction factor which is fractional (e.g. 0.7).

The law given above certainly does not apply to wind speeds over hilltops. As stated in preceding paragraphs, the effect of certain shapes of hills is an acceleration of the wind speed, at low heights over the summit, due to a compression of the lower stream of air by that above. This effect disappears at a height above ground which depends upon the actual relative dimensions of the hill. From such experience as exists on this question (see Refs. 14 and 17) it appears that it will usually be quite significant up to a height of one or two hundred feet above the summit. By increasing the wind speed at the levels near the ground this acceleration effect reduces the vertical wind gradient: there is less advantage to be gained by building higher towers on a hilltop.

To indicate the order of this reduction, on a hilltop, the ratio $\frac{V_{150}}{V_{50}}$ will probably be about 1.1 instead of 1.2 as calculated for level ground.

Wind Structure

In wind surveys and in the consequent estimation of energy obtainable from the wind at a given site, we are interested mainly in hourly average wind speeds but, for some purposes, the "structure" of the wind is of interest. By the term "structure" we mean the detailed behaviour of the wind, including its rapid changes in speed and direction both horizontally and with height above ground.

Fluid flow, which includes air flow, may be "laminar" or "turbulent". In laminar flow the air may be considered as flowing along streamlines without any whirling motion and without any mixing of its layers whereas, in turbulent flow, mixing of the air in the layers takes place due to a whirling motion - or eddies superimposed on the main flow. In general, natural winds, in the open, are turbulent although when the wind flows over a hill with a good aerofoil shape something approaching laminar flow may be assumed in calculations on its acceleration.

The "eddies" are thought of as more or less circular disturbances which travel with the wind and, according to their direction relative to that of the main stream, they create "gusts" and "lulls". The axes of these eddies are orientated in all directions so that, in a gusty wind, rapid changes of both speed and direction of the wind at any given point may occur.

The importance of wind gusts, from the point of view of wind power, lies mainly in their effects upon the stresses set up in the blades of a windmill. There is insufficient information on gusts for any general statement to be made on the diameter of the eddies which cause them but there is some evidence (Refs. 14 and 52) that this diameter may be less than that of the circle swept by the blades of the windmill rotor and, therefore, that a blade may be suddenly affected by a considerable increase in wind speed with consequent heavy stresses. Measurements on gusts have been made showing that it is possible to have, during a time of no more than 0.8 second, a change in the horizontal component of the wind speed from 55 ft/sec. to 125 ft/sec. and back again to 50 ft/sec., this being accompanied by a change in the vertical component, during 0.4 second, of 50 ft/sec. upwards to 50 ft/sec. downwards. Changes in speed of up to 15 ft/sec., or even more can occur in as short a time as 0.04 second. Although the causes of gusts are undoubtedly complex they can be caused by local obstructions in the path of the wind and this is a good reason for choosing, as a windmill site, a place which is free from any such obstructions or sudden breaks in the ground contours which may set up turbulence.

While the possibility of such rapid changes are of interest to the designer of a windmill because of the blade strength which they call for, they are unlikely to have any distinguishable effect on the power output of the machine because they are of such short duration that a large rotating mass such as the windmill rotor cannot respond to them. It is worth noting that in storms, when the hourly average wind speed is high and the conditions are gusty, the changes of speed, in the gusts, are considerable (Fig. 26). Thus, for example, records taken in a storm when the hourly average wind speed was 90 m.p.h. showed rises and falls of 30 per cent, i.e. up to 125 m.p.h. and down to 60 m.p.h. Gust speeds of the order of 130 m.p.h. are found to occur, perhaps every year, or once in two years, during storms in the very windy areas of Scotland and, no doubt, in other countries.

Somewhat slower changes of wind speed, occupying seconds rather than fractions of seconds, may have some effect on output while, if the direction of the wind changes in the same short time, difficulty will be experienced in the orientation of the windmill rotor to face into wind: the head of a large machine cannot respond quickly to a change in direction and, if the angle of the change is large the direction of the wind pressure on the blades might suddenly be reversed.

The total output of energy by a wind-driven machine during any period of time is the integration of the small elements of energy contributed by different wind speeds each of which exists for only a very short time. The power being proportional to the cube of the wind speed v the element of energy in a short time t (during which the wind speed v is assumed to be constant) is v^3t and the total is the sum of all such elements. Now, it can be shown that the average value of a number of cubes is greater than the cube of their own average value. For example, considering the numbers, 2, 3 and 4, their cubes are 8, 27 and 64 and the average value of these cubes is $\frac{8 + 27 + 64}{3} = 33$ whereas their average is $\frac{2 + 3 + 4}{3} = 3$ and its cube is only 27.

Considering the energy output again, the significance of the fact just mentioned is that, provided that the wind speed changes slowly enough for the machine to follow the change, the actual total output may be rather larger than that calculated from an average value of wind speed measured over a longer time such as one hour. This 'gain' in output is not, however, very large and it is wise, perhaps, to neglect it in estimations of output. Hence the recommendations, given earlier, to base such estimates upon hourly average wind speeds.

Wind Data for Water Pumping and for Electricity Generation

Basically, the same kinds of wind data are needed for both of these purposes. A complete record of hourly average wind speeds will afford all the information but its use, i.e. the analysis following its collection, will differ slightly. This difference results mainly from the fact that, in water pumping, there must be provision for storage of water - which means, in effect, storage of energy because pumped water represents the expenditure of energy - while, in the generation of electricity, energy storage, except on a small scale for purposes of high priority demanding little power, is not essential.

There is the same requirement for data on wind speeds during different seasons of the year and on the duration of continuous calm weather. The latter, is, however, of greater importance in water pumping since it may affect a major part of the installation - the reservoir - while for electricity generation only the size of the storage battery, representing a relatively small part of the total installation, will be affected.

Wind-produced electricity can be used for many purposes at random times as and when it happens to become available and, if there is no wind for some days, these purposes cannot be served: the work must wait until the wind returns.

When water pumping is the sole object of the windmill, provision must be made for a supply of water continuously, either directly from the wind-driven pump or from the reservoir which it has filled. The windmill output throughout the year must, therefore, be studied closely with special reference to demands on the reservoir on a day-to-day basis.

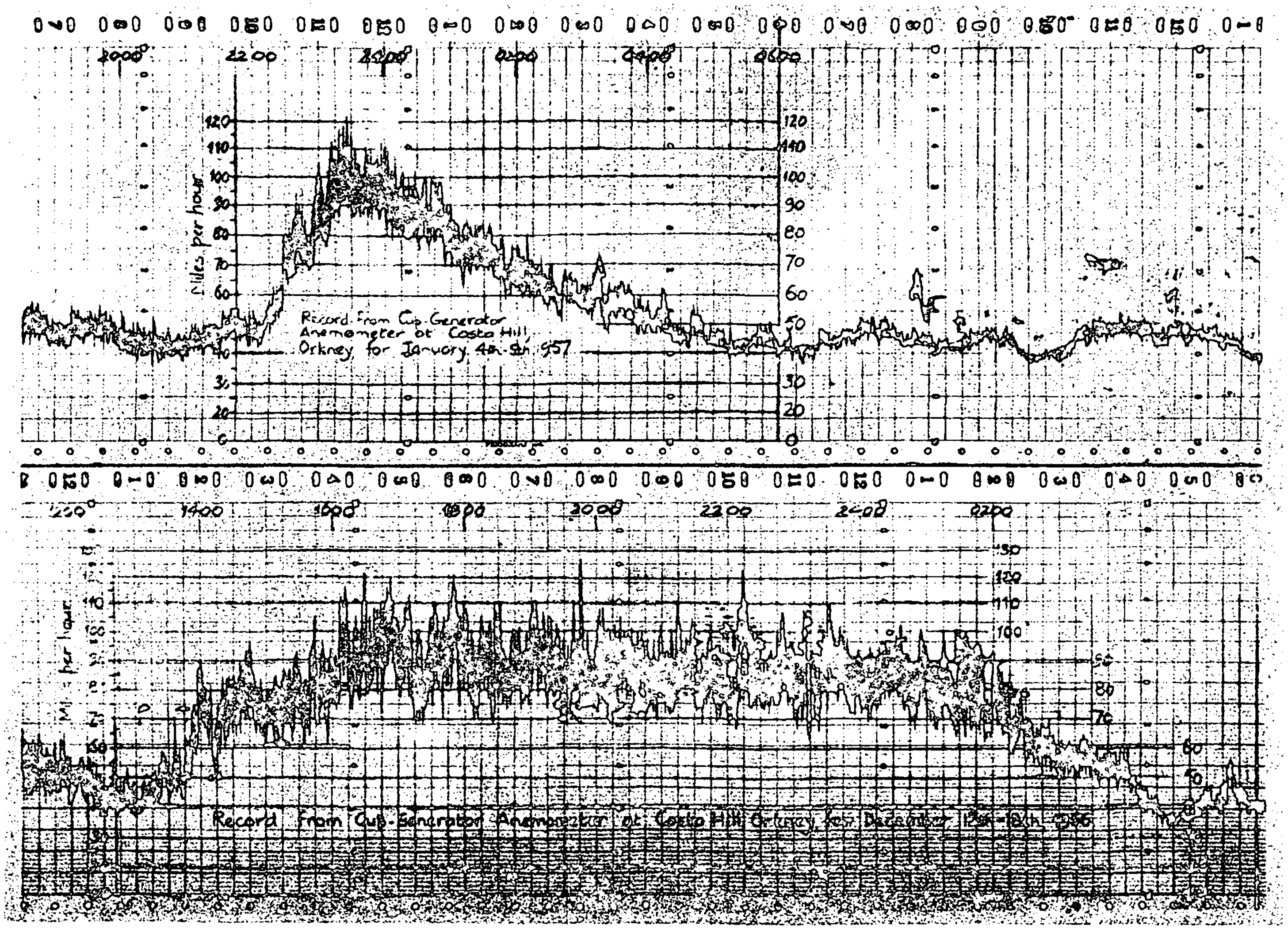


Fig. 26 - Wind records in an Orkney storm.

