C.S.O.

1201

(Formerly)

SUBJECT :

LARGE SCALE GENERATION OF ELECTRICITY BY WIND POWER.

CONNECTED FILES.

NUMBER AND YEAR.	
1398	Camp Hydro-Electric Scheme
120/44	Suggestions for harnessing tide for power
0428/D	Murrel River Hydro-electric project.

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GRAMS: CREEPHOLE, PARL. LONDON.
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CONSULTANTS:
SIR A. H. PREECE. J. H. RIDER.

VIA AIR MAIL

Sir Miles Clifford, C.M.G., O.B.E., E.D.,
Governor,
Falkland Islands.

Dear Sir Miles,

The Technical Report by the British Electrical & Allied Industries Research Association on "Largescale Generation of
2 Electricity by Wind Power" has now been published and I enclose a copy.

I think you will be interested in this report. If you consider that a wind power installation would be successful in the Falkland Islands, it would seem that the initial step would be to obtain recording instruments to determine extent and duration of winds.

Wishing you the Compliments of the Season,

Yours sincerely,

C. H. Pickworth

Enclosure

Sir Kalen Clifford

2

U.D.C.: 621, 311, 24

The British Electrical and Allied Industries Research Association

TECHNICAL REPORT

REFERENCE C/T101

LARGE-SCALE GENERATION OF ELECTRICITY BY WIND POWER—PRELIMINARY REPORT

BY

E. W. GOLDING, M.Sc.Tech., M.I.E.E.

THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION
THORNCROFT MANOR, DORKING ROAD,
LEATHERHEAD, SURREY
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LARGE-SCALE GENERATION OF ELECTRICITY BY WIND POWER
PRELIMINARY REPORT

PREFACE

This is the first of a new series of reports which it is intended to issue on the various aspects of the utilisation of wind power for large-scale electricity generation. It describes the steps which are being taken to determine the possibilities of this method of generation in Great Britain and gives some account of the results obtained so far in the investigations. Suggestions are also made concerning future research and development.

CONTENTS

LARGE-SCALE GENERATION OF ELECTRICITY BY WIND POWER
PRELIMINARY REPORT

SUMMARY

This preliminary report has been prepared at an early stage of the investigations on large-scale utilisation of wind power for electricity generation. Its object is to give a brief account of what is being done, of the aims of the work and of the technical and economic problems which will have to be solved if such a project is to come to fruition.

The results already obtained are given and conclusions are drawn from them which have a bearing on the possibilities of successful development of this method of generation in Great Britain. The position of wind power development abroad is also outlined and suggestions are made concerning the future research programme.

(1) INTRODUCTION

World-wide shortages, not so much of fuel itself but of the labour needed to produce and transport it, have aroused, both during and since the war, renewed interest in the potentialities of the wind as a source of electric energy. This interest has taken practical shape in the United States of America, France, Denmark, Germany and Russia in which large wind-driven generators have been built or, at least, designed while in many other countries serious thought is being given to the matter. In this country also, and with every justification in view on the one hand of our economic position and on the other of our windy coasts, the possibility of aerogeneration on a significant scale was considered at a number of discussions which culminated in the formation of the E.R.A. "Wind Power Generation" Committee in January 1948.

The Terms of Reference of this Committee are :—

"To study the technical and economic problem of large-scale aerodynamic generation in Great Britain ; including the collection of all available information and evidence, the principles of the selection of sites and the wind energy derivable therefrom, the co-ordination of wind-driven generators with supply systems, the essential design features of wind-driven generators and the design problems which remain to be solved."

To avoid confusion, it must be emphasised that the primary purpose of the new Committee is to study the possibilities of developing comparatively large wind-driven units which may be able economically to make a significant contribution to electricity generation by feeding their output into a supply network. E.R.A. researches concerned with the use of small wind-driven generators for isolated premises have been in progress for some time and are being continued, but it is important to realise that, although the source of energy is the same in these two forms of aerogeneration, there are wide differences between the problems involved in them. Inevitably there is some overlapping of the investigations but it is preferable to regard them quite separately.

Since its formation the Committee has been very active ; considerable progress in this necessarily lengthy and comprehensive study has been made with encouraging results. Some publicity was given to its work with the object of discovering ideas which might not otherwise have been brought to light although perhaps of value. More recently public interest has been aroused by the fact that both the British Electricity Authority and the North of Scotland Hydro-Electric Board have taken steps towards assisting the work very materially through the installation and commercial operation of 100 kW wind-driven units.

This short report has been prepared at the present early stage of the investigations with the double object of clarifying the lines which are being followed and of making known the factual information so far obtained. The intention is that further reports shall be issued as the work progresses.

(2) THE GENERAL PROBLEM

Wind power has the obvious advantages of being free and inexhaustible. An equally obvious disadvantage is its uncertainty of availability at any particular time ; this involves its acceptance as and when it is available with some form of storage if it is to provide "firm" power. A further disadvantage, not always so clearly appreciated, is the low kinetic energy in unit volume of air even when it is moving rapidly in a high wind. This necessitates the utilisation of large volumes of air to provide a significant amount of power.

Energy storage in most forms is expensive and separate provision for it would make economic aerogeneration on a large scale more difficult. The only practical course is, therefore, to absorb any available wind-generated energy in an electrical network whose firm power is supplied by steam or hydro stations, thus achieving a corresponding reduction in the coal or water used.

Wind power must clearly be regarded primarily as a fuel-saver although, through diversity in its occurrence at different points or by combining it with hydro-electric schemes under certain conditions, it may be able to contribute some firm power. In general, its value when fed into a network is the incremental cost of the fuel-generated energy which it displaces.

The annual cost of this fuel saving is almost completely covered by the fixed annual charges on the capital cost of the plant required ; running costs should be relatively very small. It thus follows that the two overriding factors in the economy of generation by wind power are, on the one hand, the annual energy output obtainable at the sites on which the aerogenerators are to be installed and, on the other, their capital cost when erected there.

At the outset, having regard to American and Danish experiences, it appeared that figures possibly attainable in this country—they may be shortly expressed as "targets"—would be an annual output of 4,000 kilowatt-hours per kilowatt of aero-generator capacity with a corresponding capital cost of £50 per kilowatt. On this basis, and taking annual charges at 8 per cent., the cost of energy so generated would be 0·24d. per kilowatt-hour which was considered to be an amply economic value even if a further small allowance of (say) 0·01d. per kWh has to be made to cover additional transmission costs occasioned by the distances of wind power sites from the nearest supply lines.

The first job to be undertaken was thus to determine, (a) whether there existed sites windy enough to give an annual output of 4,000 kWh/kW and (b) whether it was likely that aerogenerators capable of extracting this energy could be constructed under present price conditions in this country at a cost of around £50 per kilowatt.

(3) PROGRESS MADE IN INVESTIGATIONS

When considering the attack upon this problem two main lines of investigation, one concerned with meteorological data and the other with construction costs, are at once clearly indicated. The Wind Power Generation Committee, at its first meeting, decided that several studies and experimental researches bearing on these aspects should be undertaken and their order of priority was laid down. In the diagram of Fig. 1 an attempt is made to place these approximately in their proper perspective and to indicate the relationships between them. It is rather difficult to do this because, of course, the various components of the problem are so intricately inter-related, but it may be worth while in an effort to clarify the work to be done and the significance of each investigation as part of the general scheme.

To explain the diagram : The two main lines—output and running cost studies—divide into investigations on wind régimes and aerodynamic factors on the one hand and on general design factors and types of aerogenerator on the other. Following determinations of wind régimes there must be work on selection of favourable sites and on details of wind behaviour. Design details will emerge from the studies of general design factors and of types. Operating experience with a wind-driven generator connected to a supply network should be obtained at an early stage since it will have a direct bearing on probable outputs and costs of running and will influence the design requirements as well as pointing to some lines which should be followed in aerodynamic research. The double line joining " wind régimes," " aerodynamic research " and " general design factors " is drawn to emphasise the very close relationship which there must be between the three ; they are interdependent and should be studied concurrently with effective co-ordination.

The investigations which have been put in hand are described in the following sub-sections in which the progress made to date is also stated.

(3.1) Costing Study

Since it would obviously be a waste of time and effort to carry out a comprehensive programme of research on wind power if the cost of construction of large wind-driven generating units were eventually to prove prohibitive, it was decided to undertake a costing study as a first step. A panel of committee members having knowledge and experience of engineering construction, particularly of the aerodynamic, mechanical, electrical and structural component parts, estimated the present-day costs, in this country, of units having different sizes but all being of the propeller or airscrew type most commonly accepted heretofore as best suited to the purpose in mind. The panel based their estimates on information obtained both by personal contacts and from published reports, from Denmark and the United States, on large aerogenerators which have been constructed and operated for public supply purposes in those countries and on existing projected designs.

Their estimates gave costs per kilowatt ranging from £92 for a 25 kilowatt set down to £48 for a unit of 6,500 kW capacity with a general magnitude of £50 to £55 per kilowatt indicated as being attainable, with some volume of production, for units of 1,500 to 2,500 kW capacity ; this order of size has been stated in American reports to be probably the most economic.

Thus an indication was given, at an early stage of the work, that the probable construction cost may not be far from the original " target."

It must be clearly understood, of course, that too much significance should not be attached to these estimates. They were made as a pointer and as a safeguard against the possibility of expending effort on a " wild goose chase." Precise estimates cannot be made without a detailed consideration of the actual design; they may prove to be higher than the figures mentioned, but on the other hand they do not take into account improvements in design which should result from researches yet to be carried out, nor the possibilities of cost reduction by adopting different types of unit about which information is already available. The eventual costs may well be less than those estimated.

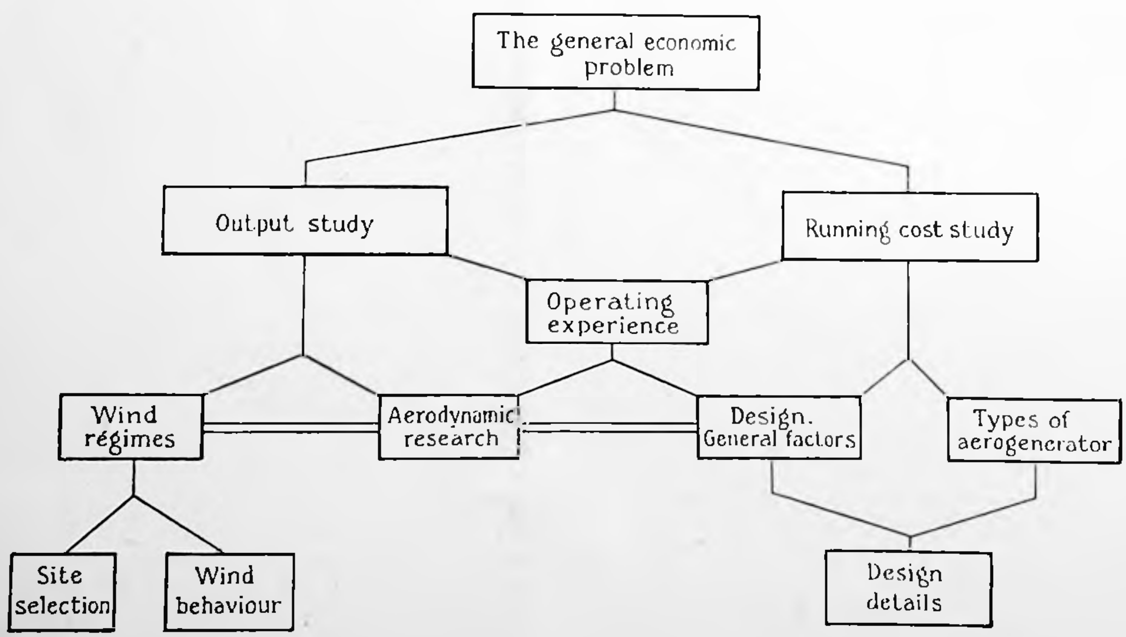


Fig. 1.—Investigation plan.

(3.2) Meteorological Work

After this first "precautionary" costing study the next investigation—one which was obviously of prime importance—namely that on wind velocities, was started.

By this time a study of the Meteorological Office long-period records of wind velocity at stations in different parts of Great Britain had been completed* and to the information so obtained was added data on wind behaviour, and on air flow over different types of terrain, supplied to the committee by two of its members having special experience in this field. A very full description by P. C. Putnam of the valuable meteorological work carried out by the team of workers connected with the 1,250 kW Grandpa's Knob wind turbine project in Central Vermont, U.S.A. (see Ref. 1) was also available and was closely studied.

With this guidance a comprehensive programme of research was outlined, the first stage of which was a wind velocity survey embracing the whole country but paying particular attention to the western coastal districts which were known to be the windiest. Succeeding stages were to cover more detailed examination of the potentialities of the more favourable sites and experimental work to determine the wind régimes and idiosyncrasies of the wind at these sites.

Putnam has emphasised the advantage, in increased wind velocity, which may be gained by choosing the sites on the summits of hills or ridges which are so shaped that they act as aerofoils and speed up the wind over the summit. He shows that in this way it is possible to obtain "speed-up factors" of 1·2 or even more, *i.e.* the wind velocity may be twenty or more per cent. higher than that at the altitude of the hill top when the wind is passing over flat country without interference. A further advantage from compression of the streamlines which occurs when air flows over such a hill is that turbulence is damped out.

The power available in the wind is proportional to the cube of its velocity so that steady, high-velocity winds are very much to be desired.

The wind velocity survey was thus aimed at discovering suitable sites for large wind-driven generators by (i) choosing a district which is known, from long-term records, to be windy; (ii) taking high ground in that district so as to obtain the benefit of the well-established accelerating effect of altitude; and (iii) seeking out hills of the right contours and orientation, relative to the prevailing wind, to give Putnam's speed-up effect. It is also desirable that sites shall be close to electricity supply networks; this is more important for the erection of relatively small pilot plants than it may be at a later stage of development if and when units, or groups of units, having a capacity of (say) twenty or thirty megawatts are built.

(3.2.1) Orkney.

Orkney Mainland was chosen for the start of the survey. There were several reasons for this choice: (*a*) it is a very windy district; (*b*) the North of Scotland Hydro-Electric Board, at the commencement of the committee's work, expressed its willingness to operate a medium size wind-driven generator connected to its distribution network on the island; (*c*) there are plenty of easily accessible hills, of apparently suitable slopes, lying quite close to the network. The distance of Orkney from E.R.A. headquarters introduces some difficulties, but for wind power work it is a fairly simple proposition and this is an important point when starting investigations on a subject about which relatively little accurate information exists as a basis.

* This had been undertaken in connection with the E.R.A. work on small-scale wind power generation and has now been reported upon in report Ref. W/T16 "The potentialities of wind power for electricity generation (with special reference to small-scale operation)." By E.W. Golding, M.Sc.Tech., M.I.E.E., and A. H. Stodhart.

(3.2.1.1) Preliminary Survey on Orkney Mainland.

In June 1948 it was decided to carry out a preliminary wind-velocity survey on some of the hills on Orkney Mainland and, on the advice of the Meteorological Office, measurements were made at a height of 10 feet. (This low height saves much labour both in setting up and reading the instruments and it is satisfactory on smooth, bare hilltops when interference from trees or broken ground is non-existent.)

Cup counter anemometers, which integrate the flow of wind, in miles, passing them were used. Mounted on light 10-ft. wooden poles they could be read from the ground.

Two hills, both within a few hundred yards of the distribution network, were chosen before the island was visited, from examination of the contours on a one-inch map.

In July a small survey party from the E.R.A. and the North of Scotland Hydro-Electric Board inspected these two hills and several others and decided that the original choice was sound. Three anemometers were installed on the summit of one hill—Costa Head (480 ft.) on the north-west tip of Orkney Mainland—and two on the summit of the other—Vestra Fiold (420 ft.) on the west coast (see Fig. 2). At the same time a similar

Fig. 2.—Map showing Orkney sites used in the wind velocity survey.

anemometer was set up on the 35-ft. mast at Bignold Park, Kirkwall (130 ft.) which, although now disused, was for many years the Meteorological Office Station at Kirkwall so that long-period records of the wind there are available. These records show a long-term annual average wind speed of 14·8 m.p.h.

Measurements made daily between July 12th and August 9th—the least windy period of the year—showed that,

(i) The mean wind speeds during the period were 19·5 m.p.h. at Costa Head and 15·1 m.p.h. at Vestra Fiold as compared with 12·3 m.p.h. at Kirkwall. Corresponding ratios of wind speeds, taking the last figure as a basis, are 1·58 (for Costa Head) and 1·23 (for Vestra Fiold). Consultation of past records for Kirkwall showed that both directions and mean speed of the wind were about normal for that time of the year ;

(ii) there was no significant difference in wind speed for points one or two hundred yards apart on the summits ;

(iii) the direction of the wind varied considerably from day to day, almost all possible directions occurring at some time during the period. The gains in wind speed observed were thus not due to the wind being from one particular direction ;

(iv) on Costa Head the wind speed exceeded 10 m.p.h. for approximately 80 per cent. of the time.

These observations showed that it is possible to select hilltop sites which have mean wind speeds considerably greater than that for the surrounding district and that the advantage to be gained is not simply a matter of altitude—the shape and actual location of the hill play important parts. They also gave an indication that both hills, and particularly Costa Head, might be favourable sites and merited fuller investigation of their wind régimes.

Measurements made over a fortnight, on a third hill (Greenay, 450 ft.) roughly midway between the other two, which are some 10 miles apart, showed that the mean wind speed there was slightly higher than at Vestra Fiold but well below that at Costa Head. They served, however, to confirm the impression that other favourable sites could be found on Orkney without much difficulty if a careful search were made.

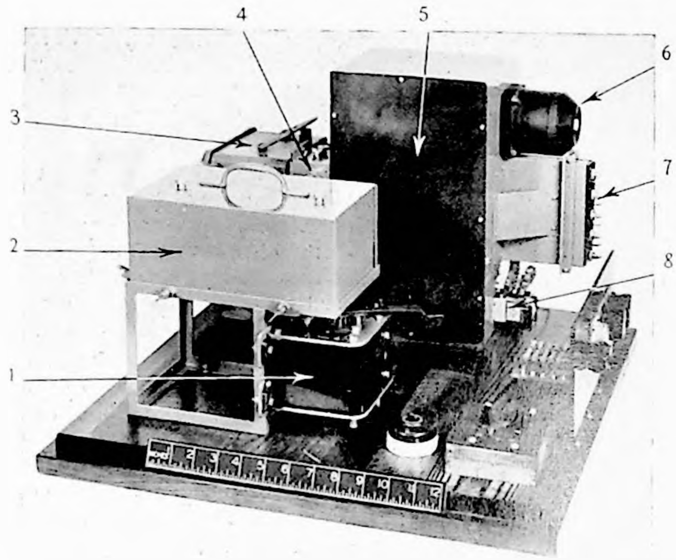
(3.2.1.2) More Comprehensive Measurements on Orkney.

The preliminary results convinced the North of Scotland Hydro-Electric Board that an Orkney site with ample wind velocity could be found and they thereupon started negotiations for the construction of a wind-driven generator of about 100 kW capacity* probably to be erected on Costa Head. Since the unit would have a tower height of between 70 and 80 ft. it was decided to record wind velocities up to about this height and to start the work as soon as possible to obtain information on the winds of winter. To make sure also that the superiority of Costa Head, from measurements at 10 ft., was not fortuitous but was borne out by measurements at greater heights, it was also decided to duplicate these measurements on Vestra Fiold.

The necessary equipment had to be developed, assembled and transported to Orkney in less than two months during which time some suitable form of recorder which could run with only weekly attention had to be devised and built in duplicate.

Two tubular steel masts, 66 ft. high, were used as supports for the instruments which included, at the top of each mast, a wind direction indicator, two cup contact anemometers and a cup generator anemometer (giving instantaneous wind speeds) and at 35 ft. two more cup contact anemometers. These instruments integrate miles of wind flow and transmit their readings electrically to the recording device (see Fig. 3). This records, photographically, on a clockwork-driven roll of sensitised paper, the readings of five instruments at half-hourly intervals. One of the five was mounted at 10 ft. to link up with the preliminary measurements made in July and August. No records of instantaneous wind velocities could be obtained from the cup generator anemometer ; its readings were observed visually.

* A contract for the construction of this generator has now been placed.



1 Camera motor. 3 Time switch. 5 Light tight box. 7 Counters.
2 Camera 4 Prism mounting 6 Wind direction indicator. 8 Exposure initiating relay.

Fig. 3.—Photographic recorder developed for use in the Orkney wind survey.

Two anemometers of a special type, integrating available wind energy directly, in kilowatt-hours per square metre, which had been lent to the E.R.A. by the research department of Electricité de France were installed on 30-ft. lattice towers, one on each hill.

A view of the Costa Head field station is shown in Fig. 4, while Fig. 5 shows a general view of the hill.

Fig. 4.—Costa Head survey station.

Fig. 5.—General view of Costa Head.

The difficulties encountered in establishing and servicing the two field stations on the tops of bare, wind-swept hills, steeply sloped and without even footpaths to aid transport, during the bad weather of the Orkney autumn and winter need not be elaborated but were certainly numerous and were increased by the fact that there was no opportunity to try out the newly developed equipment beforehand. However, with the luck that often favours such enterprises, sufficiently continuous records have been obtained to provide valuable information on the winter and spring wind régimes of the two hills and to enable conclusions to be drawn about their suitability for wind power generation.

Briefly, the superiority of Costa Head over Vestra Fiold, the gain in wind speed as compared with that at the Kirkwall Meteorological Station and the probable suitability of at least the former hill—and possibly both—as wind power sites were fully confirmed. The average wind velocities at a height of 35 ft., during the seven months December to June were 26·8 m.p.h. and 24·8 m.p.h. for Costa Head and Vestra Fiold respectively, while the average obtained at Kirkwall was 15·9 m.p.h. There appeared to be a fairly constant ratio of the average speed at 66 ft. to that at 10 ft. on the two hills ; it was 1·11 at Costa and 1·25 at Vestra.

For an accurate estimate of the potentialities of a given site measurements should be made for at least twelve months and preferably longer. The best that can be done at present is to make a "judicious guess" at the annual average from the data obtained up to the present. In this way one obtains the figures 4,600 kWh per annum per kW for Costa Head and 3,900 kWh per annum per kW for Vestra Fiold assuming a rated wind speed* of 30 m.p.h., a "cut-in" speed of 17 m.p.h. and furling at 60 m.p.h. These are reasonable values for the operating wind speed limits and approximate closely to those used in estimating costs of construction (see Section 3.1). The furling speed could, in fact, be raised to perhaps 70 m.p.h. which would bring about a slight increase in these outputs.

* *i.e.* The wind speed giving full rated output. Above this wind speed the output is regulated so as to remain constant at about the full value. Except where otherwise stated these ranges of usable wind speed are assumed in succeeding estimates.

Records of wind velocity and direction on Costa Head are still being obtained and, in addition, preparations involving the development of new types of instruments are being made to furnish design data by measuring both the horizontal and vertical components of the wind at different heights above the ground and the velocity and duration of gusts. The equipment installed for these purposes will also be used for the meteorological side of the performance tests upon the 100 kW generator when it has been erected on the site.

(3.2.2) **North Wales.**

In March of this year a preliminary wind velocity survey was started in North Wales where either cup-counter anemometers or cup-contact anemometers, with recorders of a new type (see Fig. 6) developed for easier maintenance than those used on

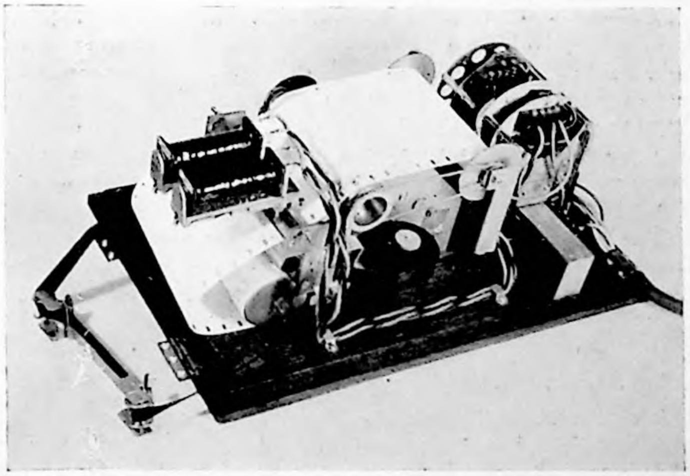


Fig. 6.—Recorder unit used in North Wales survey.

Orkney, were installed on 10-ft. poles or 30-ft. lattice towers respectively. The recorder is a clockwork mechanism, as used in the Evershed recording voltmeter, with the "chopper bar" replaced by modified Post Office type relays. These are energised from a 6-volt battery through a mercury switch in the cup-counter anemometer. A contact is made for each 1/20th mile of wind and a summator mechanism is used to integrate these fractions so that a dot is produced on the chart for every two miles of wind. Each recorder can be used with up to four anemometers.

The hills chosen were :—

Mynydd Mawr	(520 ft.)
Mynydd Rhiw	(1,000 ft.)
Mynytho Common	(500 ft.)

all in the Lleyn peninsula in Caernarvonshire, a site at 1,340 ft. above Dolgarrog, where two recording instruments were used, and a hill (400 ft.) forming part of Holyhead Mountain, Anglesey. Records obtained are being compared with those from the Holyhead Meteorological Station.