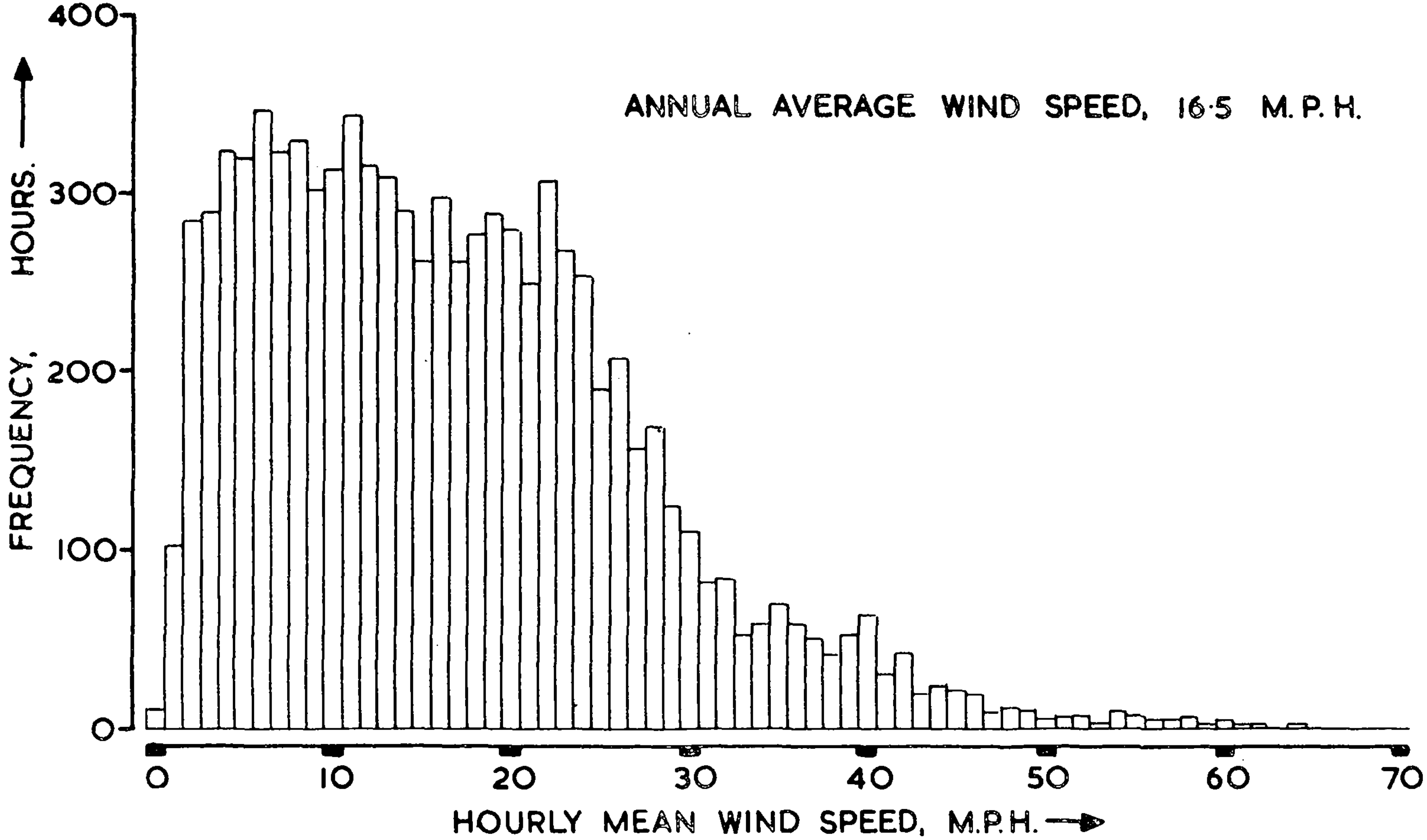


Fig. 27 - Velocity-frequency histogram

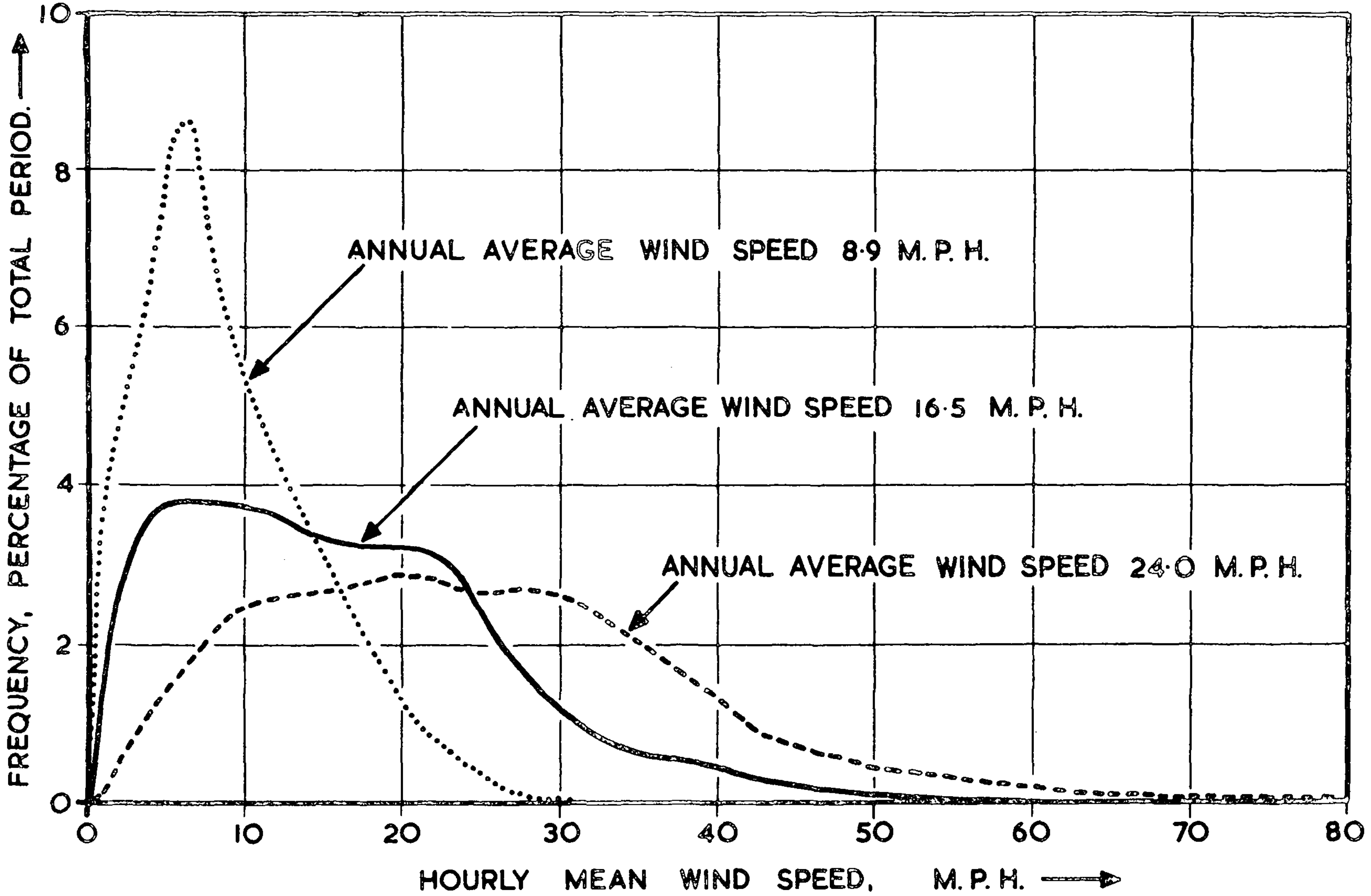


Fig. 28 - Velocity-frequency curves.

One aspect from which the information needed for electricity generation is more demanding than for water pumping is that of diurnal variations in wind speed. When the wind power is to be mainly used directly, without storage, it is of some importance to know at what hours of the day there will be enough wind for purposes which could be fulfilled during those hours. For example, if, during the season of the year when power could be used for the threshing of grain, the wind were to blow mainly at night this would be a disadvantage as it would be, also, if cooking, or the driving of ventilating fans, by wind-produced power were in prospect. On the other hand, power at night would be useful for lighting or for heating.

In water pumping there is little or no distinction to be drawn between power in daylight hours and that during the night. These questions will be discussed in more detail in the succeeding section.

Perhaps, before concluding this discussion on wind data, it might be useful to point out a method of presenting annual wind speed data which is alternative to that of the velocity-duration curve. This is the velocity-frequency diagram for which exactly the same basic information is needed as for the velocity-duration curve, namely a record of hourly average wind speeds, but which provides a clearer conception of the annual duration of speeds of different values.

In this diagram, the form of which is illustrated in Fig. 27, the vertical lengths of the blocks represent the annual duration, in hours, of each wind speed - in one mile per hour or one kilometre per hour intervals. Whatever the distribution of the wind speeds in the year, the total area of these blocks must be the same in every case because it must represent the number of hours in the year, i.e. 8,760. Sometimes it is found convenient to draw a curve through the peaks of the blocks but this can be misleading because no attempt is being made to indicate a continuous variation of duration for all wind speeds. The diagram is a histogram and should, strictly, always be presented in block form. In Fig. 28 three velocity-frequency curves, for sites with different annual average wind speeds, are shown. It will be seen that the duration of the most frequent wind speed diminishes as the annual average wind speed increases.

III. WIND POWER FOR DIRECT WATER PUMPING

The direct pumping of water by a windmill is done through an installation which is a combination of windmill and water pump so that the characteristics of each of these two component parts are combined in the whole. The appropriate matching of the characteristics to produce a satisfactory output is done, of course, by the manufacturer. Unlike a wind-electric plant, the wind pump gives the user no opportunity to vary the loading conditions significantly: he must accept it as it is and make the best use of it. Further (when using the commonest form of installation - the piston pump), there is little choice of site with a wind pump because it must be installed vertically above the water to be pumped even though the site is not especially windy. There are, also, other limitations to the water output of such an installation. The first is the obvious one of availability of water at a depth shallow enough to be reached by the pump, and a second is the reservoir capacity.

The planning of a windmill water pumping installation is, therefore, somewhat more complicated than that for a wind-driven electric generator. It is not a simple engineering operation but demands knowledge of the geological and geomorphological conditions in the area concerned. Scientists skilled in these subjects, and in the associated one of ground-water hydrology, should be consulted before any major scheme for water pumping - as distinct from an individual pumping project at known wells - is undertaken.

This bulletin is not the place for a dissertation on ground water but there are a few salient facts which should be borne in mind by anyone interested in the provision of pumped water by means of wind power. The first is that water often lies under apparently very dry ground but varies in depth below the surface according, partly, to the surface contours, i.e. there is a water table, in any given area, which can be considered as a surface which can be reached more easily in the valleys than on the hilltops in the area. The actual depth of this table, the contours of which do not always correspond with those of the ground surface above it, depends on many factors, topographical and geological, and on the distance of the area from any main source of water such as lakes and rivers of major size. Thus, for example, in northern Egypt, there is underground water, in the coastal strip, which has flowed down, underground, very slowly from the upper reaches of the Nile until it falls into the Mediterranean.

A well, driven down into the underground layer of water, may be found to have limited capacity because of the rate at which new water flows in to take the place of that which is withdrawn by the pump. This rate obviously depends upon the nature of the sub-soil adjacent to the well. Sometimes horizontal tunnels are driven, underground, to lead water into the well shaft and so increase the rate of inflow. This is an important question in considering the use of a wind pump because, clearly, it is useless to install a machine whose potential rate of pumping is appreciably greater than that of the inflow to the well.

Another problem is that of salinity in the underground water. Especially in coastal areas, but not exclusively there, underground streams, or layers, of brackish water often lie at no great distance from those of sweet water. Clearly it is first necessary to make sure that the water to be pumped has a sufficiently low salt content for it to be used for animal consumption or for irrigation. This question of salinity is a complex one and it forms the field of study of specializing laboratories in different parts of the world.

Men and animals can usually tolerate more salt, in their drinking water, than is permissible for the irrigation of crops. It is not easy to give definite figures for drinking water because people and animals in dry areas, who become accustomed to drinking saline water, sometimes use water with a salt content of 2,000 or more parts per million up to 5,000 or even 6,000, although 1,000 parts might be considered as the desirable limit.

For irrigation, the degree of salinity which can be tolerated depends, to a considerable extent, upon the rainfall in the area. Salt accumulates in the top few inches of the soil, especially if the drainage is poor and this can be leached out only if there is sufficient rainfall (or other alternative supplies of sweet water) with adequate drainage.

Plants vary greatly in their tolerance, and classifications are given in the publications of the U.S. Department of Agriculture (Refs. 42, 43, 44, 45 and 46). One such classification, for field crops, is shown in Table 5. (U.S. Department of Agriculture, Agriculture Information Bulletin, No. 217, March 1960)

Table 5
Salt tolerance of various crops

Tolerant (1)	Moderately tolerant (2)	Sensitive (3)
Barley (grain)	Rye (grain)	Field beans
Sugar beet	Wheat (grain)	
Rape	Oats (grain)	
Cotton (upland)	Sorghum (grain)	
	Sorgo (sugar)	
	Soybeans	
	Sesbania	
	Broadbean	
	Corn	
	Rice	
	Flax	
	Sunflower	
	Castorbean	

(1) Electrical conductivity of soil 8 to 12 millimhos per cm. at 25°C. (One millimho is usually equivalent to 640 parts per million of salts in solution)

(2) 4 millimhos to 8 millimhos.

(3) 2 millimhos.

A UNESCO publication (Ref. 39), on the utilisation of saline water, gives much valuable information on this subject and includes a "standard scale adopted by the Casablanca Laboratoire Officiel de Chimie Agricole et Industrielle, Morocco". This is given in Table 6.

Table 6

Uses of waters of different salt contents

Proportion of chlorides, expressed as NaCl, in grammes per litre in the irrigation water	Suitability for irrigation
less than 0.5	suitable for all irrigation
0.5 to 1.0	suitable for most irrigation
1.0 to 1.5	slightly high choloride content, usable for most irrigation but precautions needed for use on sowings of delicate varieties.
1.5 to 2.0	definite chloride bias but usable for irrigation except for sowings of delicate varieties
2.0 to 2.5	high chloride content but usable with suitable precautions
2.5 to 3.0	high chloride content but still usable for certain crops
3 to 4	very high chloride content, practically unusable for irrigation
above 4	salt water entirely unsuitable for irrigation

A difficulty arises from the fact that, in areas with mixed underground waters, sweet water may over-lie brackish water in the well so that, after a certain period of pumping, the output becomes too brackish for use and the pump must be stopped until the well can refill with usable water. For this reason it is often advisable to install several wind pumps, each of relatively small capacity and perhaps no more than a hundred yards apart, rather than to attempt to produce the same quantity of water from one large pump.

Studies of underground water problems and surveys to provide information on the question are now being made in many parts of the world. The Arid Zone Research Advisory Committee of UNESCO has been much concerned with the matter and a number of useful papers (see Refs. 37, 38 and 39) have been given at recent UNESCO conferences. It is strongly recommended that such papers should be consulted, or that the advice of ground-water experts should be sought, before any significant expenditure on water pumping is undertaken.

From what has just been said it will be appreciated that no general rule on the capacity of a wind pump for installation at any given site can be given. Unless adequate information on the underground water supplies is available, some trials with different sizes of pump may be necessary. This is not, in fact, so serious a matter as may appear at first sight because, in any extensive scheme, different sizes of pump will certainly be needed and the changing of a plant is not a major operation: it can usually be done by local labour without any high degree of skill being called for.

By far the commonest type of wind pump is the slow-running wind wheel driving a piston pump. A description will be given later but, for the moment, we are concerned with the water output which can be expected from machines of this kind.

The wind wheels range in diameter from about 6 feet to about 18 or 20 feet (2 metres to 5 or 6 metres). Piston pumps demand a constant torque. For any given installation, therefore, the torque required of the wind wheel is constant whatever its rotational speed and whatever the speed of the wind. Standard types of low speed windmill provide the necessary torque to start pumping in a wind speed of 5 or 6 miles an hour (2 to 2.5 m/sec). The rate of pumping then rises until wind speeds reach about 15 m.p.h. (6.5 to 7 m/sec), after which the wheel begins to turn, automatically, out of wind, so limiting the rate of pumping, for higher wind speeds, to little more than that corresponding to 15 m.p.h.

The pumping rate depends, of course, upon the height through which the water is to be raised as well as on the diameter of the wind wheel.

Pumping Rates

The rates of pumping, for different sizes of windmill, quoted by manufacturers, differ so widely that it is necessary to establish figures which can be used as reference standards. It should be clearly understood, here, that the manufacturers' figures are not deliberately misleading; the pumping rates quoted can doubtless be achieved by the machines mentioned, but the major doubt is the wind speed for which they will be attained. If such figures include any mention of wind speed at all this is usually vague - "In a light breeze", "For an average wind speed", "In wind speeds of 12 to 16 miles an hour", etc.

For any serious estimate of annual output, based on a measured wind régime, something more precise is needed and the following tables have been drawn up to meet this need.

Basic data for this purpose are, of course, the values calculated for the power available, in the wind, at different wind speeds. These must be combined with an assumed value for the overall efficiency of the windmill-pump combination. Vadot (Ref. 48) takes an efficiency of 20 per cent which is arrived at as follows:-

Maximum theoretical efficiency of a windmill	59.3%
Actual efficiency of a slow-running rotor, as a fraction of the theoretical efficiency	55% to 60%
Efficiency of the pump and driving mechanism	60%

These component efficiencies are multiplied together to obtain the overall efficiency which is .593 x .6 x .6 = .2 or 20 per cent. This efficiency of 20 per cent should be regarded as a probable maximum rather than as an average: much will depend upon the quality of the actual installation and on its maintenance. Certainly it will not, in fact, remain constant over the whole operating range of the wind pump from the start of pumping to the point of full output. The pumping rates given in Table 8 are, therefore, maxima: if the actual efficiency of the wind pump were known to be x per cent, the true pumping rates could be calculated quite easily by multiplying those in the table by $\frac{x}{20}$.