It is too early yet to draw definite conclusions from the results of the measurements at these North Wales sites but it is probable that Mynydd Mawr, and perhaps one or two of the other hills, will prove to be quite satisfactory sites though inferior to Costa Head, Orkney, which appears to be exceptionally good. An interesting, though not entirely unexpected, result is that the Dolgarrog site, in spite of its greater altitude than the others used so far, is not likely to show a very high annual mean wind speed. This is almost certainly owing to its being screened from westerly and south-westerly winds by the Snowdon range. It was chosen because of its convenient situation close to the Dolgarrog Hydro-Electric Station.

(3.2.3) Cornwall.

The wind survey in Cornwall was begun in May of this year with the installation, on seven sites, of instruments and supports similar to those used in North Wales. The hills are :—

Chapel Carn Brea	(657 ft.)
Watch Croft	(830 ft.)
Carn Bean	(665 ft.)
St. Agnes Beacon	(630 ft.)
Tregonning Hill	(620 ft.)
Carnmenellis	(819 ft.)

and a site near to the Lizard Meteorological Station to serve as a link with the long-term records from that station which acts as a standard of comparison.

Again, the duration of the recording period is too short for definite conclusions to be drawn, but the indications are that the wind speeds at several of the sites are at least as high as those at the best sites in North Wales.

(3.2.4) South Wales.

Four hills in South Wales have been selected for testing in the same way and arrangements have been made to start work on them in the near future. They are :—

Mynydd Castlebythe	(1,140 ft.)
Mynydd Kilkiffeth	(1,100 ft.)
Foel Eryr	(1,530 ft.)
Rossilli Downs	(650 ft.)

The first three are near Haverfordwest and the fourth on the Gower Peninsula.

(3.2.5) Conclusions from the Results of the Preliminary Wind Survey.

Although care is needed in drawing conclusions from preliminary investigations, it appears safe to draw those which follow.

(i) Hill-top sites can certainly be found which have an average wind speed considerably in excess of that for the surrounding district and this is not due merely to the effect of altitude; Putnam's "speed-up" effect is evident.

(ii) The wind régimes at some sites are good enough to warrant expectation of specific outputs of between 4,000 and 5,000 kWh/p.a./kW from wind-driven generators having a rated wind speed of 30 m.p.h. while there should be little difficulty in finding a number of sites to give 3,500 to 4,000 kWh/p.a./kW.

(iii) The gain in average wind speed in ascending from 10 ft. to 70 ft. above the hilltop is usually between 10 and 20 per cent.

(iv) With a hill of favourable shape the direction of the prevailing wind is mainly important only from the point of view of interference by obstructions upwind from the hill.

(v) Rapid changes of appreciable magnitude in wind direction at a height of 60 or 70 ft. above a hilltop occur very infrequently, especially when wind speed is fairly high.

(vi) Troubles from icing in winter are not likely to be serious in any of the districts surveyed up to the present.

(vii) The character of the vegetation on a possible site can be used as a guide only in a negative sense ; very windy hills have no vegetation other than very short heather or rough grass. Again, they usually have a shallow depth of soil with underlying rock which would probably provide a sound foundation for the wind power plant.

(3.3) Aerodynamic Investigations

While the aerodynamic theory underlying the performance of windmills of the sail type has been understood for many years, relatively little attention has been given, especially in this country, to that of the more modern types which may be used for large-scale power production. This is, of course, quite understandable in view of the absence, until recently, of interest in the possibility of using windmills for the purpose. The very large amount of aerodynamic research and development which has been carried out during recent years in connection with aircraft construction forms, however, an excellent basis for the study of the performance of such plant and there should be no great difficulty in extending aircraft theory, particularly perhaps that for helicopters, to cover windmills.

Theoretical studies of different aspects of the aerodynamic problem have already been carried out by members of the Committee and by investigators associated with them and a report* dealing with the design of the more conventional airscrew type of windmill will be issued shortly.

Defining the efficiency of a wind-driven rotor as the ratio of the power developed by it to that available in the undisturbed wind passing through a disc of the same area, there is a theoretical limit to the efficiency which, from the commonly accepted theory due to A. Betz (Ref. 15), is 59·3 per cent. Since, in the past, rotors have already been designed with efficiencies of over 40 per cent., increases to be brought about by improvements in design cannot be sensational. Again, a low value may be counterbalanced, without excessive cost, by making the rotor a little larger. The source of the power being free, efficiency is not of quite the same importance as with power plant using expensive fuel. The main value of a high efficiency lies in the reduction which it may bring about in the cost of construction for a given output.

A wind-driven generator connected to an a.c. supply system must run at constant speed, within narrow limits, whatever the wind speed ; its output should increase from a very low value at "cut-in" up to its full capacity at rated wind speed and

* Ref. C/T102 : "The Aerodynamics of Windmills used for the Generation of Electricity." By L. H. G. Sterne, M.A., and G. C. Rose, M.A.

thereafter remain almost constant until the wind rises to hurricane force when it may become necessary for it to "furl" to avoid damage. The efficiency should be highest at rated wind speed and should not fall greatly for at least the upper part of the operating range between cut-in and this speed. Aerodynamic research can thus be of most value in determining the best type and design of windmill to fulfil these conditions with the minimum constructional cost.

(3.4) Information on Wind-Power Projects

A very considerable amount of information on wind power for electricity generation exists in the form of books and technical articles but most of it relates to small d.c. units, used with battery storage, for supply to isolated premises. It has thus little direct bearing on the problem of large-scale utilisation. On this, most help has been obtained from the United States of America, France, Denmark and Germany. To supplement published data, visits have been paid and personal contacts with interested parties made, in the first three countries, by members of the Wind Power Generation Committee and by E.R.A. staff. Information on large-scale projects in Germany has been received through correspondence.

The information concerning progress in these and other countries is summarised below :—

(*a*) *United States of America :*

The most serious attempt at large-scale aerogeneration ever made led to the construction of the Smith-Putnam, 1,250 kW a.c. generator at Grandpa's Knob in Central Vermont during the early part of the war. It was run, under difficult war conditions, for some 1,100 hours on test and was then placed in commercial operation in parallel with a public utility network. Unfortunately after 23 days a blade broke and the project was eventually abandoned. There is doubt as to the economy of such a generator under present-day conditions in Central Vermont where an adequate supply of water power exists and where the wind velocities are lower than in this country. (The sponsors of the project believe strongly that power generating conditions in Great Britain are such that development of wind power here would be well justified.) Sound reasons have been given for the mechanical failure. During its period of service the set operated satisfactorily generating 61,780 kWh during 143 hours running. It generated 1,500 kW with a 70 m.p.h. wind and was exposed to a wind of 115 m.p.h. while out of operation.

(*b*) *France :*

Electricité de France have established more than a hundred stations for the measurement of wind energy in different parts of France to determine the best sites. They are also sponsoring several different designs for 1,000 kW (or larger) sets. Expressing keen interest in the work of the E.R.A. Committee, they have supplied much useful information.

There is great interest in the potentialities of large-scale wind power in France (although it appears doubtful whether mean wind velocities there are anywhere so high as those in our western coastal districts). Discussions with French engineers in different parts of that country have resulted in some useful ideas and have yielded information on two quite original designs for ...n of which small prototypes are in existence.

(*c*) *Denmark :*

The recent war caused a rapid increase in the number of wind-driven generators, of between 30 and 70 kW capacity, at Danish village power stations. In 1944 there were 88 in use—almost all d.c.—of which 58 are still operating. During ... years to December 1947 these sets generated 18,055,455 kWh. The best individual output in 1947 was 118,729 kWh by a 70 kW generator although this was shut down during night time due to the low night load on the system.

Average wind velocities in Denmark are lower than in this country and there is much less possibility of selecting favourable sites on high ground.

Extensions to the main rural supply network are causing some wind-driven sets to be shut down, but the general opinion in Denmark is that wind power is quite successful if it can be absorbed by a network as and when it is available. Several engineers at the village stations were confident that their wind-generated output could be doubled if night running were possible.

While the Danish sets are not large individually the experience gained with them may be very helpful if it were eventually to prove more economical, for large-scale operation, to use a large number of relatively small units rather than a few large ones.

(*d*) *Germany :*

Several designs for very large aerogenerators exist in Germany where wind power has long been of interest. The most recent are those of Honnef (20,000 kW : date 1945) and of Maschinenfabrik Augsberg Nurnberg (14,000 kW : date 1947). No large-scale project appears to have reached the development stage. Details of the two designs mentioned have been obtained.

(*e*) *Russia :*

An experimental 100-kW aerogenerator was erected in 1931 near Yalta and was operated in parallel with an a.c. network. It is known to have run for 10 years but was destroyed during the war. A Central Wind Energy Institute is established in Moscow and the 100-kW set was one step leading to the development of a 5,000-kW aerogenerator which is said to have been built already but about which no information can be obtained.

(*f*) *Other Countries :*

Information on aerogenerator designs and indications of interest being shown in wind power have also been obtained from Finland, Italy, Switzerland, Norway, Holland, Rumania, India, New Zealand, Australia, Canada and South and Central Africa, Malta and the Canary Islands.

In addition to the information obtained from abroad, well over one hundred suggested designs and offers of assistance in various forms from individuals and organisations in this country have been sent to the Committee as a result of the publicity which has been given to the work being carried out. These have been gratefully received and are being carefully studied to ensure that no wind power projects which may have possibilities remain dormant.

(3.5) Operational Experience

The importance of gaining experience in the operation of a wind-driven generator of significant size connected to an a.c. supply network was recognised at an early stage of the Committee's work and the help being given by the North of Scotland Hydro-Electric Board and the British Electricity Authority in arranging to instal such units having a capacity of about 100 kilowatts has already been mentioned. The units will be erected on sites which have been the subject of preliminary experimental studies by the E.R.A. and which show promise of having favourable wind régimes. Future research may indicate the desirability of installing others, possibly of the same type but incorporating improvements which may be suggested by the results of the investigations in hand, or perhaps of different types if a study of their design indicates that these merit experimental investigation under operating conditions.

these has hollow blades through which the

Although wind-driven units installed to gain operational experience would be built with the expectation of satisfactory performance, their design must perforce be based on information obtained from those with experience on wind generation abroad coupled, of course, with the structural, mechanical, electrical and aircraft engineering knowledge required for the construction of the various component parts. They should, however, be regarded as experimental units—pilot plants rather than prototypes—installed primarily to gain experience under normal operating conditions except in so far as this may be interfered with intentionally for the purpose of investigations. Obviously neither the cost nor the annual output of units so built and operated can be taken as a measure of what may finally be attained, but it is anticipated that they will provide valuable data for use in further developments if these prove justifiable—data which neither theoretical study nor laboratory experiments are likely to furnish.

(4) CONCLUSIONS FROM THE EVIDENCE OBTAINED

The most obvious conclusion to be drawn after some eighteen months close contact with the problem of using wind power on a large scale is that there is a keen and very widespread interest in the subject and a firm conviction on the part of some electrical engineers both here and abroad that it should be an economic proposition at least in this country.

To turn, however, to the evidence on this point and summarising the results of the investigations already described it may be concluded :—

(*a*) It is possible to find, within easy reach of electricity distribution lines, sites with wind régimes favourable enough for an output of about 4,000 kWh per annum per kilowatt to be expected from wind-driven generators of economic design erected on them.

(*b*) Although the evidence on this point is not conclusive the optimum size of the conventional propeller type unit may lie between 1,000 and 2,000 kilowatts.

(*c*) Constructional costs for units of this size, of the conventional airscrew type, may be about £50 per kilowatt in the post-development stage. It is possible that lower costs may apply to units designed in the light of the results of future investigations upon this and other new types.

(*d*) Without assuming any value from " firm " kilowatts and considering wind-driven units solely as fuel savers, generation by this means may be economic ; generating costs might be no more than 0·25d. per kWh at good sites as compared with an economic price of about 0·4d. per kWh for energy in a fairly remote district at a date some few years hence when wind-driven plant may be available.

(4.1) The Influence of Wind Régime upon Economy

A generating cost of 0·4d. per kWh is high enough to render economic the utilisation of both good and fairly good sites. It is very probable that a large number of sites in these categories exist, in coastal districts, where annual outputs of between 3,000 and 4,000 kWh per kW could be obtained from generators with a rated wind speed of about 30 m.p.h. An alternative way of stating the case would be to say that at these sites 4,000 kWh/p.a./kW could be obtained from plant designed for a rated wind speed which is high enough to ensure an economic cost of construction.

The relationship between the usable energy in the wind and the size—and therefore indirectly the constructional cost—of a wind turbine becomes clear from consideration of the power equation and of the power duration curve.

Thus :—

$$P = kAV^3$$

where P = power in the wind,
A = effective area of the turbine rotor,
and V = wind velocity.
k is a constant depending upon the air density.

As an example, Fig. 7 shows a typical velocity duration curve for a good site and, above it, the corresponding power duration

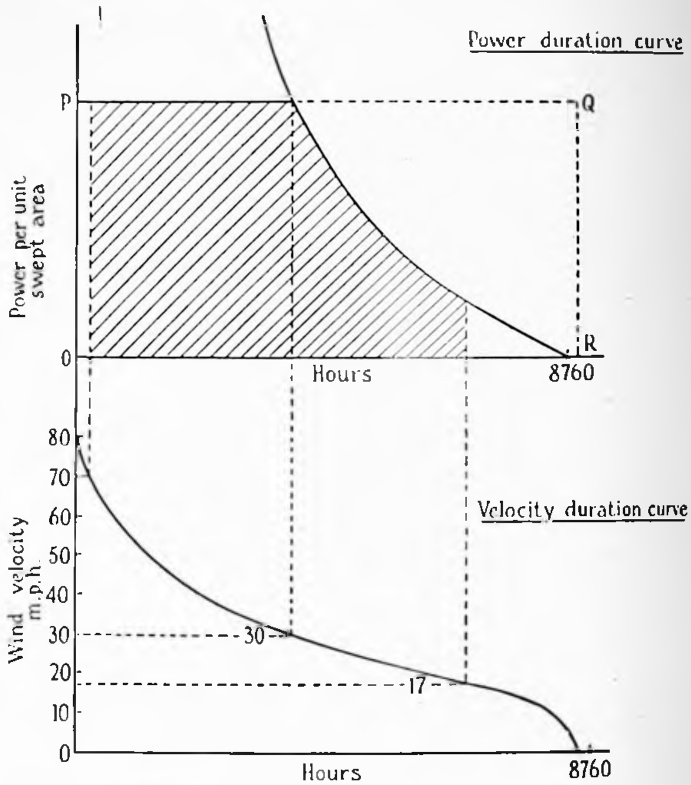


Fig. 7.—Wind velocity and power duration curves.

curve. Choosing a rated wind speed of 30 m.p.h. and a cut-in speed of 17 m.p.h., and assuming that for wind speeds above 30 m.p.h. the power is controlled to be constant up to 70 m.p.h.—the furling speed—then the annual energy available for use by the wind turbine is represented by the shaded area. The ratio of the shaded area to the area of the rectangle OPQR, when multiplied by 8,760, gives, approximately, the specific energy in kWh/p.a./kW.*

It is obvious that choice of a lower rated wind speed (say V_1) increases the specific energy but involves an increase in the area swept by the rotor to maintain the same kilowatt capacity. The new swept area would have, to that for a 30 m.p.h. rated wind speed, a ratio of $\frac{30^3}{V_1{}^3}$ which inevitably means an increase in constructional cost. It is a question, therefore, of striking a balance between economic output and economic cost of construction.

Although sites with the same average wind speed have different wind régimes, and therefore different power duration curves, it is generally true that an annual average wind speed of 22 to 25 m.p.h. implies a specific output of about 4,000 kWh/p.a./kW, while an annual average of 20 m.p.h. means a specific output of about 3,500 kWh/p.a./kW.

* This assumes constant efficiency for the unit over the whole of the operating range 17 to 30 m.p.h. Actually, falling efficiency towards the lower limit would cause a small diminution in total output but this does not materially affect the point made in the example.

(4.2) Possibilities of Development

The promise of economic utilisation of wind power has appeared from the results of the preliminary investigations described already but the possibilities can usefully be placed in three categories :—

(i) In combination with steam-generated power : since the bulk of the electrical energy in this country is steam-generated it is well that the costs of generation by wind power should be compared with those for this method in deciding the basis for economy. This has been done, in effect, in paragraph (*d*) of Section (4) when a probable cost for wind-generated energy of 0·25d. per kWh was seen to compare with a value of about 0·4d. per kWh when it is fed into a system supplied mainly by steam generation. While this comparison should perhaps form the main criterion of the economy of wind power, the remaining two categories are quite important.

(ii) In combination with hydro-electric power : under these circumstances there may be some " firm " kilowatts from wind power which would add to its value as a fuel saver. Wind-generated energy fed into a network which is supplied in part from hydro-electric sources conserves water in the reservoirs in direct proportion to the infeed and thus gives the effect of extra rainfall or additional catchment area. Thus it might justify the installation of larger penstocks, turbines and generators in projected hydro-electric schemes. Since the incremental cost of hydro plant capacity is low, some less promising hydro projects, not hitherto considered practicable, might be brought into the economic range. The complementary nature of the characteristics of wind and hydro power could bring about, in this way, both cheap energy and cheap kilowatts.

(iii) Utilisation in an isolated small network : on islands round the coasts of Britain and in many other parts of the world there are, already in existence or planned for development, isolated electricity supply networks. Both the amenity and utility value of electricity are high on such islands which seldom have any significant amount of water power : generation is by Diesel-driven plant which may lead to a fuel component of generating cost of 0·65d. per kWh or more. Wind velocities are, however, frequently high so that specific outputs of 4,000 kWh/p.a./kW or above could be expected from wind-driven plant which could be used, in combination with the Diesel plant, with every prospect of economic success. Clearly a strong case can be made for wind power in connection with isolated networks of this kind.

(4.3) The Return on Investment in Wind-Power Plant

In estimating the possible return on capital invested in wind-driven generators, if these indeed prove practicable, consider the least favourable case of their use in combination with steam-generated power.

The economic price of wind-generated energy in this case has already been given as 0·4d. per kWh. Take the constructional cost per kilowatt installed as £50 plus £2 per kW for special transmission from the wind power site to the network and assume a specific output of 4,000 kWh/p.a./kW.

The annual value of the output is thus

$$£\frac{4000 \times 0{\cdot}4}{240} = £6{\cdot}67$$

which represents a gross return, on £52 capital expenditure, of 12·8 per cent.

With 20 years' life, and a sinking fund earning three per cent., the annual deduction for replacement is 3·7 per cent., which leaves 9·1 per cent. for running costs and net return on the capital outlay.

The wind-power plant would be designed to run automatically so that annual maintenance and other running costs should not exceed one to two per cent. Experience with the medium size Danish sets supports this estimate.

Fig. 8.—70kW wind-driven generator. (F. L. Smidth & Co. Ltd., Copenhagen.)

It is of course impossible, at the present stage of the investigations, to say to what extent it will prove practicable to develop wind power in this country. The degree of development of the very large wind energy resources available depends not only upon the technical progress which may be made during the work now in hand but on future economic and political conditions. The question " What total amount of wind power and energy could be obtained in this country ?" is, however, frequently asked. An answer to it, even if it be only a rough approximation and subject no doubt, to criticism on the grounds of excessive optimism, seems desirable—it can, at least, form a basis for discussion.

Perhaps the best that can be done to provide such an answer is to make the not unreasonable assumption that several hundred sites could be found each of which might accommodate 2,000 kW of wind power generating plant to give an annual output of around 4,000 kWh/kW, and several hundred more to give about 3,500 kWh/kW. The total capacity may thus lie between, say, one and two million kilowatts producing from 3,750 million to 7,500 million kilowatt-hours per annum with a corresponding annual saving of coal of about two to four million tons. The labour needed to produce this amount of coal could be transferred, with national advantage, from mining to manufacturing industries.

It is not without importance that development of wind power for electricity generation on a significant scale might well lead to the establishment of a new industry with good export possibilities.

To present some sort of picture of the form which such ultimate development might take, one can imagine, erected on some hundreds of sites—most of them on fairly high, uncultivated moorland near the sea—windmill generators having a unit capacity of perhaps 2,000 kW. They may be installed singly or, on suitable hills, in groups of ten or more. If units of the propeller type were found to be the best they would probably stand on towers 150 to 200 feet high, would have two or three metal blades, about 100 ft. long and rotating at 100 r.p.m. or less, and would drive, through gearing, either induction or synchronous generators connected to the nearest supply network. It may be possible to use weather reports to predict their output some hours in advance.

(5) FUTURE RESEARCH

The research programmes initiated by the Wind Power Generation Committee at the start of their work, and which are now progressing, have been described in Section (3) where some account was given of the results so far obtained. Most of these researches are necessarily lengthy and are not yet completed but, since all are proving effective in furthering knowledge of the main subject, they will be continued.

Naturally, in a project of the possible magnitude already outlined, research and development must progress stage by stage, further work being undertaken only as it is proved to be justifiable and taking shape from the results of earlier work.

It has become clear from the meteorological investigations carried out that there remains much to be learned of the behaviour of the wind as it flows over the particular shapes of hills or ridges in which we are interested. In addition to determining its behaviour from measurements on the actual sites, it is thus intended to develop the technique of site selection by laboratory work with models of typical hills, using an electrical analogy to simplify the measurements.

It must be emphasised that although up to the present more attention has been given to the conventional propeller type unit about which most information is available the possibility that some other type may prove more suitable has not been overlooked. Some consideration has already been given to several other types and it is clear that full theoretical studies of both conventional and unconventional types of wind-driven plant should be undertaken to compare their relative advantages as a guide to the selection of the one best suited to the purpose in mind. In these studies particular attention should be paid (i) to the probable costs of construction; (ii) to the possibilities of producing them in quantity without too much modification of normal manufacturing methods; and (iii) to their probable performance under the onerous conditions which might apply to plant called upon to operate automatically on very exposed and weatherbeaten coastal sites with reliability and without introducing inconvenient disturbances to the supply system.

An important part of the investigations in the near future will be the performance tests upon the 100 kW pilot plants to be installed by the supply authorities. Concurrent meteorological, mechanical and electrical measurements over an extended period and covering a wide variety of weather and operating conditions must be made to obtain the maximum amount of data which will certainly be very valuable whatever the results may be.

Another requirement is a very thorough consideration of the problems—aerodynamic, mechanical, electrical and structural—which are likely to arise in further development on an increased scale. In this the results of the performance tests just referred to will give great assistance. Without anticipating the conclusions to be reached it is certain that the problems to be met cannot all be solved on paper so that experimental research of a rather complex nature, involving a mixture of the different engineering aspects, will be needed. This should lead to improvements in design of the conventional type of unit or, perhaps, to the adoption of some radically different design indicated by experimental work upon the performance of other types on model scale.

The result of such researches should be the construction of one or more relatively small prototypes which, after being tested for performance under identical wind conditions, could be subjected to more rigorous tests under actual operating conditions on good sites.

Assuming continued success, both technical and economic, in the work it should be justifiable—and this must, of course, remain the aim of the whole project—to construct a full-scale prototype to be put into normal commercial operation.

That difficulties will arise in carrying through the programme suggested is only too well recognised. But there must be a research plan to ensure any reasonable progress and there is, at least, this to be said for the development of wind power—it can be carried out in stages, with checks at the end of each, to ensure that continuation is justified before an excessive amount of work and money is expended.

(6) ACKNOWLEDGMENTS

It will be clear from the foregoing account of the work which has been carried out already, and of that which is being planned, that it involves a combination of the efforts of many people. In presenting the report the author is very conscious of this and wishes the great assistance afforded by the Wind Power Generation Committee, by interested organisations both in this country and abroad, by members of the public and by his E.R.A. colleagues, to be fully appreciated. He is most grateful for all the help which has been so generously given but may, perhaps, be forgiven for not attempting to give a list of the very large number of persons who are collaborating. Nevertheless, this brief account of the steps which are being taken to harness the wind for electricity generation cannot be allowed to close without mentioning the Chairman of the Committee, Mr. T. G. N. Haldane who, with unremitting effort and lively interest, has done so much to inspire and further them.

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WATERLOW & SONS LIMITED, LONDON WALL, LONDON.

Mr. Hawkins.

I should like your views about this: my impression is that before very long we shall be requiring more power in Stanley and it is for consideration as to whether we might not supplement our supply by aerodynamic generation. If, as is implied we shall be able (when they are in commercial production) to obtain units at a cost of approx £50 per kw. there seems something to be said for it. Is it worth ordering wind-measuring apparatus? The saving on maintenance & running costs appeals to me. MC 12/1.50

What approx. is our annual average wind-speed?

Mr. [illegible] to see these pp. on return. MC.

HCS,

My apologies for holding this file so long.

2. Our mean wind speed is about 18 mph on the Met Office site and my first impression on reading the pps is that a site on Sapper Hill would be well worth investigation. There are two things we can do as soon as time permits :-

a) Reanalyse the available wind data for this Office, so as to find the daily and annual distribution of wind speed (Mr. Gutteridge will want to know this in order to estimate how the output from wind plant would vary and compare with peak loads).

b) Set up a remote-reading anemometer on Sapper Hill and take hourly readings throughout the daytime hours (when the office is occupied) for comparison with readings taken at the Office. This should yield a factor which may be applied to the office records to give "long term" for Sapper Hill. (Mr. Mercer is enquiring about telephone lines which we might use for the remote-reading anemo.).