The formula for the power in the wind is

$$\text{kilowatts} = 0.000005AV^3$$

where A = area swept by the windmill rotor (in sq. feet)

V = wind speed in miles an hour

Converting this to horse-power and introducing the 20 per cent efficiency, we have for the h.p. per 1 square foot of swept area, the expression

$$\text{h.p. per sq.ft.} = 0.00000133V^3$$

Values of this expression, for wind speeds from 5 m.p.h. to 22 m.p.h., are given in Table 7.

Table 7

h.p. per sq.ft. (at 20% efficiency) for different wind speeds in m.p.h.

Wind speed (m.p.h.)	h.p. per sq.ft. of swept area	Wind speed (m.p.h.)	h.p. per sq.ft. of swept area
5	0.000167	14	0.00366
6	0.000288	15	0.00450
7	0.000456	16	0.00546
8	0.000684	17	0.00655
9	0.000972	18	0.00778
10	0.00133	19	0.00918
11	0.00177	20	0.0106
12	0.00230	21	0.0123
13	0.00293	22	0.0142

The pumping rates in Table 8 are based on a pumping "head" of 100 feet. This head includes:- (i) the depth of the water below the ground surface, (ii) the height, above ground surface, to which the water is to be pumped, and (iii) an allowance for pressure loss in the water pipes. The pressure loss, due to pipe friction, depends on the length and diameter of the pipes: it is not a large proportion (perhaps 1 or 2 per cent) of the total head when the reservoir into which the water is pumped is very close to the well head but, if the water is to be pumped to a distant point, the loss due to pipe friction may be quite a large percentage of the total head.

As a fair approximation it may be assumed that, for other pumping heads, the pumping rate is inversely proportional to the head so that, if the head is 200 feet, instead of 100 feet, the rate is halved.

With a 100 ft. head the pumping rate, for a power of 1 h.p., is almost exactly 2,000 gallons per hour so that this rate is easily obtained by multiplying the h.p. by 2,000.

If we work in metric values, instead of in British units, we have, still assuming 20 per cent overall efficiency,

$$\text{C.V./sq. metre} = 0.000162\, V^3$$

where V is the wind speed in metres per second.

Table 7 then becomes as shown in Table 9.

Table 8

Pumping rates and h.p. for different diameters of wind pump, with 100 feet head and assuming 20% efficiency throughout

Wind speed m.p.h.	6 feet		8 feet		10 feet		12 feet		14 feet		16 feet		18 feet	
	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr	h.p.	gals/hr
5	.0047	10	.0083	17	.0125	25	.019	38	.025	50	.033	66	.042	84
7	.0128	25	.0228	42	.036	72	.051	102	.069	138	.091	182	.116	232
10	.0372	75	.066	132	.10	200	.15	300	.20	400	.266	532	.337	674
12	.064	128	.115	230	.18	360	.26	520	.35	700	.46	920	.59	1,180
14	.102	204	.183	366	.29	580	.41	820	.56	1,120	.73	1,460	.93	1,860
16	.153	306	.273	546	.43	860	.61	1,220	.83	1,660	1.09	2,180	1.39	2,780
18	.218	436	.389	778	.61	1,220	.87	1,740	1.20	2,400	1.56	3,120	1.99	3,980
20	.297	594	.53	1,060	.83	1,660	1.19	2,380	1.60	3,200	2.12	4,240	2.70	5,400
22	.398	796	.71	1,420	1.11	2,220	1.60	3,200	2.2	4,400	2.84	5,680	3,62	7,240

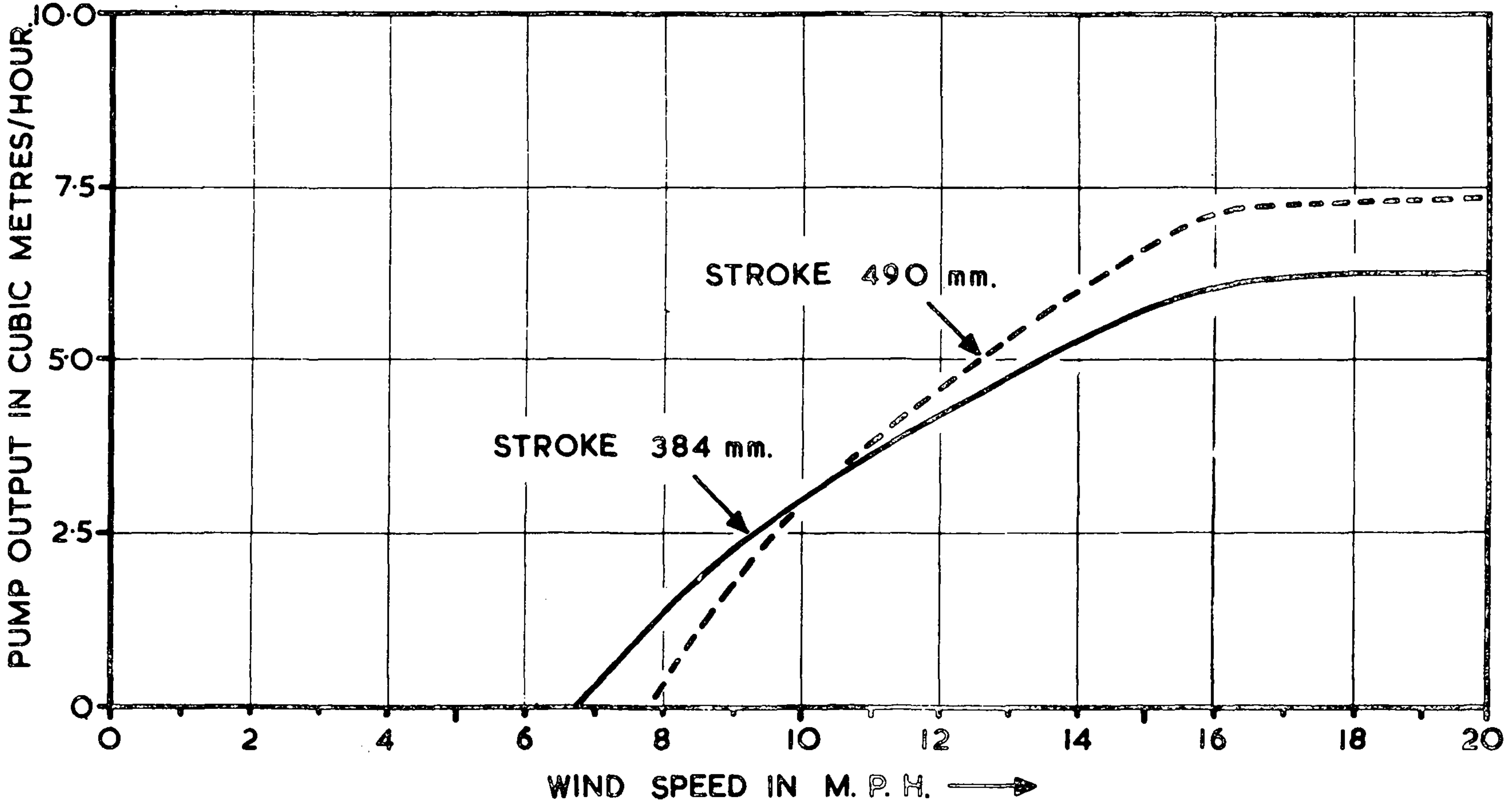


Fig. 29 - Output wind speed curves for wind pumps.

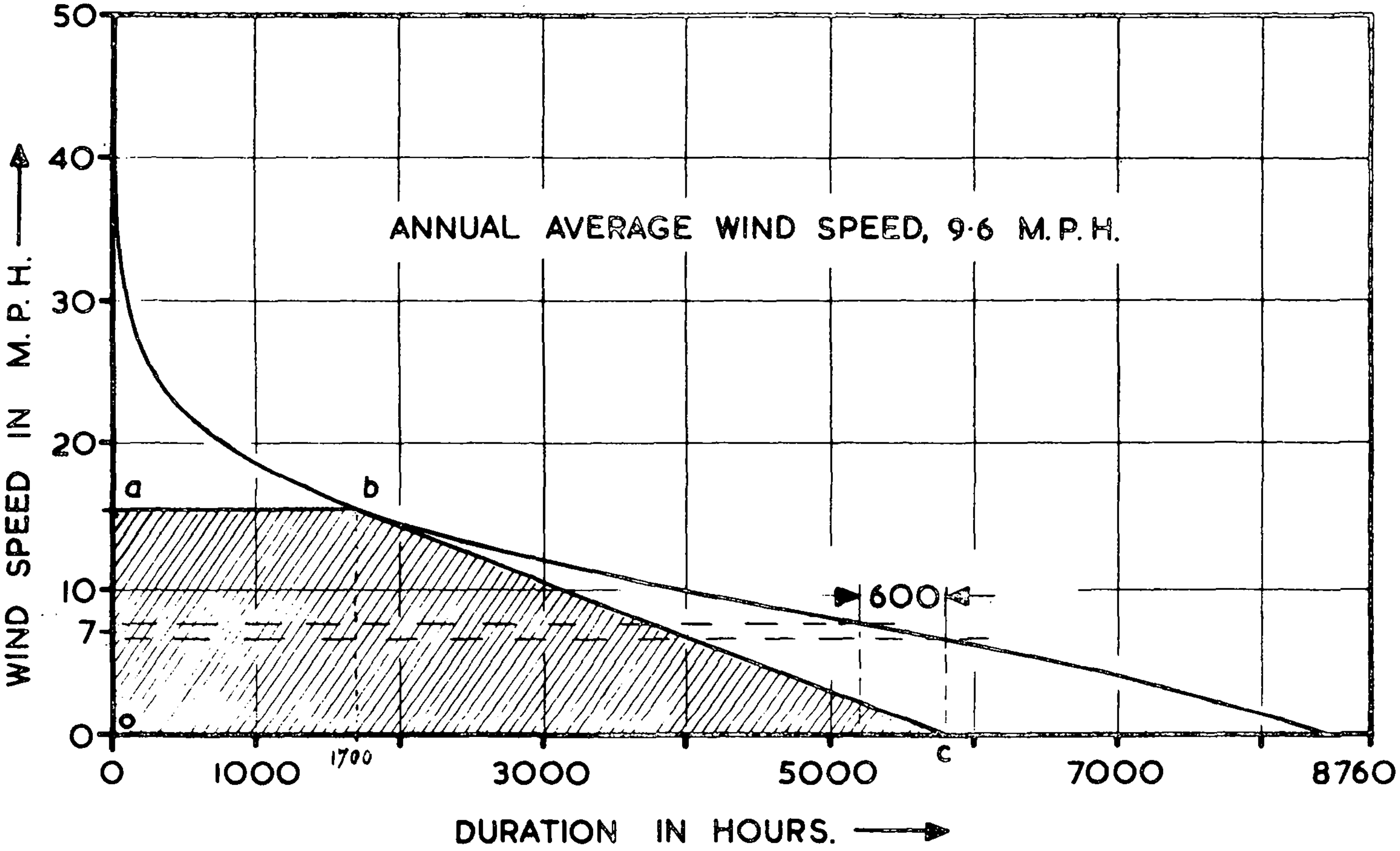


Fig. 30 - Velocity-duration curve.

Table 9

C.V./sq.metre (at 20% efficiency) for different wind speeds in m/sec.

Wind speed (m/sec.)	C.V. per sq. metre of swept area	Wind speed (m/sec.)	C.V. per sq. metre of swept area
2	0.0013	6	0.035
2.5	0.0025	7	0.056
3	0.0044	8	0.083
3.5	0.0070	9	0.118
4	0.0104	10	0.162
4.5	0.0146	11	0.215
5	0.0202	12	0.280

Now, to obtain, for metric quantities, a table similar to Table 8, and which will be numbered Table 10, let us assume a pumping head of 50 metres and calculate, for different wheel diameters, the rates of pumping in cubic metres per hour. 1 C.V. pumping against a head of 50 metres, will raise 5.4 cubic metres of water per hour.

Annual Output of Water

To determine the quantity of water which will be pumped against a known head, by a wind pump of known characteristics, when operating in a known wind régime, we can proceed as follows:-

Suppose that the rate of output for the machine (of the slow-speed, piston type), for different wind speeds, is as given by the curve of Fig. 29 (which happens to apply to a machine with a wind wheel of diameter 6.1 metres with a pumping head of 40 metres (see Ref. 48)). Pumping starts at a wind speed of 3 m/sec (6.7 m.p.h.) and full output of 6 m^3/hour is attained in a wind speed of 6.75 m/sec (15 m.p.h.). It is assumed that, at this wind speed, the wheel turns out of wind so that, for higher wind speeds, the full output of 6 m^3/hour is maintained but is not exceeded. Actually the output will probably rise slightly for higher wind speeds, i.e. the control of output will not be quite so sharp as that shown in the figure. Estimates based on this curve are thus a little pessimistic.

Suppose, also, that the wind régime at the windmill site is as represented by the velocity-duration curve given in Fig. 30. This is for a site having an annual average wind speed of 9.6 m.p.h. (4.32 m/sec.). From this curve, it

Table 10

Pumping rates and C.V. for different diameters of wind pump with 50 metres head and assuming 20% efficiency throughout

Wind speed (m/sec)	1.5 metres		2 metres		2.5 metres		3 metres		4 metres		5 metres		6 metres	
	C.V.	m^3/hr	C.V.	m^3/hr	C.V.	m^3/hr	C.V.	m^3/hr	C.V.	m^3/hr	C.V.	m^3/hr	C.V.	m^3/hr
2	.0023	.012	.0041	.022	.0064	.035	.0092	.050	.0164	.090	.0255	.14	.0368	.20
3	.0078	.042	.0138	.074	.0216	.12	.0311	.17	.0554	.30	.086	.46	.125	.68
4	.0184	.10	.0327	.18	.0510	.28	.0735	.40	.131	.71	.204	1.10	.294	1.59
5	.0358	.19	.0634	.34	.099	.53	.143	.77	.255	1.4	.396	2.14	.572	3.10
6	.062	.33	.11	.59	.17	.92	.25	1.35	.44	2.38	.69	3.73	.99	5.35
8	.147	.79	.26	1.4	.41	2.2	.59	3.2	1.05	5.7	1.63	8.8	2.35	12.7
10	.287	1.55	.51	2.8	.79	4.3	1.14	6.2	2.04	11.0	3.17	17.1	4.58	24.8

is possible to determine the number of hours, in the year, for which the wind blows at any given wind speed, i.e. a velocity-frequency curve can be derived from it. Actually the full frequency curve is not needed: we need only the duration, in hours, for each of the wind speeds from 7 m.p.h. (approx. 3 m/sec.) up to the full rated speed of 15 m.p.h. (6.75 m/sec.). As indicated on the figure, as an example, the duration of 7 m.p.h. = 600 hours.