3. I would like to see the pps again after Briscoe has gone south again - you may care to pass to Mr. Guttridge meanwhile, who could also comment on a) & b) above?

G.H.
7.3.50.

E.E. These papers for Mr. Guttridge's information & observations.

R.

9 MAR 1950

M.G. pl read & discuss with me EH 9.3.50.

Mr Bunting,

I have read through the Technical Report ref C/T101 and wish to report that. If it was decided to introduce this type of prime mover along with the existing Diesel units the capital plant outlay would be approximately doubled thereby increasing the cost per unit generated. This increase in cost would be offset to a degree depending upon the output when available of the wind generator. It should be remembered that the installation of a wind generator could not take the place of a Diesel unit due say to an increase in the town demand through development. They would be installed along with Diesel plant of the same capacity, capital outlay would of course be doubled. The overall saving in fuel, working from figures given in the report indicate that with an annual average wind speed of 20 mph and wind plant of capacity 450 kW, 1.675×10^6 units would be generated, this would indicate no fuel would be required, 1.675×10^6 units being in excess of units required working on a reasonable load factor of 15%. It does not follow however that no fuel would be required and the Diesel sets not run, during periods of calm Diesels would have to take the whole load which may be a peak load thereby justifying their installation and purchase. The staffs would in no way be reduced for a continuous watch would still have to be kept. It is difficult not having a good estimate of future demands to arrive @ figures but I believe the cost per unit with plant consisting of both units would be slightly less than that of a plant consisting of Diesel engines only, with fuel @ the present price. If the price of fuel decreased to the normal average of other parts of the World then I would estimate that due to the increase in capital expenditure on Diesel plus Wind driven plant would be either on par or a little above that of Diesel plant only.

Owing to lack of real operating knowledge of this particular type of plant and the fact that there are relatively few in number of wind generating plants used by Public Undertakings I would hesitate to recommend their installation.

5

H.C.S.

I agree with Mr Gutteridge's conclusions
ie that until such time as we have more
knowledge as to capital outlay & maintenance
costs this installation should not be considered

E. T. B.

19. April 1950.

T.E.

May wish to see from f. 4 w.r.t. your minute at 3.

[initials] 21/4/50.

C.D.

But all this is v. previous. It is merely
something to be kept in view should circumstances
necessitate augmenting the new power supply.
Of academic interest only at the moment.

M.C. 21/IV

[initials]

8

PREECE, CARDEW & RIDER
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29 OCT 1951

1201 A

7th September, 1951.

OUR REFERENCE CHP/

YOUR REFERENCE

Sir Geoffrey Miles Clifford,
K.B.E. C.M.G. E.D.
Governor and Commander-in-Chief,
Falkland Islands.

Dear Sir Miles,

During your recent visit to the office I promised to let you have some further particulars regarding the progress which had been made on the development of manufacture of Wind Generators for the North of Scotland Hydro Electric Board and British Electricity Authority and also to let you have some information on the question of instruments necessary for a research in the Falkland Islands.

9 I enclose a copy of some notes made by one of my Senior Engineers of a discussion with Mr. Golding of the E.R.A. Mr. Golding is one of the Heads of Departments of the British Electrical and Allied Industry Research Association and is responsible for rural electrification and wind power research.

You will see from the notes that the North of Scotland Wind Generator has already been installed. We gather the Hydro Board does not welcome visitors but when the usual "teething" troubles connected with new developments have been overcome the Board will be pleased to arrange for an inspection of the plant.

While Mr. Golding's estimate of the cost of a survey is from £ 500 to £ 1,000 I judge this includes for the cost of staff as well as instruments. I gathered from my conversation with you that you would have no difficulty in arranging staff for an investigation. Hence it would seem that the only expenditure entailed would be for instruments and even these might be borrowed or hired.

It is interesting to know that the Managing Director of the Falkland Islands' Company - I have no information of these people - has also been in communication with Mr. Golding on the subject.

11 & 12 Copies of the report and Paper referred to in the notes are attached.

Please let me know if I can be of any further help in this matter.

With kind regards,

Yours sincerely,

C. H. Pickworth.

Enclosure

CdS.

B.
C.S.
I thought that MO would take this on if we cd. get the instruments. P.A. pass to him after filing & to S/PH.
MO
[illegible] 29/10/51.

Reply at 17

MR. PICKWORTH

29 OCT 1951

9

WIND POWER GENERATORS

NOTES ON DISCUSSION WITH E.R.A. (MR. GOLDING) ON 6.9.51.

1. Mr. Golding handed to RWLH spare copies of the undermentioned documents, which he suggested might be suitable for sending to the Falkland Is. to indicate the nature of the work carried out by E.R.A. :-

BEAIRA Report C/T 101

Large scale generation of Electricity by Wind Power - Preliminary Report

by E.W. Golding

IEE Paper 30/1/51

Wind and Gust Measuring Instruments developed for a wind power survey

by H.H. Rosenbrock & J.R. Tagg

In view of the large number of enquiries which Mr. Golding has received from all parts of the world, he has prepared a further Paper to assist prospective users to make wind surveys. This is at present in the hands of the printer, but is unlikely to be available for 2 - 3 months.

2. E.R.A. have surveyed over 50 Sites on the West Coast of Scotland, Wales, Northern Ireland, Donegal and Cornwall. Further Sites are about to be surveyed on the West Coast of Eire.

3. The 100 kW. wind generator ordered by the North of Scotland Hydro Board from Messrs. John Brown has now been installed in the Orkneys, and is undergoing trial runs and adjustment.

A ~~The~~ second 100 kW. generator has been ordered by the B.E.A. from Enfield Cables (sub-contractors ~~to~~ English Electric and de Havillands), and will be installed in North Wales. It is hoped to commission this next year.

4. The rated wind speed for the above two units is 30 miles per hour with cut-off at 17 miles per hour, and sails furled at 60 miles per hour.

5. Mr. Golding stated that a survey such as suggested for the Falkland Is. would cost from £500. - £1,000. if carried out in this country, this covering the supply of say two wind recorders and perhaps twelve cup anemometers, but the cost in the Falklands is likely to be higher, even though no Engineer is sent out from this country to organise the tests.

6. He suggested that the wind regime is predictable within plus or minus 20%, if records are taken for a trial period of one year.

7. The wind recorders are made by E.R.A. in their laboratories using Evershed & Vignoles' recording Voltmeters as a basis. He does not doubt that E.R.A. would collaborate in making two instruments for the Falklands, the cost of which would be about £60. each.

Cup

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Cup-counters and cup contact units can be obtained from Messrs. R.W. Munro of Cline Road, Bound's Green, N.11, the cost being about £17. each. Cup generators can be obtained from Messrs. Short & Mason of MacDonald Road, E.17. Some recorders can be hired from the Meteorological Office at Harrow, but it is unlikely that they would be prepared to release them for sending to the Falklands.

8. The Managing Director (whose name Mr. Golding thought was Mr. Young) of the Falkland Is. Company has already been in communication with Mr. Golding on this subject. It is understood that this Company operates a Shipping Line and a number of estates in the Islands, from which they propose to supply electricity generated by wind power. In a letter dated June 1951 the Falkland Is. Co. stated that they were arranging for a wind survey to be carried out. (If deemed desirable, they could be contacted by telephone at Weybridge 2100).

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9. Mr. Golding is very enthusiastic about the prospects for wind power generators for working in conjunction with Diesel Stations as a means of saving fuel oil. He stated that, provided a small number of standard sizes of generators are manufactured in reasonable quantities, it is estimated that the capital cost should be about £50. per kW. Based on this capital cost, and allowing a working life of 20 years the cost of units generated by wind power should only be about ¼d. He stated that E.R.A. would be very pleased to assist in analysing the results of wind surveys, and give all other possible assistance, and particularly requested that he should be kept in touch with developments.

They only [illegible] as stated before.

10. Mr. Golding also stated that he had had one or two enquiries about the use of wind generators from Malta, but was not able to remember the names of the organisations concerned.

[signature]

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THE INSTITUTION OF ELECTRICAL ENGINEERS

SYMPOSIUM OF PAPERS ON
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WIND- AND GUST-MEASURING INSTRUMENTS DEVELOPED FOR A WIND-POWER SURVEY

By H. H. ROSENBROCK, B.Sc.(Eng.), and J. R. TAGG, B.Sc.(Eng.), Graduates.

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SUMMARY

A description is given of two recorders and an anemometer for measuring gusts, which were developed for use in a survey of the available wind-power in Great Britain. The essential feature of the recorders is that they operate unattended for a period of one week. The first instrument is a photographic recorder which shows, at intervals of half an hour, the wind direction and the run of wind past four standard cup-contact anemometers. The second instrument records a mark for each two miles of wind, and will make up to four simultaneous records. The anemometer for measuring gusts uses a perforated aluminium sphere as the detecting element and a mechano-electronic transducer valve to convert the mechanical response to an electrical output. It is compensated for changes of temperature and for the static effects of atmospheric pressure. When used with an amplifier-driven recording voltmeter, the response of the prototype instrument to an instantaneous change of wind speed from 65 to 85 m.p.h. was completed in about 0·07 sec. Modified forms of the instrument are described which measure, respectively, the horizontal components of the wind in two directions at right angles and the vertical component.

(1) INTRODUCTION

The wind survey for which the instruments were developed was undertaken towards the end of 1948. Its purposes were to determine the annual energy which might be expected from wind-driven electric generators situated in different parts of Great Britain and to find the best sites for such generators in certain selected areas. The information available from the stations maintained by the Meteorological Office was found to be insufficient for these purposes. These stations are intended to give typical rather than extreme conditions, and are therefore not generally situated at abnormally windy sites. In addition, the stations at which recording anemometers are installed are not close enough together for a comparison to be made between different sites in a small area.

It was decided that the essential information required for the survey was a record of mean wind speed over half-hourly periods, recorded continuously at a number of hill-top sites in each area to be assessed. It was also desirable to record the wind direction, but this was not essential since the information could be obtained if necessary from the nearest Meteorological Office station. At sites where it was probable that a generator would be installed, the wind speed was required at several different heights, since the normal velocity gradient would be disturbed as the wind flowed over a hill. Finally, at most sites it would be difficult to find anyone who could visit the station daily, and the instruments had therefore to record for at least a week without attention. It was found that these requirements could not be fulfilled by any of the standard Meteorological Office instruments, and two recorders were therefore developed for use with the standard type of cup-contact anemometer.

A further object of the survey was to determine the structure of wind gusts, since these may have an important effect on the operation of a wind-driven generator and little is known about them. No instrument was available with a response time short enough to give the required information, and an anemometer of completely new design was therefore built and has since been considerably developed.

(2) PHOTOGRAPHIC RECORDER

The photographic recorder was developed at extremely short notice for use at an isolated hill-top site in the Orkney Islands. It was intended to record the indications of a remote-indicating wind vane every thirty minutes, and also the integrated totals of miles of wind* passing four cup-contact anemometer positions during this period. The anemometers and wind-vane are of the standard pattern used by the Meteorological Office, but the indicator of the wind-vane is modified by substituting a thin aluminium disc for the pointer. The disc is marked with an angular scale at intervals of five degrees. The disc has a matt-black surface and the scale is in white, so that a clear photograph is obtained.

The run of wind is obtained by connecting in series with the mercury switch of the anemometer a battery and the operating coil of a telephone-type message register, which has a cyclometer dial. Power for the counter circuits is supplied from wet Leclanché cells.

Basically, the recorder consists of a light-tight box containing the wind-direction indicator and five message registers, four of which are connected to their respective anemometers, while the other is used for timing purposes. Also in this box are two

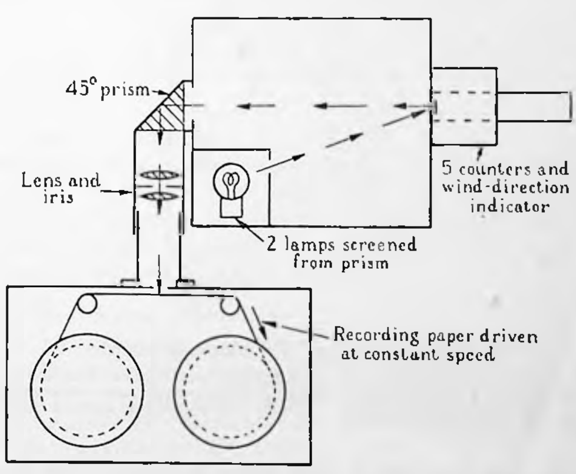

Fig. 1.—Diagram showing the optical system of the recorder.

The camera is fitted with a sliding shutter and can be removed from the recorder. The lens assembly slides in its tube for focusing.

bulbs which are switched on at intervals of half an hour by a time switch. The bulbs are supplied with current from a car-type accumulator. Fig. 1 shows the optical system and the general arrangement of the recorder. The reflected light is

(U.D.C. 551.508.5 : 621.317.39)

Mr. Rosenbrock and Mr. Tagg are with the British Electrical and Allied Industries Research Association.

* The run, or number of miles, of wind passing a given point is equal to the mean wind speed multiplied by the time. The number of revolutions of an idealized cup anemometer is proportional to the run of wind.

passed through the prism to a lens and thence directed on to the recording paper which is contained in a detachable camera.* The prism forms a convenient means of obtaining an image in the correct sense.

Recording is initiated by the time switch, which energizes a relay circuit for a period of six seconds. The three contacts of the relay respectively switch on the lamps for the exposure, move the timing counter through one digit and open the circuit of the four other counters. Both the movement of the recording paper during the exposure and the error introduced into the anemometer readings by the brief period of open circuit are negligible. No steps are taken to prevent movement of the wind-direction indicator during the exposure, and in gusty winds the direction records are slightly blurred. It is possible to read the wind direction under all but the most gusty conditions, and it is sometimes useful to have this indication of gustiness.

(3) IMPULSE RECORDER

After some experience had been gained with the photographic recorder, the need arose for several instruments at similar isolated sites, capable of recording the indications of one or two anemometers without the added complication of the wind-direction indicator. Furthermore, it was considered desirable to dispense with the photographic method, owing to the inevitable delay before any faults which might have developed in the instrument could be detected. Allowing time for processing and transit, a full week might elapse from the time the record was removed until the local attendant could be advised of a fault and could rectify it.

Fig. 2 shows the type of recorder which was developed. On a paper chart moving at three inches per hour, a dot is made after each two miles of wind passing the anemometer position. Analysis of the wind speed over any period is made by counting the number of these dots and relating them to the length of the period. The chart is driven by a standard eight-day clock movement taken from a recorder using a chopper bar and an inked ribbon. This principle has been retained, but the chopper bar is replaced by a number of marking edges at fixed positions, each operated by its own solenoid.

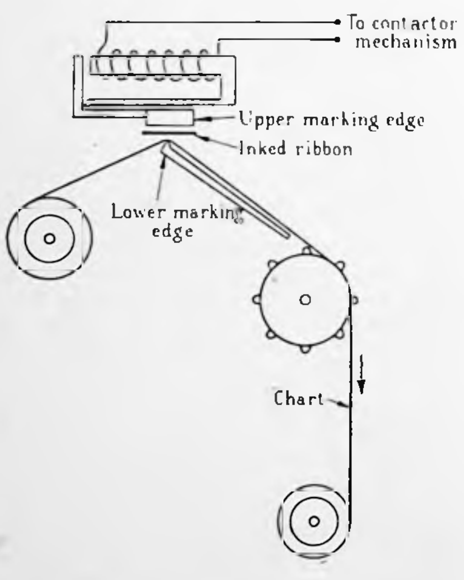

Fig. 2.—Diagram of the impulse recorder.

The chart runs between two edges at right angles, the lower one fixed and the upper one attached to a modified relay. An inked ribbon is drawn across the paper where it passes between the marking edges. Operation of the marking solenoid causes a dot to be made on the chart.

The contact of the anemometer closes twenty times during the passage of one mile of wind, and, as a mark is required only after two miles of wind have passed, a dividing mechanism is inserted in the circuit. The operating coil of a contactor mechanism, shown in Fig. 3, is wired in series with five large dry Leclanché cells and the anemometer mercury-switch. When the coil is energized, the armature moves the insulated disc through 1/120 of a revolution by means of a rachet wheel and closes a subsidiary contact at the same time. The insulated disc has three symmetrically arranged slots in its circumference which engage with a second contact and close it three times during one revolution. These two contacts are wired in series with the operating coil of the marking solenoid and the battery. If the subsidiary contact were omitted, the marking solenoid would remain energized for the period between two impulses. This would seriously reduce the life of the batteries, and the system shown ensures that current is taken only during the short period of an impulse.

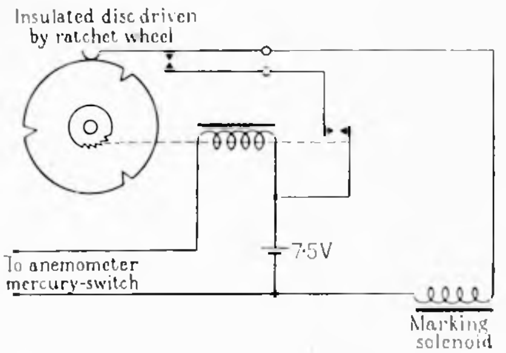

Fig. 3.—Circuit diagram of the contactor mechanism.

During the passage of two miles of wind the anemometer switch closes forty times, the disc rotates one-third of a revolution and one mark is made on the recording paper. Movement of the inked ribbon—which is necessary to prevent it from drying out at one spot—is accomplished by mounting a driving spool on the main driving shaft of the clock. This rotates at a speed of one-third of a revolution per hour, and when an ordinary typewriter ribbon is used it is conveniently traversed in an eight-day period.

(4) ANEMOMETER FOR MEASURING GUSTS

(4.1) Requirements

The ordinary definition of velocity applies only to a solid particle, and it is necessary to inquire what is meant by the "wind velocity" measured by an anemometer. Several different mean velocities can be defined:

(*a*) It is easy to define the mean velocity of a given body of air at any instant; this is simply the vector mean velocity of the hypothetical particles, all of equal volume, into which the air can be divided.

(*b*) A mean velocity can also be defined at any one point over a period of time by taking the vector mean velocity of all the elementary particles which successively occupy the point.

(*c*) A third mean can be obtained by dividing the volume of air which passes through a given area in a given time by the values of the area and the time.

* A similar system of recording has been used before and is described by E. L. Deacon: "Two Types of Sensitive Recording Cup Anemometer," *Journal of Scientific Instruments*, 1948, 25, p. 44.

Definition (*c*) gives the mean velocity normal to the area during the given period, and it is this quantity which an anemometer is generally required to measure. It is easily seen that there are two alternative definitions which lead to the same result as the one given: either the mean normal velocity with area can be formed at each instant and the mean of the result with time can then be found, or the mean normal velocity with time can be found at each point of the area and the mean of this result with respect to area then formed. If the configuration of a body of air which passes normally through the area does not change appreciably, the mean defined in any of the last three ways is nearly equal to the mean velocity of the body of air, as defined in (*a*), at any time during its passage.

Unfortunately, none of the common types of anemometer measures any of these simple mean velocities. The pressure-plate anemometer will be discussed in detail, but a similar discussion applies to most other types of anemometer. The force on a suitably designed pressure plate depends upon the mean square of the speed of the air in contact with it at any instant. This, in turn, is governed by the speed and acceleration of the adjacent air, so that the force on the pressure plate depends on the air within a certain distance from it, the influence decreasing as the distance increases. The indication of the anemometer depends on the forces which have acted upon it during some previous period, those forces having the greatest influence which acted some short, but quite definite, time before the instant considered. The force acting at any instant, and the forces which acted some minutes before, are equally without effect on the indicated velocity at that instant. Thus, the indication of such an anemometer is a very complicated function of the velocities which have existed in a space around it during some previous time. It follows that the velocity indicated by an anemometer is a property not only of the wind, but also of the anemometer, and the type of anemometer to be used must be carefully chosen so that the information which it provides is useful for the purpose in hand.

There are two ways in which gusts affect the operation of a wind turbine used for the generation of electric power. First, the mean wind speed taken over the swept area varies with time, and this will cause the output of the generator to vary. The gusts which have an important influence upon the output will be those which affect a relatively large body of air, having dimensions comparable with the diameter of the swept circle. The inertia of the rotating parts will ensure that smaller masses of air moving faster or slower than their surroundings will not greatly affect the output as the blades sweep through them.

The second effect of gusts is to set up stresses in the blades. The air near the tip of a blade, for instance, may have a lower speed than that which is near the root. As the blade rotates the distribution of wind velocity along it will change very rapidly. Whatever method of stress alleviation is used, the blades can be adjusted only for the mean conditions, and there will be residual stresses caused by the uneven and changing distribution of velocity over the swept area. The bodies of air which are most important in this connection are those having dimensions several times greater than the chord of the blades but less than the diameter of the swept area.

As the first experimental generator was to have an output of 100 kW it was decided that bodies of air having dimensions less than about 10 ft could be ignored. The greatest wind speed at which the generator was likely to be operated was 70 m.p.h., and the time for 10 ft of air to pass a given point at this speed is nearly 0·1 sec. Thus, an anemometer which responded in 0·1 sec to the changes in wind speed would give just sufficient information to determine the effect on the blades.

By making the projected area of the detecting element small, an anemometer can be designed to give an approximation to the mean velocity with time, effectively at a point. Several such anemometers can then be spaced along a length equal to the radius of a blade, or placed at different points on a circle representing the swept area. The mean of the various anemometer readings will give an approximation to the mean velocity as defined in (*c*). This is approximately equal to the mean velocity of a certain body of air according to definition (*a*). By averaging the anemometer readings over longer or shorter periods, and by spacing them more or less widely, the mean velocities of bodies of air having dimensions from 10 ft to 100 or 200 ft can thus be obtained. It was therefore decided that several instruments should be built, each having a small detecting element.

(4.2) Choice of the Detecting Element

The possible types of anemometer which received consideration are now described and the reasons for which they were rejected are given.

(4.2.1) The Hot-Wire Anemometer.

The hot-wire anemometer has the smallest effective projected area of all types. Its time of response is very good, but the calibration holds only for short periods and there is no way of recalibrating except by placing the anemometer in a wind tunnel. The sensitivity falls rapidly with increasing wind speed in the constant-current type, and it would be difficult to adapt the constant-resistance type for automatic recording. Anemometers are also available in which a thermistor or thermocouple detects the cooling effect of the wind on a small element. These were not considered, as their response time is too great for gust measurements.

(4.2.2) The Bridled-Cup Anemometer.

In the bridled-cup anemometer a horizontal disc having a number of cups on its circumference is turned through a small angle by the action of the wind. The disc is restrained by a spring. Some experiments were conducted on these lines, but it was found impossible to attain the required speed of response, chiefly owing to the difficulty of damping the motion. The torque on the cups also fell off very rapidly when the wind was not in the plane of the disc, and this would have led to false readings when the wind velocity had a vertical component. The difficulty could probably have been overcome by reshaping the cups, but a good deal of trial and error would have been unavoidable. This type of anemometer was abandoned at an early stage.

(4.2.3) The Cup Anemometer.

Whether fitted with a generator or with a frequency-indicating system, the cup anemometer generally has too much inertia to give the response which was required. There is also the difficulty, as with the bridled-cup anemometer, that winds having a vertical component may be incorrectly indicated.

(4.2.4) The Windmill Anemometer.

The windmill anemometer fitted with a small generator, or with some device to give a frequency proportional to the rotational speed, may be used. Suitable devices would be an inductance or capacitance which varied as the windmill rotated and so modulated a relatively high-frequency current. Such an arrangement would put no appreciable load on the windmill and would give a frequency directly proportional to the wind speed. This seemed a very attractive possibility, but there was some doubt whether the tail of the anemometer would keep it normal to the wind during gusty conditions. Any defect in this respect would lead to readings which would be too low. A similar and unavoidable error would arise when the wind had a vertical component.

(4.2.5) The Pressure-Tube Anemometer.

Fitted with a flexible diaphragm to detect the pressure difference, and indicating electrically, the pressure-tube anemometer might be made more responsive than any of the previous types, since the natural frequency of the moving parts might be several thousand cycles per second. There would be difficulties similar to those of the last type, however, when the wind direction was changing or was not horizontal.

(4.2.6) The Pressure-Plate Anemometer.

The pressure-plate anemometer resembles the pressure-tube one, but has the diaphragm at the front of the instrument and not at the end of a pressure tube. By suitable design, the change in response with wind direction might be made quite small, but this would require a long process of trial and error. An interesting anemometer of this type has been described by two American investigators.*

(4.3) Principle of the New Anemometer

To avoid some of the difficulties of the normal types of anemometer, a completely new instrument was designed, the principle of which is shown by Fig. 4. A light sphere is mounted on an arm which is pivoted near its centre so that it is free to move in all directions. A steel wire connects the lower end of the arm to a spring diaphragm which supplies the controlling force. A stop at its lower end limits the movement of the arm, and the wire is immersed in a viscous fluid. This damps the motion of the sphere and also prevents oscillation of the wire.