We now place these durations in a table as in Table 11.

Table 11

Annual output of water for a given wind régime

Wind speed		Annual duration	Output rate	Total output
m.p.h.	m/sec.	hours	m^3/hr.	m^3
7	3.15	600	0.3	180
8	3.6	500	1.4	700
9	4.05	500	2.3	1,150
10	4.5	400	3	1,200
11	4.95	500	3.7	1,850
12	5.40	450	4.2	1,890
13	5.85	450	4.7	2,115
14	6.30	300	5.2	1,560
15	6.75	300	5.7	1,710
15 plus		1,700	6	10,200
		Total 5,700		Annual Total 22,555 m^3

The duration of wind speeds above 15 m.p.h. (7.2 m/sec.), for which the output is assumed to be at the full rate of 6 m^3/hr., is 1,700 hours. It will be seen that the total annual output, in this case, is thus calculated as 22,555 m^3.

This procedure can, however, be simplified considerably with a resulting error which is not usually large enough to be important when making an estimate of the annual output of water in given circumstances. Referring again to Fig. 32, full output of 6 m^3/hr. continues for 1,700 hours. Now, suppose we assume (which is not far from the truth as seen by Fig. 29) that the output from 15 m.p.h. down to the starting point of 3 m/sec. (6.75 m.p.h.) follows a straight line as shown. The total annual output is then proportional to the area shaded and, taking the maximum ordinate (for full output) as 6 m^3/hour, we find that this area is

$$6 \left(\frac{ab + oc}{2}\right) = 6 \left(\frac{1700 + 5700}{2}\right) = 22,200 \text{ m}^3.$$

This figure is obviously sufficiently near to the previously calculated value of 22,555 m^3 for purposes of estimation.

We can thus formulate a simple rule for this calculation of annual outputs:- The output is given by the maximum rate of output of the wind pump (in m^3/hr.) multiplied by the average of the values of the hours for full output and for the total operating hours. From the velocity-duration curve we need, therefore, only two figures:- (i) the duration of the velocity which gives full output rate (in this case 1,700 hours) and (ii) the total duration of pumping at any rate, i.e. above the starting point (in this case 5,700 hours).

It is of some interest to calculate the overall efficiency of the machine in this case.

The horse power at full output, when the pumping rate is 6 m^3/hour to a head of 40 m, is almost exactly 0.9 h.p. or 0.67 kW, whereas the power in the stream of wind passing through the wind wheel of 6.1 metres diameter is 5.18 kW (from the formula kW = 0.000005 AV^3).

The overall efficiency, at full output, is, therefore, $\frac{0.67}{5.18} \times 100 = 13\%$ (approx.). (This compares with the efficiency of 20 per cent assumed, as a probable maximum, in the calculations for Tables 7 to 10.

Provision is made, with piston pumps of a given bore, for changing the length of stroke and so changing their capacity and, therefore, their output. Thus, in the case discussed above, in which the bore was 125 mm and the stoke 384 mm, (giving a capacity of 4.7 litres) the stroke could be increased to 490 mm. The result would be that a higher wind speed would be needed before pumping could start but, at higher wind speeds, the output would be greater than for the case calculated. The output curve is now shown dotted in Fig. 29, assuming, again, that full output is that for 15 m.p.h. (6.75 m/sec.).

This output would be 7.25 m^3/hr., instead of 6 m^3/hour previously, but the number of hours of pumping, per annum, would be reduced from 5,700 hours (during which the wind speed exceeds 3 m/sec. (6.75 m.p.h.)) to 4,900 hours.

The new output would be (following the simplified method)

$$7.25 \left(\frac{1700 + 4900}{2}\right) = 23,925 \text{ m}^3.$$

This is some 2,000 m^3 higher than the output for the shorter stroke but, in some circumstances, it might be advantageous to accept the rather smaller annual output because of the longer operating time (5,700 hours against 4,900 hours). It is usually a simple matter to change the length of stroke of the machine so that, if some attention could be given to the plant while operating, it would be possible to use a short stroke for low wind speeds and a longer stroke for higher wind speeds, thus obtaining the double advantage of a long annual operating period together with a large annual output of water.

Pumping Periods and Reservoir Capacity

The next point to be considered is the relationship between the distribution of the pumping periods, during the year, and the utilization of the water, via a reservoir. It has already been mentioned that the pumping rate and therefore the size of the wind pump, must be related to the quantity of water flowing into the well: clearly it would be pointless to install a pump which, in the wind régime at the site, would pump faster than the water flowed into the well to replace that pumped out.

There can be no hard-and-fast rules for reservoir capacity because this capacity must depend upon the maximum rate of pumping by the wind pump, the rate at which the water is used and the probability of calm periods of different durations. For water supplies to domestic premises a calm period of perhaps 3 or 4 days should be catered for by the storage tank. The quantity of water which should then be stored can then be based on the household needs, e.g.:-

Daily use per person	...	10 to 20 gals
Each bath	...	30 gals
Daily domestic (kitchen) water	...	20 gals
Daily laundry water	...	10 gals
Toilet, and other small uses	...	20 gals

This makes a total, for a household of four persons, of about 200 gallons per day so that a storage capacity of some 600 to 800 gallons might be needed.

For agricultural purposes the following figures may be used as a basis:-

Horse	...	10 gals/day
Cow	...	15 gals/day
Pig	...	4 gals/day
Sheep	...	1 to 2 gals/day
Poultry (per 100)	...	4 gals/day
Irrigation (1 acre-inch)		22,700 gals.

The average quantity of water lifted daily from a given depth, by a wind pump of given size, depends - as shown earlier - upon the wind régime and the operating characteristics of the machine. Thus, at a site with an annual average wind speed of 10 miles an hour, the annual output will be equivalent to about 4,000 hours at maximum pumping rate. For wind pump with a wheel diameter of 10 feet, pumping against a total head of 100 feet, the maximum hourly output might be 400 gallons so that the annual total pumped, at this site, would be 4,000 x 400 = 1,600,000 gallons giving an average daily total of $\frac{1,600,000}{365}$ = 4,380 gallons.

An analysis of the wind data is needed to determine how far the daily production, throughout the year, varies from this average. Some figures given by A.H. Scott (Ref. 33), who made a thorough test on a water pumping windmill near Perth, West Australia, as long ago as 1923, are interesting as an example of such an analysis. These are shown, in Table 12, as average values for 6-monthly periods although, in his report, Scott gives the figures, in the same form, for each month.

The site had an annual average wind speed of 12 m.p.h. The tests showed that a wind pump with a wheel of 10 feet diameter, pumping against a head of 108 feet, provided 564,450 gallons of water during the six summer months: this is equivalent, in terms of irrigation, to 25 inches of water on one acre. One million gallons were pumped in 13 months and 7 days. The maximum pumped in one day (in the summer) was 7,550 gallons and the minimum daily output was 250 gallons. A storage tank of capacity 10,000 gallons was used with the installation.

The machine did not start to pump water until the wind speed was 9 m.p.h. and, by comparison with the figures given in Table 8, it would appear to have been a rather inefficient machine. Developments during the last forty years since it was built have improved the performance of present-day machines considerably and, under the conditions of this test, an annual output of about 2 million gallons might be expected.

As already mentioned, the total head against which a wind pump works includes the height of the tank, or reservoir, above ground surface. The higher the tank the greater the pressure of the water supplied for use in the house or for other purposes. Approximately two feet of height above ground are needed for each 1 pound per square inch of pressure required. Incidentally, the tank should have an overflow pipe and, if it is placed in a loft so that water can spill, or drain, into lower rooms, it is advisable, especially if it is a steel tank, to stand it on a drip tray to catch water which may condense on the sides.

[illegible]
1 m H_2O [illegible]
= [illegible]

It is possible to fit a float control which will shut down the wind pump when the tank is full although, of course, shutting down the machine when there is sufficient wind for pumping is wasteful of energy and will result in an annual output smaller than that estimated according to the methods previously described. If it is at all possible, an alternative use for the water should be arranged so that such waste is avoided.

[illegible]

Table 12

Hours per day of winds of different speeds

Average for 6 winter months	6 m.p.h. and over	7 m.p.h. and over	8 m.p.h. and over	9 m.p.h. and over	10 m.p.h. and over	11 m.p.h. and over	12 m.p.h. and over	13 m.p.h. and over	14 m.p.h. and over	15 m.p.h. and over
	17.5	15.4	14.0	11.5	10.3	8.2	7.3	6.1	5.6	4.5
Average for 6 summer months	6 m.p.h. and over	7 m.p.h. and over	8 m.p.h. and over	9 m.p.h. and over	10 m.p.h. and over	11 m.p.h. and over	12 m.p.h. and over	13 m.p.h. and over	14 m.p.h. and over	15 m.p.h. and over
	22.0	21.0	20.3	19.1	18.0	16.1	15.1	13.3	11.8	10.5

Types of Water-Pumping Windmills

There are two main types of wind pumps:- that using a slow-running multi-bladed wheel driving a piston pump and the high-speed windmill driving a propeller pump or a centrifugal pump. Wind pumps of the first type have been in very common use for the past fifty years but the high-speed machines are a more modern development.

Other possibilities are being studied experimentally, e.g. a windmill driving a compressor, to provide compressed air for water pumping, is being tested at the Russian wind power research station at Istra, near Moscow, where there is also a windmill driving a continuous, perforated belt running down the (shallow) well and dipping into the water a small quantity of which it brings up in the holes in the belt.

Electrically-driven, submersible pumps can be supplied with electric power from wind-driven generators and this question will be referred to in Section V.

1. Slow-running windmills driving piston pumps

The main features of these machines (see Figs. 31 to 33), of which there are many manufacturers having their own specialities, can be stated briefly, in itemized form, as follows:-

Wind wheel. This consists of a number - usually from 8 up to perhaps 18 or 20 - of galvanized sheet-steel sails, slightly curved to give a good aerodynamic shape. They are carefully balanced, and are carried on two rings attached to six tensioned wheel arms, the whole wheel being mounted on a shaft, which runs in either ball bearings or Babbit bearings, automatically oiled. The wheel diameter ranges from 6 feet to 18 or 20 feet.

Gearbox and driving mechanism. There are duplex gear wheels, running in an oil bath, so that they are self oiling. The gear ratio varies from 2.33:1 to about 4:1. Two pitmen drive the pump rod and the length of stroke can be changed by altering the lengths of these pitmen. This can be done easily.

Means of orientation. The windmill head is mounted on a turn-table, usually running on ball bearings, so that the wheel can be turned into wind easily by a shaped, galvanized sheet-steel tail vane. There is a windlass fitted at the base of the tower so that the wheel can be turned out of wind manually if necessary, e.g. at times of exceptionally strong winds.

Furling. The wind shaft is offset slightly from the centre of the tower so that, in strong winds, it turns towards the tail vane - which is fitted with a control spring - and thus presents a smaller surface to the wind. This "wind spilling" automatically controls the power output as the wind speed increases but, because of the high inertia of multi-bladed rotors, the diameter for which this method is practicable is limited to about 24 feet.

Fig. 31 (a) - Hercules water pumping windmill
(By courtesy of H.J. Godwin, Ltd.)

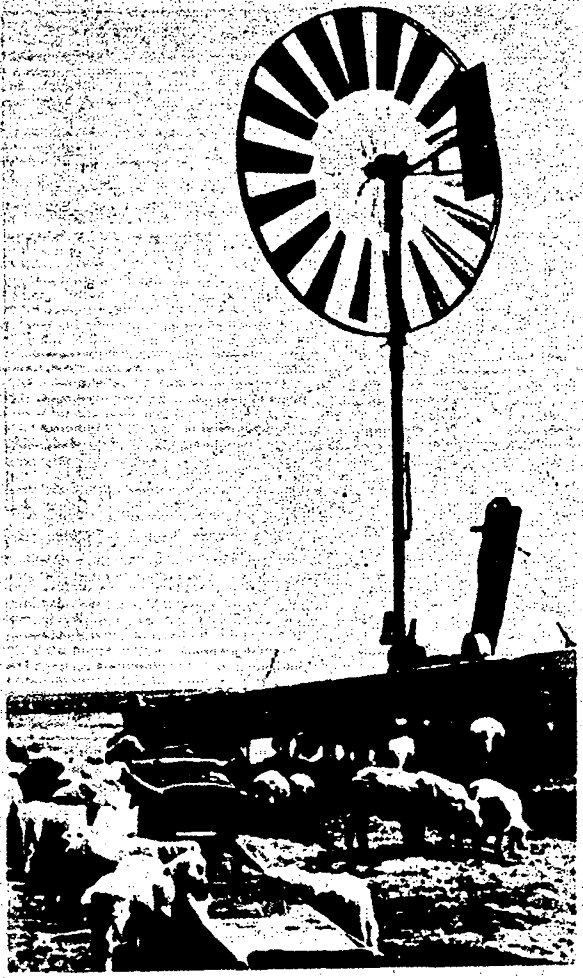


Fig. 31 (b) - Russian water pumping windmill.

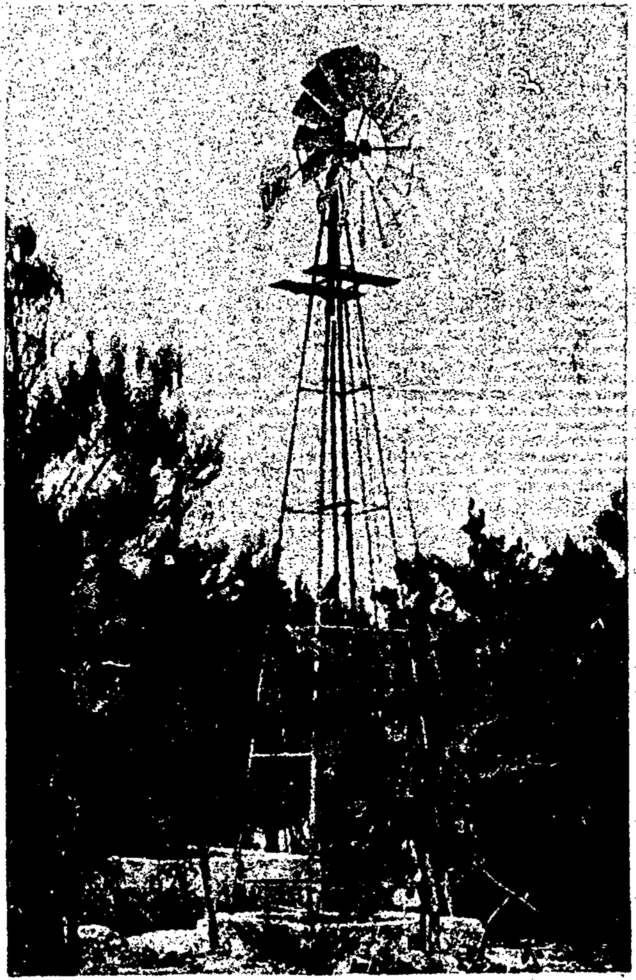


Fig. 32 - Climax windmill (Thomas and Son (Worcester) Ltd.) installed in Northern Egypt.

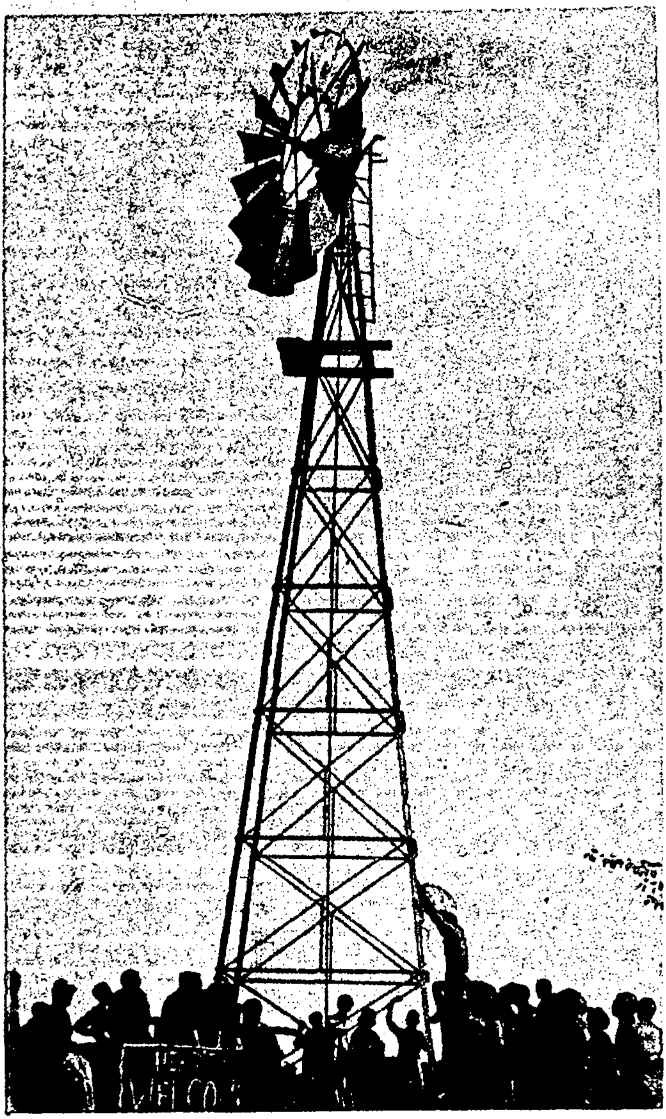


Fig. 33 - Australian water pumping windmill installed near Delhi, India.

There is also a brake to bring the machine to rest and to hold it stationary.

The characteristics of this type of windmill are a high starting torque - necessary for a piston pump - and a low efficiency at high wind speeds due to the constant torque with such a pump. As already mentioned, some improvement can be obtained by varying the stroke, using a longer stroke in higher wind speeds.

2. High-speed windmills driving rotary pumps

If windmills are needed for pumping at higher powers than can be provided by the type just described, they drive either a centrifugal or propeller pump, both of which must run at high speed. It is, therefore, convenient to use a high-speed windmill and thus to reduce the cost of the gears. High-speed windmills, having rotors with a small number of blades, are characterized by a low starting torque and are, therefore, not suitable for driving piston pumps, but the rotary pumps also demand only a small torque at starting so that this is not a great disadvantage. The efficiency of this type of windmill is higher than that of the slow-speed, multi-bladed type but it is essentially a plant for sites with a fairly high average wind speed. Vadot (Ref. 48) discusses this type of windmill very thoroughly and he suggests that, for low lifts, a low cut-in wind speed and a large water output in high winds could be achieved by using it to drive a propeller pump with blades of automatically variable pitch, the pitch diminishing in a low wind to reduce the power absorbed.

Because the starting torque of centrifugal and propeller pumps is very low and because of the shape of their power/speed characteristic, it is possible, when these are driven by a high-speed windmill, to choose operating conditions such that both the windmill and the pump work at, or near, their maximum efficiency.

The general conclusion of Vadot (Ref. 48) is that low-speed windmills, driving piston pumps, should be used for low power outputs but that when higher powers are needed for pumping, and the working efficiency is more important, the high-speed installation should be used.

In the Netherlands, however, high-speed windmills driving small centrifugal pumps are used for small powers. An example of a plant of this kind, made by the firm of Bosman at Piershil, Holland, is illustrated in Fig. 34 and more than 1,000 four-bladed windmills of a similar type are in use in Holland for drainage purposes. Each one can deal with drainage of the excess water for an area of about 5 hectares, the water being raised against a very low head of a few decimetres, up to perhaps 6 dm or 2 feet. The transmission between the main shaft of the windmill and the pump shaft consists of a single bevel gear and old automobile parts are often used in building some of these small pumping plants to reduce the cost of construction. Although their efficiency is not high - usually under 30 per cent - these machines serve a very useful purpose in draining low-lying land.

Windmill Towers

The towers for the slow-running type of windmill, most commonly used, are made in heights of 25 feet up to about 60 feet. The general rule is that they should be high enough for the wind-wheel axis to be well above any trees, or other obstructions, lying within a distance of 200 to 300 yards. There should be a clearance of some 10 feet between the height of these obstructions and the lowest point of the periphery of the wind wheel. On flat ground there is some advantage, in increased wind speed, to be gained by building a high tower but this is not usually worth while at a hill-top site because there the increase of wind speed with height is not so marked.

The towers are usually built of galvanized rolled angle steel. They may have three corner posts though four, which gives a stronger tower, are more commonly used. There are girts, connecting the corner posts horizontally at about 5 feet intervals up the tower, and tensioned steel rods are used as cross-braces to give more strength. Anchor posts and earth plates are fitted at the bases of the corner posts and castings and foundation bolts are provided so that the tower can be bolted to concrete blocks in the ground to ensure a good foundation.

There is also a steel ladder fitted to one side of the tower and an inspection platform, with a safety handrail, is built near the top.

Pumps and Auxiliary Equipment for Water Pumping

The range of pumps, of auxiliary power plant, and of miscellaneous equipment associated with water pumping by wind power, is too great to be covered here in detail. Manufacturers' catalogues usually give full information on this subject and these should be studied by the would-be user. The following notes are, therefore, brief and are intended only as an indication of what is available from the makers in different countries.

1. Pumps

These can be classified according to whether they are to be used for shallow or deep wells and whether they are reciprocating pumps, running at slow speed, or high-speed rotary pumps.

Shallow-well pumps. The use of the siphon pump is limited to suction lifts of about 22 to 25 feet (vertical lift from the water to ground surface) and this type of pump is intended for the lifting of large quantities of water against a low head. It has the advantage, for windmill use, that it is always primed. The pump is located at the foot of the windmill and connected to the well by a suction pipe (preferably run underground) which has, at its end, a foot-valve and strainer. The windmill should, of course, be near the well but need not be vertically above it.

With this, and other wind-pumps installed to raise the water to some height above ground equal to, or greater than, that of the windmill tower, a force head is used. In this there is an air chamber in which sufficient pressure is created to lift the water to the required height and a check valve, in the delivery pipe, is usually incorporated. When a siphon pump is used this height should not exceed 100 feet.

For lower pressure heads the storage tank may be adjacent to, or even built into, the windmill tower (see Fig. 35). Fig. 36 shows the arrangement, within the well, when the pump is situated in it.

Deep-well pumps. In these pumps the effective part, the cylinder, is in the water close to the bottom of the well and is driven from the pumping shaft descending from the windmill head. The design of cylinder differs somewhat according to the depth of the well and Figs. 37 and 38 show two designs by Bosman (Netherlands) for wells up to 400 feet in depth and for greater depths, the latter having ball valves instead of spear valves. A typical arrangement for a windmill pumping system with this type of pump is shown in Fig. 39.

Other types. As already mentioned, centrifugal or propeller-type pumps can be used with high-speed windmills but these are much less commonly used than the two pumps mentioned above. For very low heads, up to about 2 metres, Archimedian screws, driven by a bevel gear at the foot of the windmill, can be used, especially for drainage purposes.

2. Water systems

The arrangements made for dealing with the water when it is raised to the surface depend, of course, upon the location and purpose of the installation. The simplest of all is the storage tank placed, at ground level, immediately adjacent to the wind pump so that the water is discharged directly into it. From this the water can be released into irrigation channels or into a drinking trough for animals.

If pressure is needed, to carry the water through a more complex system of supply, the water tanks can be located on a nearby hill or on a steel-lattice tower close to the windmill.

3. Auxiliary power

Several circumstances may lead to windmills being used in combination with other sources of power for pumping. It may be essential to maintain a windmill-produced water supply when there is a prolonged period of calm weather or, on the other hand, it may be economical to install a windmill to take over, when there is ample wind, the work of pumping otherwise done by an oil or petrol engine. This is especially likely at up-country places where oil fuels are inevitably expensive because of high transport costs.

Arrangements are therefore made for the upper part of the pumping rod of the windmill to be disconnected from the lower part, passing down into the well so that the pumping can be done either by hand (when the pump is of small capacity) or by an engine which can be coupled to it. Figs. 40 and 41 illustrate this.

4. Miscellaneous equipment

The most important item under this heading is perhaps a reefing device which is fitted at the bottom of the tower and which can be operated quickly and easily to turn the windmill head out of wind - and to stop it - when the wind is too high or when an inspection is to be made. This usually consists of a spring-controlled lever which pulls a wire connected to the windmill head and to the tailvane.

Amongst such equipment, also, is a regulator which can be operated, from a float in the storage tank, to stop the windmill when the tank is full and to start it when the water level falls.

Sometimes the windmill cannot be placed vertically above the well and, if the pumping depth is too great for a siphon type of pump, a mechanism is required to transfer the movement of the windmill pumping rod to that located in the well and attached to the pump. The design of this mechanism depends on the horizontal distance between the windmill rod and the pump rod.

Another piece of equipment which may be supplied by the windmill manufacturer is a winch for use when erecting the windmill tower.

Installation, Operation and Maintenance

The most obvious recommendation is to follow the manufacturer's instructions carefully when installing a windmill: different designs call for different methods in erection. Probably the most important general points are:- (i) that the foundations for the tower must be very well made to ensure adequate strength of the tower which, throughout the life of the machine, will have to withstand very heavy pressures in gales; (ii) that the tower itself must be built up systematically with proper attention given to the tightening of bolts and the tensioning of braces; (iii) that the wind wheel must be assembled strictly according to the maker's instructions, ensuring that all the sail pieces are attached in such a way that there is no distortion and that the wheel is well balanced.

The operation of the machine is automatic and calls for very little attention except starting up and shutting down according to the demands on the pump.

Maintenance consists in regularly oiling the moving parts and periodically inspecting the whole installation to check that no parts have been broken or loosened in storms.