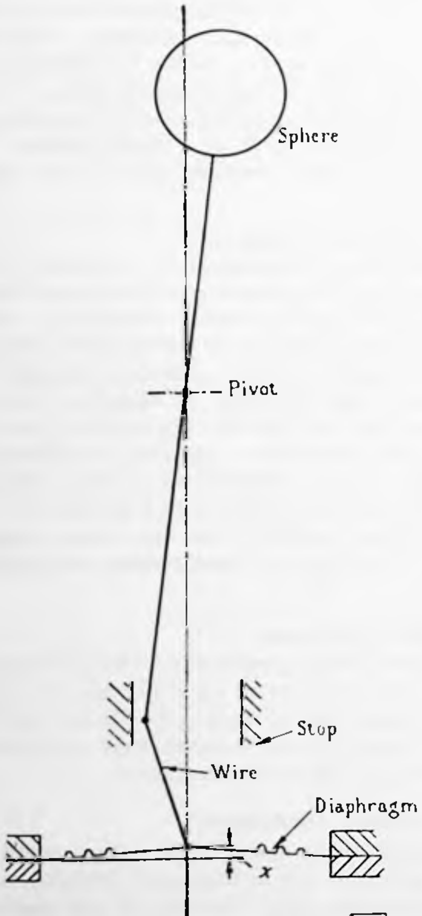

Fig. 4.—Diagram to show the principle of the gust anemometer.

With a sphere of 1½-in diameter, which is the size used for the normal instrument, and with wind speeds from 40 m.p.h. upwards, the Reynolds Number of a plain sphere lies in the critical range. The force on the sphere is then not proportional to the square of the wind speed, and may even decrease with increasing speed. When the sphere is in a wind tunnel, the force on it may also differ considerably from that in free air at the same speed, owing to differences in the turbulence of the air. To avoid these difficulties, the sphere of the anemometer was perforated with small holes which served to break up the large eddies behind the sphere. Experiments in the wind tunnel showed that the force on the sphere was then proportional to the square of the wind speed over the working range of the instrument. This modification was based upon earlier experiments carried out at the National Physical Laboratory with spheres of 10-in diameter perforated with ½-in diameter holes. It was not expected that the size or the number of the perforations would be critical in the present case, and when the first attempt proved successful no further experiments were made.

When the sphere is exposed to gusts which occur too quickly for it to follow, it will take up a position corresponding to the mean force upon it. Since the force exerted depends on the square of the wind speed, the anemometer will then indicate the r.m.s. value of the speed, which is greater than the arithmetic mean of the instantaneous gust speeds.* This effect is common to all anemometers which rely upon wind forces. In the present case, any fluctuations in wind speed which the sphere cannot follow are probably small, and their effect is unimportant. It is also rather doubtful whether the arithmetic mean for these small fluctuations is more significant than the r.m.s. value, since the pressure upon any structure which cannot follow such fluctuations depends upon the latter.

Another feature which is common to all anemometers relying upon wind pressures is that the indication does not show the correct wind-speed if the air density differs from that for which the anemometer is calibrated. The indication, in fact, shows the speed which air of density equal to that used during calibration would need to have to give the same pressure as the wind which is being measured. The anemometer will normally be calibrated for standard conditions of temperature and pressure. In this case, the nominal velocity readings can be used with the standard density to obtain the force upon any structure at the indicated wind speed. If the true wind speed is required for any purpose it can readily be calculated from the anemometer reading, given the temperature and pressure. The difference between true and indicated wind speeds may reach 5%, and it is necessary to allow for this variation when comparing the readings of an anemometer of this type with those of the windmill or the rotating-cup type. Both of these indicate the true wind speed without sensible dependence on the density.

If the interfering effects of the arm and the body of the anemometer are neglected, the magnitude of the force on the perforated sphere, for a given wind speed, is independent of the wind direction. The deflection of the diaphragm depends on the component of this force in the horizontal plane. As the force is proportional to the square of the wind speed V, the deflection of the diaphragm does not strictly indicate the horizontal component of the wind, $V \cos \phi$, but the larger quantity $\sqrt{(V^2 \cos \phi)}$, where ϕ is the inclination of the wind direction to the horizontal plane. In fact, the interference of the arm and the anemometer body reduces the indication when the wind is not horizontal.

* Sherlock, R. H., and Stout, M. B.: "An Anemometer for a Study of Wind Gusts," *University of Michigan Engineering Research Bulletin*, No. 20, May, 1931.

* If the wind changes direction during the gusts, the indicated direction will be a rather complicated function of the mean direction.

The prototype instrument was found to indicate the horizontal component correctly when the inclination was 10° and to read 3% low when the inclination was 20°. These results are for an upward inclination of the wind, for which the interference of the anemometer body is greater than with downward inclinations.

It is readily shown that, if the force exerted by the diaphragm when it is deflected a distance x is $F = a + bx$, then

$$a^2x + 2abx^2 + b^2x^3 = KV^4$$

where K is a constant and a and b are constants of the diaphragm. There must be some tension in the wire when the sphere is undeflected, to prevent the pivot from lifting out of its seating, so that a cannot be zero. It follows that, when x is small, $x \propto V^4$ and the instrument is very insensitive to low wind speeds. If, when x is large, the term b^2x^3 is the most important, then $x \propto V^{\frac{4}{3}}$. Thus, if the electrical output is proportional to x, the upper part of the calibration curve can be made nearly linear. An example of a calibration curve, taken from the prototype instrument, is given in Fig. 5. Some adjustment to the shape of

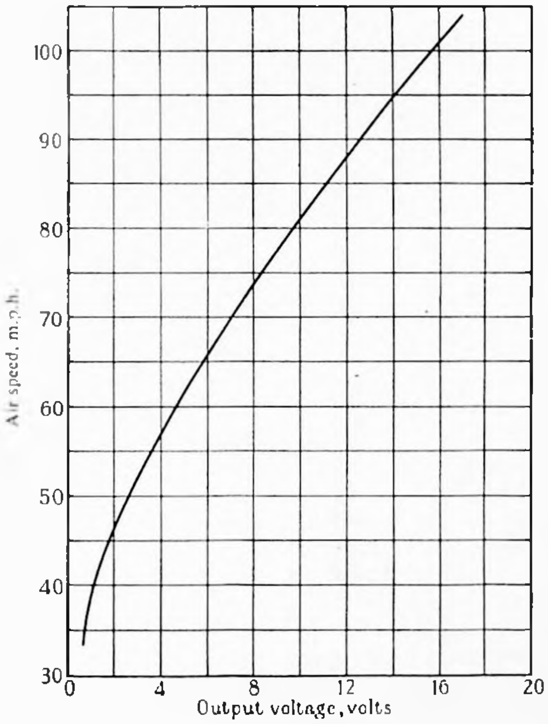

Fig. 5.—Calibration curve of the prototype gust-anemometer.

this curve is possible by altering the ratio $a : b$, that is, by using a stiff diaphragm with small initial tension or a flexible one with larger initial tension. Non-linear diaphragms might also be used to give a modified calibration curve. For the purpose of the wind survey the type of curve shown in Fig. 5 is satisfactory, since gusts at low wind speeds are not expected to be important in the operation of a windmill.

If an undamped linear system has a natural frequency of 10 c/s, then when critical damping is applied the system will reach its final position (within 1% nearly) in 0·1 sec after any sudden change. The controlling force on the sphere increases more quickly than the deflection, however, so that the system of this anemometer is not linear and the natural frequency of small oscillations increases with an increase of the mean deflection. A natural frequency of 10 c/s for small oscillations of the sphere in the undeflected position was aimed at when designing the instrument.

(4.4) Choice of Indicating Arrangements

Given the mechanical movement of the diaphragm, several methods were available for obtaining an electrical indication depending upon it.

A small potentiometer was considered, but it was found that the movement of the diaphragm would have to be magnified by some mechanical means. The slider of the potentiometer would then impose an appreciable load on the diaphragm. It was desirable that the force controlling the sphere should be provided entirely by the diaphragm, so that the electrical element could be replaced without altering the mechanical response of the system, and the potentiometer was consequently rejected.

A system depending on a change of capacitance was rejected as it would require the use of relatively high frequencies, and the capacitance of the leads to the anemometer would then lead to serious difficulties.

A change in the inductance of a circuit carrying a fairly-low-frequency current was a possible means of providing the electrical output. This system was successfully used in the American investigations already mentioned.* At the present stage it seems that it would have required about the same amount of development, and been as successful, as the system actually used.

The mechano-electronic transducer finally adopted is a miniature triode which is usually operated with the grid connected to the cathode. The body of the valve is of metal, and it has a metal diaphragm sealed to the top. A small anode pin passes through the diaphragm, and can be moved through an angle of ± 0·5°, so altering the spacing between anode and grid, and consequently changing the anode current. The diameter of the valve body is $\frac{5}{16}$ in, and the length is $1\frac{9}{32}$ in. The nominal anode resistance, with the anode pin undeflected, is 72 000 ohms. A moment of 6·7 gm-cm is required to give a deflection of 0·5°.

The normal application of this valve is the measurement of vibration at frequencies up to 12 000 c/s. It was realized that there might be difficulties in using it at zero frequency, as the anode resistance would probably alter during the life of the valve. This objection can be met by calibrating the anemometer against a horizontal force applied to the ball. If this is done immediately after the wind-tunnel calibration it is an easy matter to recalibrate the anemometer against a similar horizontal force at any time, and there is no need to place it in the wind tunnel again.

In other respects, the transducer valve is a very convenient device. The voltage sensitivity is high, being 40 volts for a movement of 1° with a supply at 250 volts, and the load imposed on the diaphragm of the anemometer is negligible. The relation between output voltage and angular movement is very nearly linear.

(4.5) Recording Instrument

The choice of a recording instrument lay between the oscillograph and an amplifier-driven recording voltmeter. The former would give the desired speed of response without difficulty, but the necessity for photographic recording was a very considerable disadvantage in apparatus which was to be used under rather difficult conditions in the field. A recording voltmeter, having a servo-operated pen driven by a valve amplifier, was eventually chosen. This has a response of 12 c/s for an amplitude of one-half of full-scale, which is just sufficient to record faithfully the output of the anemometer. Four chart speeds are provided, namely ½, 1, 3 and 6 in/sec. A speed of 1 in/sec is sufficient to show all the detail in the records, but the higher speeds are useful for testing the response time of the anemometers. The rolls of chart will

* SHERLOCK, R. H., and STOUT, M. B.: *loc. cit.*

accommodate a record of 12 min at 1 in/sec. Each recorder has two pens recording on the same roll of paper, and two such instruments will be used to record simultaneously the indications of four anemometers. An operation pen in each instrument allows the two charts to be synchronized by means of timing-marks.

(4.6) Description of the Anemometer

The mechanical construction of the second anemometer to be built is shown in Fig. 6. This is the latest model with which operating experience has been obtained, and it incorporates many modifications which were found to be desirable from experience with the prototype instrument.

The sphere is pressed in two halves from perforated aluminium sheet, and is cemented along the horizontal meridian with a thermosetting resin. The body is sealed, to prevent the entry of moisture or the loss of damping fluid, by a very thin rubber diaphragm placed on the line of the pivot. This diaphragm exerts very little controlling force against deflections of the sphere, but having a large diameter it effectively prevents all rotation about the vertical axis. The pivot is a hardened-steel point carried inside a lantern frame having three steel pillars. The bottom of the lantern frame carries the lower operating arm and a brass balance-weight, which is moved up or down until the centre of gravity of the moving system is just below the pivot. Final balance is achieved after assembly by moving a smaller weight on the upper operating arm until lateral accelerations cause no electrical indication.

A small air-vent on the side of the anemometer casing ensures that changes of barometric pressure do not cause deflections of the diaphragm, and it can be sealed to prevent loss of the damping fluid during transit. Damping is provided by a silicone fluid of suitable viscosity, which does not attack the steel wire nor the rubber sealing diaphragm and suffers little change of viscosity with temperature.

The relative location of the pivot seat and diaphragm is fixed by the brass casing of the anemometer, while the internal moving system is partly of Duralumin and partly of steel. Since these metals have temperature coefficients respectively greater and less than that of brass, it is possible to arrange the proportions in such a way that temperature changes do not cause a deflection of the diaphragm. The transducer is carried on a support which is split and provided with an adjusting screw. The final connection to the transducer is made by soldering the anode pin into a slot in the operating arm, and when this has been done the anode pin will not generally have the correct deflection. The adjusting screw allows the support to be distorted slightly, so that the deflection of the pin can be set to about 0·25° downward when the sphere is undeflected. The total movement of the diaphragm is about 0·01 in, corresponding to an angular movement of the pin of 0·5°.