Installation and Operating Costs

It can easily be understood that costs of installation and of operation must vary considerably according to the geographical position of the site, to the facilities available for transport, erection and maintenance, to the climate and other factors. Precise figures for the cost of pumping water by windmills cannot, therefore, be given. But much the same must inevitably

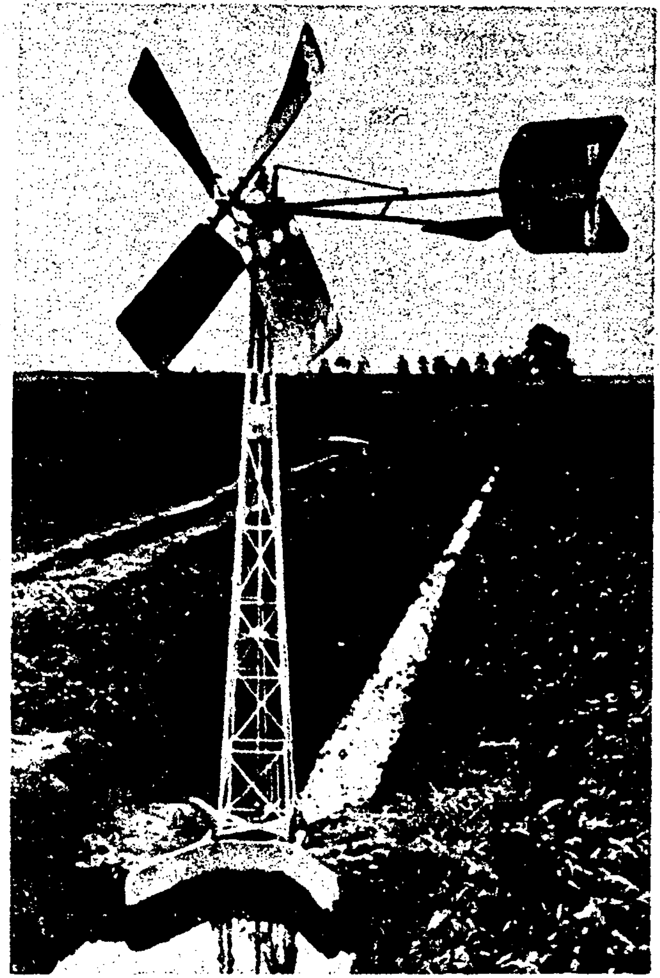


Fig. 34 - B. Bosman, Piershil (z.h.), windmill used for drainage in the Netherlands.
(By courtesy of B. Bosman, Piershil (z.h.), Netherlands)

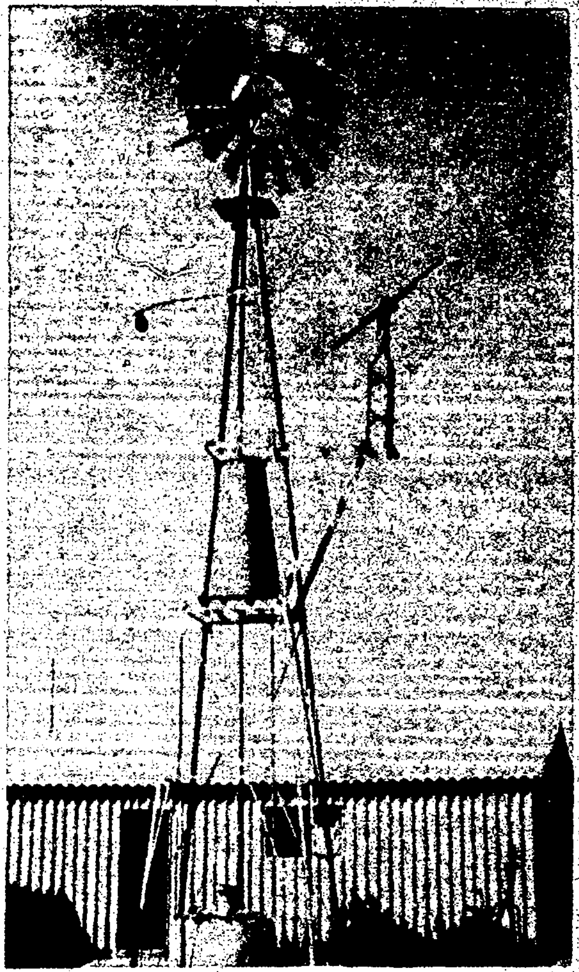


Fig. 35 - Electric and water pumping windmills mounted on the same tower in Uruguay.

apply to any alternative means of power production: the best that can be done is to make careful estimates, based on information from widespread sources, and stating the assumptions made. This method has been followed in obtaining the costs given below.

Because of the recognized limitations in the accuracy of estimates of this kind there is little point in making a comprehensive series for all possible sizes of windmill and for various operating conditions. Hence, only three sizes of windmill have been considered.

Basis of estimates

Windmill diameters ... 6 feet
10 feet
16 feet

Total head ... 100 feet

Wind régime similar to that shown in Fig. 25
(Annual average wind speed = 9.6 m.p.h.)

Wind speed for full output has been taken as 14 m.p.h. for the 6 ft and 10 ft mills and 16 m.p.h. for the 16 ft mill.

Annual charges for interest, depreciation and maintenance ... 10 per cent.

The costs and operating data can then be presented as in Table 13.

Table 13

Costs of water pumping for three sizes of windmill

Windmill diameter (feet)	Cost, excluding freight charges and foundations (£)	Annual charges (£)	Full pumping rate (gals/hr)	Annual operation at equivalent of full output (hours)	Annual output (gals)	Cost per 1000 gals (pence)
6	125	12.5	125	3,850	480,000	6.25
10	185	18.5	350	3,850	1,350,000	3.3
16	500	50	1,400	3,550	4,970,000	2.4

Taking into account the costs of foundations and other erection costs and freight charges, etc., these costs can be stated, with some degree of confidence, as:

For a pumping head of 100 feet	6 foot diameter mill ...	7 to 7.5 pence per 1,000 gals.
	10 " " " ...	4 " " " "
	16 " " " ...	3 " " " "

These costs will vary approximately directly as the pumping head: thus, for a head of 50 feet, instead of 100 feet, they will be only half those quoted above whereas for a head of 200 feet they will be double.

Costs by Alternative Methods of Pumping

The two most obvious alternative methods are (a) by electric power or (b) by internal combustion engine. Estimates of the costs, per 1,000 gallons of water, pumped against a head of 100 feet (as in the case worked out above) are given below. The uncertainties are (a) the cost per kilowatt-hour of electrical energy at the pumping site and the additional electrical distribution costs involved in carrying the supply to the pump, and (b) the cost of petrol or oil fuel delivered to the site and the annual costs for maintenance and depreciation of the internal combustion engine.

1. Electric drive

To make a direct comparison with the costs for the three windmills (6 ft. dia., 10 ft. dia. and 16 ft. dia.) calculated above, consider electrically driven pumping sets giving the same outputs as these windmills, namely, 125 g.p.h., 350 g.p.h., and 1,400 g.p.h., all against a head of 100 feet. Suppose, also, that the electric pumps are run, at full load, for the same number of hours per year as the windmill, i.e. 3,850 hours, 3,850 hours and 3,550 hours, so that their annual outputs of water will be the same as those in Table 13. The sizes of motor for these three cases are ¼ h.p., ½ h.p. and 2 h.p., while representative capital costs for the pumping sets of these three sizes are £60, £73 and £200 respectively, (without electric wiring and switchgear and without freight charges).

Annual charges for interest, depreciation and maintenance can be taken as 10 per cent per annum, which will add £6, £7.3 and £20 to the annual costs for energy. It may be assumed that the motors take an electric power input of 1 kilowatt per h.p. The pumping costs, for different prices of electrical energy, are thus as shown in Table 14 in which the last column shows the windmill pumping costs derived in the preceding Table 13.

Table 14

Relative costs of electric drive and windmill drive for water pumping

Hourly output against a head of 100 feet (gals/hr)	Motor size (h.p.)	Electric pumping Costs (in pence) per 1,000 gals. for different energy costs in pence per kWh					Windmill pumping
		1	2	3	4	6	Costs per 1,000 gals. (pence)
125	¼	5.0	7.0	9.0	11.0	15.0	6.25
350	½	2.7	4.1	5.6	7.0	9.8	3.3
1,400	2	2.4	3.8	5.3	6.7	9.6	2.4

The conclusion to be drawn from the figures in Table 14 is that electric pumping can compete with wind pumping only if the cost of electrical energy does not exceed 1 penny per kilowatt-hour. This applies for a site with an annual average wind speed of 9.6 m.p.h.; for windier sites the cost of electrical energy would have to be less than 1d/kWh to be competitive while, for less windy sites, it could, of course, cost rather more than 1d/kWh.

2. Internal combustion engine drive

Two instances will suffice in the comparison between internal combustion engine drive and windmill drive.

(i) To pump 350 gallons per hour against a head of 100 feet an engine of 1 h.p. is recommended by the manufacturers who also state that its consumption of petrol is 1 pint per hour. [illegible]

Then comparing with the 10 ft. dia. windmill giving the same output, we have:-

Approximate capital cost	...	£50
Annual charges for interest depreciation and maintenance at 20% per annum	...	£10
Fuel consumption in 3,850 hours running per annum	...	3,850 pints (= 480 gals.)
Annual fuel cost at four shillings per gallon	...	£96
Total annual costs of operation	...	£106
Cost per 1,000 gallons pumped	...	19 pence

[illegible]

(This is to be compared with a wind-pumping cost of only 3.3 pence)

(ii) To pump 1,400 gallons per hour, against a head of 100 feet, for 3,550 hours per annum (comparing with the 16 ft. windmill).

A 3 h.p. engine having a capital cost of about £120 so that annual charges for interest, depreciation and maintenance (at 20%) are £24.

Petrol consumption ...	2 pints per hour
Annual fuel cost ...	£177
Total annual operating costs ...	£201
Cost per 1,000 gallons pumped	9.6 pence

(which is to be compared with a cost per 1,000 gallons of 2.4 pence for wind pumping).

The conclusion to be drawn here is that pumping by internal combustion engine is 3 or 4 times as expensive as that by windmill. Offsetting this higher cost, to a small extent, is the fact that, with a source of power which is continuously available - such as power from an internal combustion engine - there is less need for water storage so that some saving on the cost of the storage tank, or reservoir, might be possible.

IV. THE GENERATION OF ELECTRICITY BY WIND POWER

Wind data required for an assessment of the possibilities for electrical power generation from the wind are basically the same as those needed when water pumping is in prospect. Hourly average wind speeds, from which the velocity-duration curve for the site - and, thence, the power duration curve - can be drawn, are essential. From the power-duration curve the specific output T is found as already explained. In this case it is expressed in kilowatt-hours per annum per kilowatt instead of h.p.-hours per annum per h.p., but its value, being independent of the power units, is the same. It still represents the number of hours in the year for which the machine can be considered as operating at full output, i.e. it is the full-load, time-duration, equivalent to the varying output obtained in practice.

The only major difference, in this respect, between water pumping and electricity generation lies in the fact that wind-electric machines are fast running - to minimize the cost of gearing for an electrical generator, which must run at a high speed if its cost of construction is to be economic. The rotors for these machines are therefore of the propeller type with a small number of blades - usually 2 or 3 - so that the starting torque is low and a relatively high wind speed, as compared with that for a multi-bladed rotor, is needed before the machine begins to provide power. Thus, the cut-in wind speed for a wind-electric plant may be as high as 10 m.p.h. up to even 20 m.p.h. (at a very windy site) instead of 6 or 7 mp.h. which is sufficient to start a water-pumping windmill.

On the other hand, the fact that the power generated can easily be transmitted, without excessive loss, over distances up to perhaps several hundred metres, means that the wind-electric machine may be located at a windy site in the area, e.g. on a local hilltop, whereas the water-pumping plant must be located very close to the well, where the wind speed may not be high. The practicable distance for such electric transmission depends, however, on the generating voltage and the capacity of the wind-electric machine: for low voltages and small capacities there is a limitation to only a few metres distance from the premises to be supplied.

Types of Wind-Driven Generators

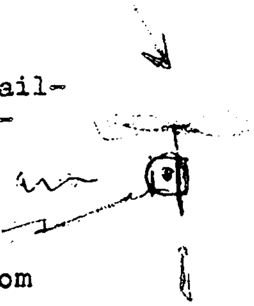
Two classes of wind-electric plants are of interest for areas without main electricity distribution networks.

They are (1) the small unit, of up to about 1 to 1½ kW in capacity, with a direct-current generator and a battery for storage of the full output, and (2) the machine of larger capacity - up to about 50 kW - with either a direct-current or alternating-current generator with or without a battery. In this second case the battery is of limited capacity and is intended for the storage of only a fraction of the total output, to supply essential loads, most of the energy generated being used, as random power, as and when it is generated.

1. Small wind-electric units

There have been many examples of such machines, made in different countries, and proved to be quite satisfactory in operation. Unfortunately, several manufacturers have ceased production because of diminishing demand as the main networks, in their own countries, have spread even to the remoter areas. There can be little doubt that the need for such machines still exists, especially in the developing countries, and it is to be hoped that this need can be expressed in sufficiently definite form to encourage re-starting of the production of these small machines. Their characteristics are as follows:-

- A 2-, or 3-, bladed propeller, of minimum diameter of 6 feet, and up to about 10 feet, rotating at high speed and driving, usually, a direct-current generator. In the smallest machines the drive is direct, i.e. without gearing, but a gear-box is used as the size increases.
- A tail-vane which holds the wind rotor into the wind.
- A speed-controlling device which may be operated by the tail-vane turning the rotor out-of-wind at higher wind speeds - the axis of the rotor being slightly offset from the main supporting axis on the tower - or may take the form of an air-brake governor.



- A furling device to enable the machine to be shut-down from the foot of the tower.

- A supporting pole or tower. This may consist of a wood pole, carrying, at its top, a stub tower on which the windmill head is mounted, or it may be a 3- or 4-legged lattice steel tower.

- A battery with an associated control panel. This panel must include a device to prevent the current reversing and driving the windmill from the battery. Examples of machines of this type are shown in Figs. 42 and 43.

The support for the machine (a pole or tower) should be high enough to keep it well clear of the adjacent buildings, otherwise it will be screened from the wind. A usual height is 40 feet (12 or 13 metres). There should be a ladder or some other means of ascending the tower to attend to the machine if this becomes necessary and it is important to ensure that the support is held rigid - either by guys or by using a heavy pole well set into the ground - to avoid vibrations which have a harmful effect on the machine.

The voltage of the generators of these small wind-electric plants is usually low, 6, 12, 24 or 32 volts being common: the higher voltages are more generally used in the larger machines (above 500 watts). This low voltage is partly because of their small size and partly to reduce the number of 2 volt accumulators needed in the storage battery. A low voltage calls for only a short run of cable from the generator to the battery and load circuit in order to avoid excessive voltage drop. Thus, for example, if the size of cable appropriate to the current to be carried is used, there will be a pressure drop of about one tenth of volt per yard run of cable: if the length of this cable is 50 yards (as it may be because the length needed to reach from the generator to ground level alone may be 12 yards) the total voltage drop will be 5 volts. If the voltage of the generator is (say) 24 volts, nearly 20 per cent of the pressure, and therefore 20 per cent of the power, will be wasted in the cable. This voltage drop is approximately the same whatever the generating voltage so that a higher value of this voltage, e.g. 110 volts, is an advantage from this point of view. Elektro G.m.b.H., of Winterthur, make wind-electric plants in a capacity range up to 5000 watts and with voltages of 65 and 110 V in the larger sizes.

The storage battery is an essential part of a small wind-electric plant. At times of high wind the battery is charged and it stores electrical energy for use when the wind speed is too low for power generation. A plant of this kind can thus be considered as being a "battery charger" and the name "wind-charger" is often used. "Wincharger" is, in fact, the trade name of one of the manufacturers in the U.S.A. - the Wincharger Corporation of Sioux City, Iowa).

Two types of battery can be used - the alkaline, or nickel-iron type or the lead-acid type. The latter is more common and has the advantage of a high voltage, 2 to 2.5 volts, per cell against only 1.5 to 1.75 for the alkaline accumulator. Although it may be rather more expensive, the alkaline battery is very robust and is less liable to damage by irregular operating conditions than the lead-acid battery. It is not, however, so successful with low charging rates.

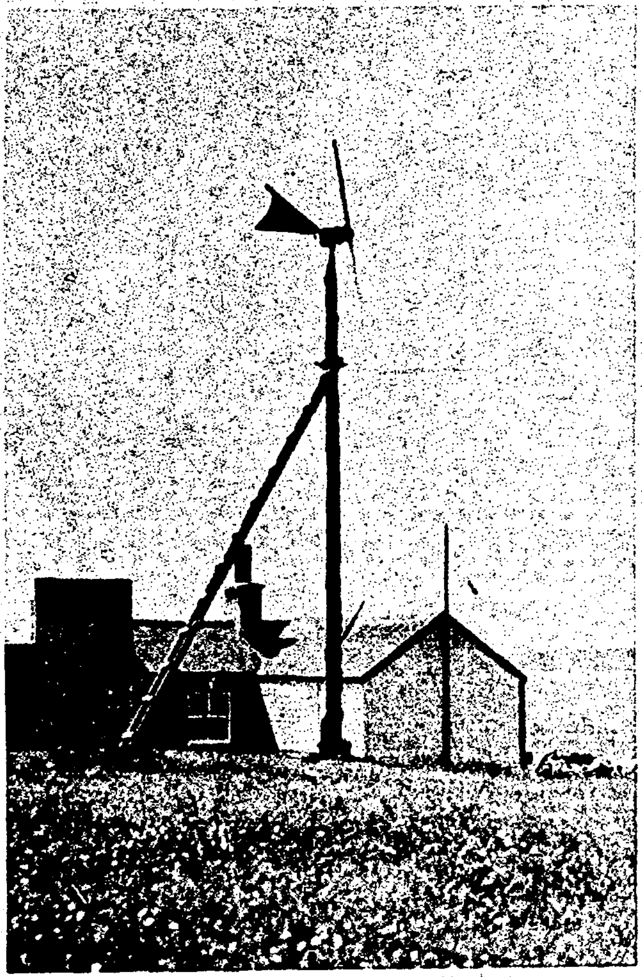


Fig. 43 - Lucas Freelite windmill installed in the Shetland Islands.

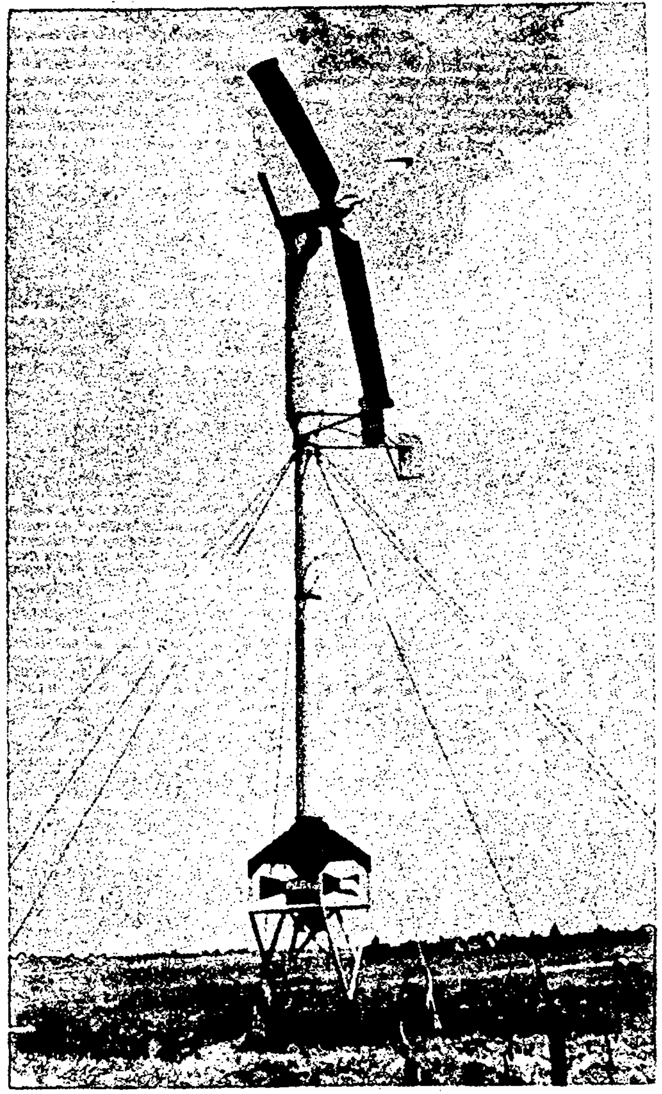


Fig. 44 - Experimental 8 kW windmill of the Andreau type.

Battery sizes are specified in terms of their ampere-hour capacity which is a measure of the product of the current, in amperes, and the time of discharge, in hours, which can be obtained before the voltage falls to the lowest permissible value of about .8 V per cell. This capacity may vary from 130 to 450 AH and, of course, the greater the capacity the longer the period of calm weather which can be catered for.

As an example, for a 200 watt unit the maximum generating voltage may be 15 volts and six (lead-acid) cells would be used, these having a voltage of 2.5 V when fully charged. The ampere-hour capacity recommended would be 230 AH. Charging of the battery would begin at a wind speed of 7 m.p.h. and the set governed so that maximum output would be reached at 23 m.p.h.

The annual output of small wind-electric machines is not generally very high because of the limitations placed on site selection due to the need to be near the premises to be supplied. Probably 1,000 to 1,500 kWh per kilowatt is a fair range of annual output to be expected. Wincharger Corporation state that usable energy outputs, per month, from a 200 watt plant, average 20 kWh, 25 kWh and 30 kWh for sites with annual average wind speeds of 10 m.p.h., 12 m.p.h. and 14 m.p.h. respectively. These figures correspond to 1,200, 1,500 and 1,800 kWh per annum per kilowatt.

Energy costs with small units. The capital cost of small wind-electric plants, complete with battery, control gear and stub tower but without the supporting pole, is of the order of £200 to £300 per kilowatt of capacity.

Taking the upper figure and assessing the life of the different components of the plant, in years, as follows:-

20 per cent of the total cost	...	20 years
50 " " " " "	...	15 years
30 " " " " " (the battery)	...	6 years

gives a total annual depreciation of £28, or 9.1/3 per cent of the capital cost. Adding to this 5 per cent for interest and 1½ per cent for maintenance we have a total of about 16 per cent per annum as the fixed charges. The annual return, in output, can be taken as 1,350 kWh per kW so that the energy cost, per kWh, is

$$\frac{16}{100} \times \frac{300 \times 240}{1{,}350} \doteq 8.5 \text{ pence}$$

Although, as compared with the cost of energy from an electrical network in an urban area, this figure is certainly high, it may not be considered excessive for such purposes as electric lighting, the operation of radio sets and small domestic uses in remote areas. Of course, if the site is very windy so that the annual output is greater than 1,350 kWh/kW or if the capital cost is less than £300 per kW, the energy cost will be less than 8.5 pence per kWh.

As for the maintenance of a plant of this kind, occasional attention, for lubrication and to ensure that no parts of the machine have become loose, is all that is required for the windmill, but the battery needs rather more attention. It should not be overcharged nor over-discharged and the cells should be topped up with pure water when the level of the acid falls below the tops of the plates. The voltages of the cells and their specific gravity of the acid should be measured occasionally to check that all are in order.

2. Wind-electric plants of medium capacity

Several plants in this category have been produced and, although none is yet in common use, they are available commercially and, in fact, await adoption by those responsible for power supplies to communities in areas remote from main electrical networks. Their capacities range from 8 kilowatts to 100 kilowatts. They differ from the small windmills described above by having (usually) an alternating-current generator rather than a direct-current one and by generating at normal voltages of about 200/240 volts, single phase, or 380/440 volts, 3 phase.

Because of the high cost of batteries for the storage of an amount of energy corresponding to a power output of ten or more kilowatts, no attempt is made to store enough energy to give the full output during calm weather. A low capacity battery, charged through a rectifier, can be used so that essential, small, loads can be catered for but the main loads, requiring several kilowatts of power, are supplied only when there is sufficient wind.

Another feature is the use of a fantail - a multi-bladed wind wheel mounted at right angles to the main rotor - instead of a tail-vane for orienting the windmill head so that it is brought into wind. Sometimes two fantails, one on each side of the main shaft of the windmill rotor, are used.

The supporting structure for medium-sized windmills may be a guyed, steel tube but is usually a lattice-steel tower for the larger machines.

Some of these plants, made in different countries, are shown in Figs. 8, 44 and 45 and brief descriptions are given below.

A German, 8 kW Allgaier machine (Fig. 8): Although later machines of this make have had an alternating-current generator, that shown had a 6 kW alternator, generating 3 phase, 380/220 V, together with 220 volt, d.c. exciter of 2 kW capacity. The exciter supplies the field current for the alternator and can also be used to charge a battery to supply light loads. The rotor of this machine has a diameter of 10 metres: it begins to generate power in a wind speed of 3.5 to 4 metres per second and gives 6 kW of output at 11 m/sec.

The latest German development in wind-driven electrical plant is the 100 kW machine already mentioned in Section I. It has a propeller diameter of 34 metres (112 feet) and is supported on a guyed tubular mast 22 metres (72 feet) high. This machine is, however, to be regarded as a unit for connection to a main electricity supply network rather than for use as an isolated unit.

A French, 8 to 10 kW Andreau machine (Fig. 44): The principle of this windmill is different from that of the others described. The blades of its wind rotor (8 metres diameter) are hollow and, as they are driven round by the wind, air is thrown out centrifugally. A depression is thus created and air is sucked up from just above ground level, through the supporting tubular structure and through the hub, to the blades. Just above the air intake an air turbine, on a vertical shaft, is mounted and this drives the electric generator. (It could, alternatively, drive a pulley from which a belt drive could be taken to an agricultural, or other, machine mounted nearby). With a machine of this type there is some loss in efficiency due to a double conversion of energy - at the top and the bottom - but this is not so important because the power input (from the wind) is free. For any windmill, in fact, this applies: capital cost, and not efficiency, is what is important.

The Andreau machine has the advantages that the generating plant is only just above ground level, so that it is easily maintained, and also that the effects of wind gusts are damped out by the long column of air which forms the coupling between the wind rotor and the air turbine.

A British-built, 100 kW machine of the Andreau type, having a rotor diameter of 24 metres, is shown in Fig. 7. This was made, as an experimental plant, for connection to main power networks. It is now in operation, connected to the network of Electricité et Gaz d'Algérie on a hill at a few kilometres from Algiers.

Another, multi-purpose, French machine, of a more conventional type, has been developed recently by Neyrpic, of Grenoble (Fig. 46).

Like the Lykkegaard machines in Denmark, this plant has a vertical driving shaft, passing down the centre of its lattice steel tower (12 to 15 metres high) to ground level. Either an electrical generator, a water pump, or other machines, can be driven.

There are two sizes - 15 h.p. and 40 h.p. - and these have, respectively, propeller diameters of 10 metres and 16 metres when used in only moderately windy areas. For especially windy sites, rotors of 8 m and 13 m diameter can be supplied for the two sizes.

The three blades are of variable pitch giving automatic control of the output which is held at the full value, to with ± 6 per cent, for wind speeds above the rated value. This rated wind speed is variable by the adjustment of a spring, from 6 metres per second (13.5 m.p.h.) to 10 m/sec. (22.5 m.p.h.). The cut-in wind speed is 3 m/sec. (7 m.p.h.). Orientation of the windmill head is by two fantail rotors.

The plant is built up on the ground and then raised by a winch.

A British machine, made by Dowsett Holdings Ltd. (Fig. 45): The main features of the specification are as follows:-

3-bladed propeller of 40 feet diameter

Rated wind speed - 25 m.p.h.

Cut-in wind speed - 10 m.p.h.

Operating range - 10 to 60 m.p.h.

Tripod tower, of height 33 feet, hinged on two legs to facilitate erection

Orientation by two fantails

Generator (a) 31 kVA (25 kW at 0.8 power factor), 415 V, 3-phase, 50 cycles per second, for connection to an existing a.c. network. The generator is of the induction type.
(b) 31 kVA (25 kW at 0.8 p.f.) at 415/240 volts, 3-phase-neutral, 50 cycles per second, self-exciting and self-regulating within ± 1½% for autonomous operation where no network exists. As an alternative, in this case, the generator can be direct current of capacity 25 kW.

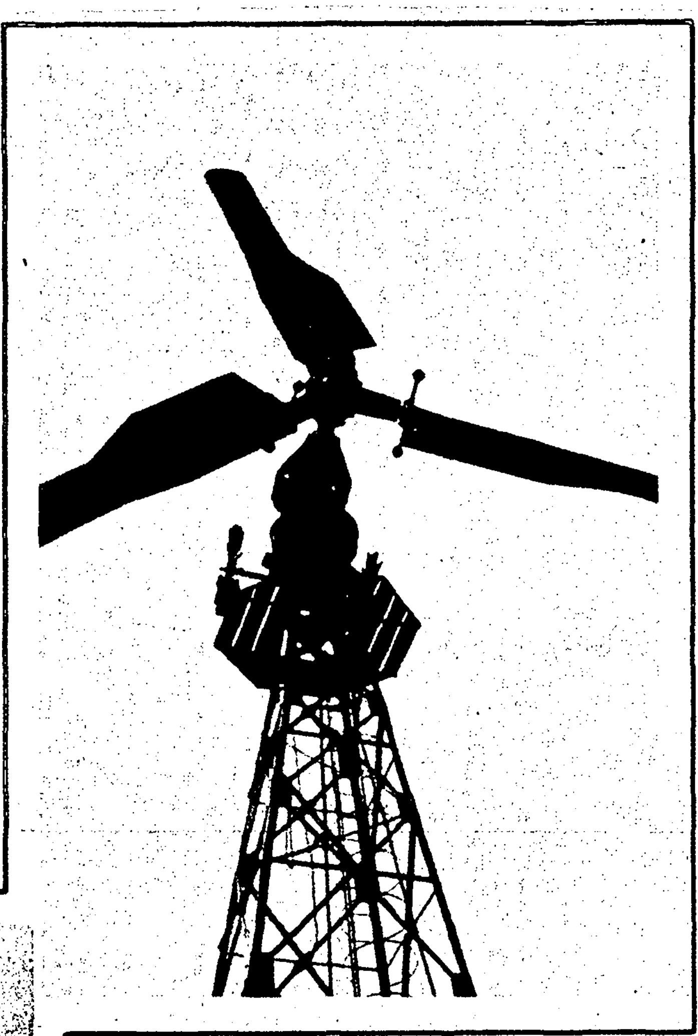
Another British wind-driven electric generator, made by R. Smith (Horley) Ltd., and currently under test in the Isle of Man (Fig. 47) has a capacity of 100 kW. It has a propeller diameter of 15 metres (50 feet) and has a tripod tower 10 metres (33 feet) high. This machine has operated successfully in tests over a period of a year and, although some small modifications may prove to be necessary before it can be put into series production, it appears to be a very promising unit which may be produced at a cost in the range of £50 to £100 per kilowatt. It is for use in connection with electricity supply networks but both this and the German 100 kW machine could probably be down-rated to (say) 50 kW to make them suitable for use connected to local networks of relatively small size in areas with lower average wind speeds.

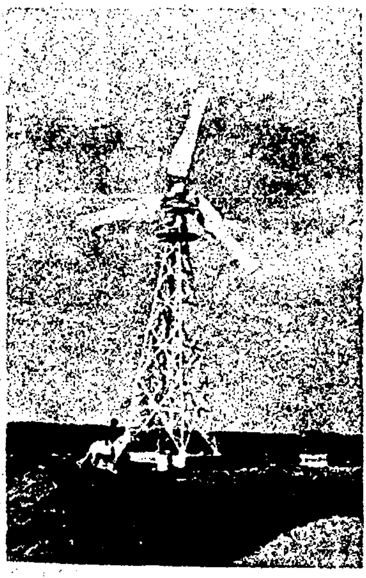
Danish Lykkegaard machines. Although, after many years of production, the Lykkegaard firm is no longer building windmills (because they now concentrate on the manufacture of pumps for irrigation and drainage) it is right to point out that their machines (already mentioned in Section I) were in the category of medium-sized plants. The capacity was up to 30 kW, with rotor diameters up to 18 metres and the generators were direct current. The generator was located on the ground the drive was through a vertical shaft, passing down the centre of the tower, with bevel gearing at the top and bottom. Many of these machines worked quite successfully, with very little maintenance, for periods up to 20 years or more.

Fig. 45 - Experimental 25 kW Dowsett windmill under test
(By courtesy of Dowsett Holdings Ltd., Tallington,
Stamford, Lincs., England)

Neyrpic (Grenoble) windmill of 13 m. diameter. Photograph (c) shows the windmill under erection. (By courtesy of Neyrpic, Grenoble, France)

EOLIENNE
RAPIDE
NEYRPIC





INSTALLATION D'ASSAINISSEMENT AVEC UNE EOLIENNE DE 13 m DE DIAMETRE.

MONTAGE D'UNE EOLIENNE.

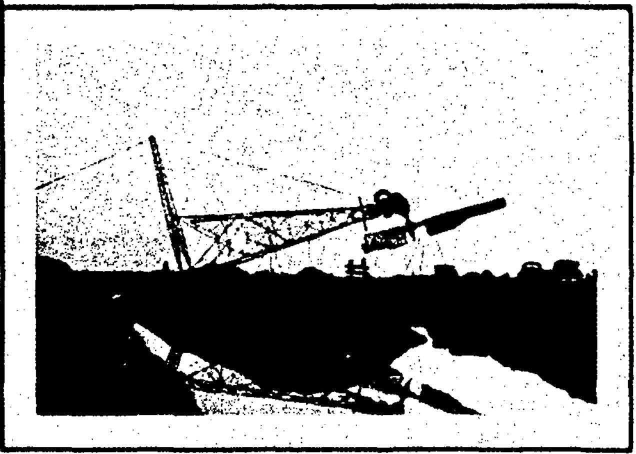


Fig. 47 - 100 kW experimental windmill (by R. Smith (Horley) Ltd.) under test in the Isle of Man. (By courtesy of R. Smith (Horley) Ltd., Surrey, England)

In Russia, medium-sized plants have been made in appreciable numbers. There are two types of plant, one with a rotor diameter of 12 metres and having a capacity of 10 kW and another of 18 metres diameter and generating 25 kW. The smaller machine has been mass produced. Some 150 have been built and about 50 are still operating. There has, however, been damage in storms due to an inadequate system of speed control.

Energy costs with medium-sized wind-electric plants. It is impossible at the present stage of development to give a precise figure for the cost of the energy produced by such plants because of the uncertainty about their capital cost when they become available commercially. Nevertheless, sufficient is known to enable a fairly realistic estimate to be made.

The capital cost is likely to be in the range £100 to £200 per kW. As an example, the quotation for the Dowsett 31 kVA (25 kW) machine intended for water pumping by an electrically driven pump, including package and freight charges (from England to Barbados) and also including foundations and complete erection, with electrical control gear, cabling, etc., and a centrifugal pump for water pumping, is £6,548. The makers estimate that the annual electrical energy output at a site with an average wind speed of 11 m.p.h. will be 1,400 kWh per annum per kilowatt and that the water output from a 3 inch centrifugal pump driven by it will be 70 million gallons per year when pumping against a total head of 43 feet. They also state that the plant can drive one, two, three or four 3 inch centrifugal pumps in minimum wind speeds of 13, 15, 17 and 20 m.p.h. respectively.

If one were to attempt an estimate of energy costs to represent a more general case for medium-sized wind-electric plants located at a site with an annual average wind speed of (say) 6 metres/second (13.5 m.p.h.) the calculation would be as follows:-

Capital cost (say) ... £150 per kW

Rate of annual charges ... 12%

Annual output in kWh/kW ... 2,100

$$\text{Cost per kWH} = \frac{12}{100} \times \frac{150 \times 240}{2{,}100} \text{ pence}$$

$$= 2.1 \text{ pence.}$$

This does not include any provision for a storage battery, which, if used, would be of small capacity and would not, therefore, increase the capital cost by a large percentage. Allowing for some limited energy storage, however, the overall energy cost might rise to 2.5 to 3 pence per kilowatt-hour.

In comparing the operation of the Dowsett machine with the alternative of a 20 kW diesel-electric plant, the manufacturers use the following basis:-

Consumption of fuel per kWh	0.7 pint
Cost of fuel per gallon (at an up-country station)	30 pence
Fuel cost per kWh	2.7 pence
Annual charges for interest (5%), depreciation (10 year basis) and maintenance (15% of capital cost)	£355
With an annual load factor of 25% the annual charges per kWh	1.9 pence

This gives a total figure of 4.6 pence per kWh for the diesel-electric plant.

V. WIND POWER FOR OTHER AGRICULTURAL USES

While it would, perhaps, be possible to adapt the slow-running, multi-bladed, water pumping windmills to the drive of machines other than the water pump, there is little or no evidence that this has been done. Their low power capacity and operating characteristics are such as to make their application to general agricultural power purposes difficult and probably not worthwhile.

The use of wind-electric machines for these purposes is, however, much more feasible. When the wind power plants have a vertical driving shaft running down to ground level, as in the Danish Lykkegaard machines or the Neyrpic machines described in Section IV, it is merely a question of driving by (say) a belt drive, another machine instead of the electric generator or pump. The purpose then served must be one which allows the driven machine to be located close to the base of the windmill. Wood sawing and the treatment of crops, e.g. threshing, or grading, or, again, food mixing, would be possible. A fan might be driven by this means but the ducting, leading away the air, should be short.

When an electric generator is driven by the windmill this limitation of close proximity of the load to the windmill is much less rigid since the power can be transmitted over an appreciable distance. With wind-electric machines in the medium-capacity range, say 5 kW and over, this opens up the possibility of other agricultural uses such as water heating or steam raising, the grinding of grain and even small cultivating machines if the ground cultivated is reasonably near the windmill. Soil warming for horticultural purposes is another possibility.

The limitation in this case is rather one of timing than of distance (Ref. 15). Because only small loads can be supplied from the low-capacity battery installed to cater for first-priority purposes during calm spells, all the main loads must be met when there is sufficient wind. For some of these, e.g. soil warming and water heating, there are no precise requirements in time: they can be met at any time during the day or night. The only important need is that they shall be met for a sufficiently long period, during a span of days or weeks, for the necessary heat to be put into the soil or the water.

Other agricultural loads, such as threshing, cultivating or grain grinding, must be met during the daylight hours because labour is needed to attend to the processes. Loads which must be supplied at particular times, e.g. machine milking, are less easy to drive from a wind-electric machine because there can be no guarantee that power will be available when it is needed.

If an oil-driven stand-by plant is available, continuous operation can be ensured and, in these circumstances, the wind power plant, when it is available, can act as a fuel saver. The usefulness of this arrangement depends largely upon the cost of the oil fuel: if this cost is high it is economic to save fuel consumption by using the power from the wind whenever possible.

When a wind-electric plant is installed to supply a wide range of loads with only very limited battery storage, an automatic load-distributing device, which passes the power to one of the connected loads when there is sufficient wind (Ref. 51), is essential for economy. Otherwise the random power is not fully used and the annual output of energy actually put to use is less than that calculated from the wind data for the site.

VI. CONCLUSIONS

The broad conclusions to be drawn from the foregoing discussions are as follows:-

(i) For the sole purpose of water pumping, satisfactory, well-proved, wind-driven pumps are available in many countries. The use of these is economic at any site where there is a reasonably good wind régime and where alternative methods of producing power are not especially cheap.

(ii) The use of wind-electric machines is justifiable economically under the same conditions. Small units, for single isolated premises, have been fully proved to be satisfactory. Medium-sized plants, for isolated communities, are now becoming commercially available and experience should prove them to be economically sound either with or without oil-driven stand-by plant. This economy can be assessed accurately if the capital charges on the plant, the wind data for the site and the cost of alternative means of power production are known.

(iii) A study of the wind régime at the proposed site for any type of windmill is an important factor in assessing the economy of wind power. This study must be based on measured wind speeds at the site and full consideration should be given to the influence of topography on the average wind speed. Choice of site, where this is possible, is very important because of the differences in average wind speed at sites close together but affected by local terrain or by obstructions on the ground.

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ALGERIA

La Compagnie Africaine de Materiel Eolien
78 Avenue Marcel Cerdan
Sidi-Bel-Abbes
Algeria
(Water lifting)

AUSTRALIA

John Danks and Son, Pty. Ltd.
391-403 Bourke Street
Melbourne
Australia

Intercolonial Boring Co. Ltd.
450-466 Ann Street
Brisbane
Australia

Metters
Murray House
77-79 Grenfell Street
Adelaide
Australia

Southern Cross Engine and Windmill Co.Pty.Ltd.
Grand Avenue
Granville
Sydney, New South Wales
Australia

(Water lifting)

CANADA

Beatty Bros.
Fergus
Canada
(Water lifting)

FRANCE

ENAG
(Pierre Gane - Constructeur)
Rue de Pont-L'Abbe
Quimper
Finistére
(Electric)

Ets. Neyrpic
Avenue de Beauvert
Boite Postale 52
Grenoble, France
(Electric and water lifting)

A. Guilleminot
Lusigny-sur-Barse
Aube, France
(Water lifting)

Ets. Poncelet et Cie
Place de la Victoire
Flancy
Aube, France
(Water lifting)

GERMANY

Allgaier-Werke G.m.b.H.
Uhingen
Württemberg
Germany
(Electric)

Tübing

INDIA

Wind Power Division
Council of Scientific and Industrial Research
Old Mill Road
New Delhi, India
(Water lifting)

ITALY

Ditta Raimondo Vivarelli
Grosseto, Italy
(Water lifting)

NETHERLANDS

B. Bosman
Piershil (z.h.)
Netherlands
(Water lifting)

SOUTH AFRICA

Stewarts and Lloyds of South Africa Ltd.
P.O. Box 1195
Johannesburg
South Africa (Water lifting)

Southern Cross Windmill and Engine
Co. (Pty.) Ltd.
Nuffield Street
Bloemfontein, South Africa (Water lifting)

SWITZERLAND

Elektro G.m.b.H.
St. Gallerstrasse 27
Winterthur
Switzerland (Electric)

UNITED KINGDOM

Dowsett Holdings Limited
Tallington
Stamford, Lincs. (Electric)

R. Smith (Horley) Ltd.
41 Balcombe Road
Horley, Surrey (Electric)

H.J. Godwin, Ltd. produceert niet meer.
Quenington
Gloucestershire (Water lifting)

Thomas and Son (Worcester) Ltd.
P.O. Box 36
Worcester (Water lifting)

UNITED STATES OF AMERICA

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2500 W. Roosevelt Road
Chicago 8
Illinois, USA (Water lifting)

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Fairbury Windmill Co. Fairbury Nebraska, USA	(Water lifting)
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