(4.7) Electrical Circuit

The prototype instrument was operated from dry batteries and an accumulator, and was used with the simplest possible circuit, shown in Fig. 7. The anode resistances of the transducers which have been tested have lain between 200 000 and 400 000 ohms instead of the nominal 72 000 ohms, but since the recorder with which the instruments were to be used had an input impedance of 500 000 ohms, it was still just possible to use the circuit shown. The design of the prototype anemometer and of the one illustrated in Fig. 6 did not allow the transducer shell to be insulated from the anemometer body, and the apparatus had therefore to be operated with the anode at earth potential. The recorder was then about 150 volts negative with respect to earth, which was inconvenient. The main

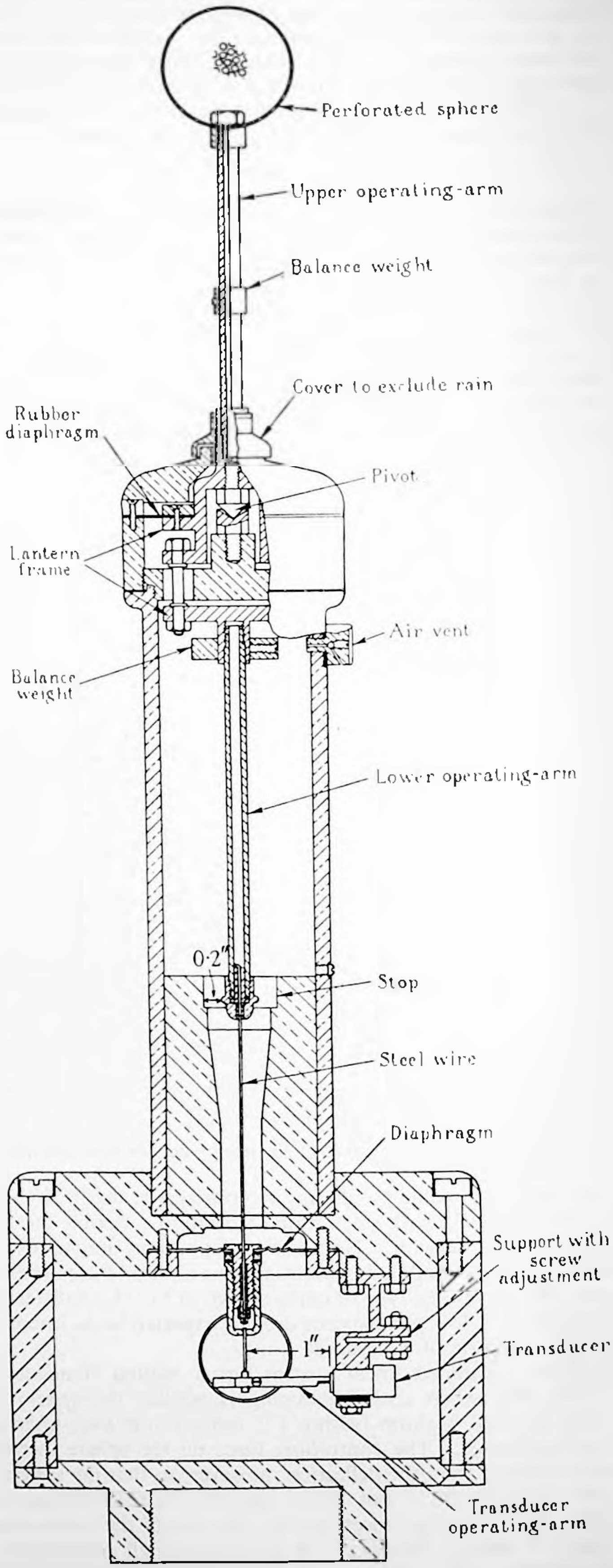

Fig. 6.—Section of gust anemometer.

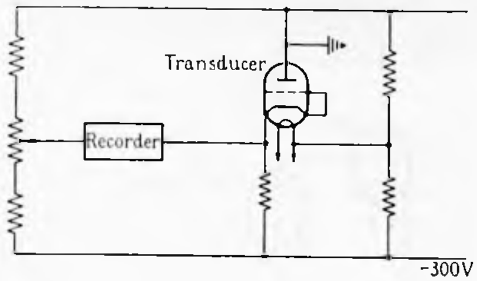

Fig. 7.—Circuit used with the prototype gust-anemometer.

difficulty in insulating the transducer is that the insulation has to be placed in a position where any change in its dimensions will cause a deflection of the anode pin. By redesigning the connection between the lower anchorage of the wire and the transducer operating arm, as shown in Fig. 8, and by insulating

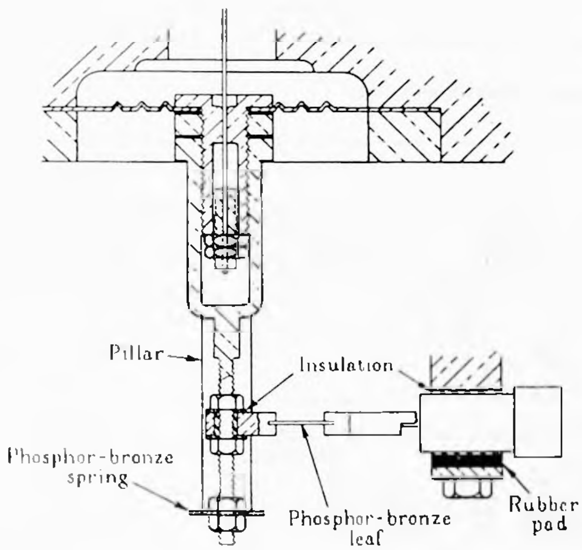

Fig. 8.—Modification of the transducer mounting and lower anchorage.

The tail of the lower anchorage is supported by a flat spring mounted on two pillars. The transducer and its operating arm are insulated from the anemometer body.

the body of the transducer, it is hoped to overcome this difficulty in future, so that the recorders can be operated at earth potential.

The instrument shown in Fig. 6 has been used with an a.c. filament supply stabilized by a barretter, as shown in Fig. 9.

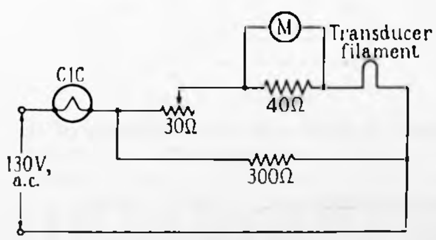

Fig. 9.—A.C. stabilizing circuit for transducer-filament supply.

The h.v. supply was obtained from a valve rectifier with a standard stabilizing circuit using an EL37 valve. Several difficulties have arisen with this arrangement when the anemometer has been operated in the field. As the output impedance of the transducer was very high, considerable 50-c/s ripple was picked up by the leads and appeared on the charts. This was minimized temporarily by keeping the filament leads away from the cathode lead and injecting a voltage in anti-phase to balance out the remaining pick-up. Then, in damp weather, although all plug connections were covered with plastic compound, the insulation resistance of the cathode lead fell. This caused a shift of the zero on the records and a slight change in the calibration. Finally, the barretter was found to give insufficient stabilization of the filament supply. A change of $7\frac{1}{2}\%$ in the mains voltage gave a change of $1\frac{1}{2}\%$ in the filament current, but this caused a zero shift at the recorder of 5% of full-scale deflection. The barretter was not operating at the most suitable point of its characteristic, but even so it seemed that a much greater degree of stability was called for than could be provided by such means.

To avoid these difficulties it is proposed to use the circuit shown in Fig. 10. A miniature valve will be placed in the base of the anemometer, so that the output impedance will be reduced to a few hundred ohms. This should eliminate pick-up from other leads and zero shift due to slight leakage in the cables. The filaments will be fed from a stabilized supply similar to that used for the h.v. supply, several filaments being operated in series. The reference voltage of the stabilizer will be compared with the voltage across a fixed resistor carrying the filament current.

In addition to the short runs at a high chart-speed which are made for the study of gusts, it is also intended to use one anemometer to record continuously, at a low chart-speed, the peak value of the wind velocity during storms. The anemometer for this purpose has a sphere of 1-in diameter, and is adjusted to cover the range from 60 to 150 m.p.h., instead of the normal range of 30–75 m.p.h. It would not be practicable to use a responsive recorder with a low chart-speed, as the record would be obscured by an excessive amount of ink. The circuit shown in Fig. 11 has therefore been developed, so that the anemometer can be used with a relatively unresponsive milliammeter recorder.

The condenser C1 is charged through the diode V2, and discharges very slowly through a high resistance R8. Since the time-constant for charging is short, the voltage across the condenser reaches the peak output of the anemometer. The slow discharge ensures that the heavily damped recorder reaches and records this peak value. Some care is necessary in building the circuit to prevent oscillation of the cathode-follower stages, and if the discharge resistance is too high there is a gradual upward creep of the voltage across the condenser after it has reached the true peak value. By a suitable choice of C1 and R8 this error can be held to a small value. The diode can be shunted by different resistors to reduce the time of discharge when necessary.

The differential cathode-follower (V3 and V4), shown in Fig. 11, replaces a simple cathode-follower with a recording milliammeter in the cathode circuit, which was the arrangement first adopted. Changes of the current used to bias the milliammeter, although not troublesome, were still noticeable, and the circuit shown should reduce this effect.

(4.8) Performance of the Anemometer

To check the response time and damping of the prototype instrument it was placed in a wind tunnel and the sphere was tied back with thread. With a suitable wind-velocity in the tunnel, the thread was burned through by a thin wire, heated by the current from an accumulator. The response of the anemometer was recorded at a chart speed of 6 in/sec, and a sample record is shown in Fig. 12. The thread has stretched before finally parting, and this accounts for the gradual rise of the trace before the zero line. As the trace is horizontal just before the line, this gradual stretching does not affect the result.

It will be seen that the response is complete in about 0·07 sec,

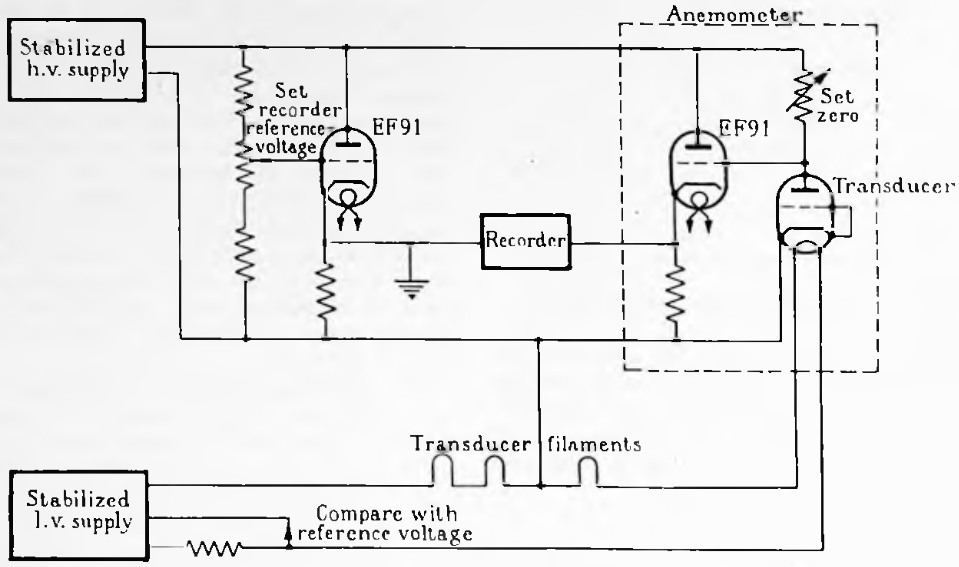

Fig. 10.—Modification of the anemometer recording-circuit.

and that the system is slightly under-damped. This prototype instrument had a perforated brass sphere, and all the moving parts were considerably heavier than those of the redesigned instrument shown in Fig. 6. No measurements of the response time of the later instrument have yet been made, since it was put into use as quickly as possible to obtain records during the winter of 1949–50. A sample record of the natural wind taken with the later instrument is shown in Fig. 13.

(4.9) Proposed Modifications of the Design

The anemometer shown in Fig. 6 was found to give a different calibration with the wind in different relative directions. The chief reason for this is that the diaphragm, besides its upward movement, also receives a bending motion from the wire. With the wind in certain directions this causes a lateral movement of the transducer operating-arm. The transducer is quite sensitive to such movement, and the calibration is therefore changed. To prevent this effect the lower anchorage of the wire has been redesigned and a light spring strip has been used to steady the tail of the anchorage, as shown in Fig. 8. This also makes it possible to insulate the transducer and operating arm, as mentioned before.

A minor cause of the asymmetrical calibration is that the air vent in the side of the anemometer communicates the local pressure to the top of the diaphragm. When the vent is to windward, this local pressure is higher than that below the diaphragm, while when it is to leeward the pressure is lower. To avoid this difficulty the vent will be connected by a small tube to the cavity in the base of the anemometer, and this in turn will be provided with a small orifice in the centre of the base-

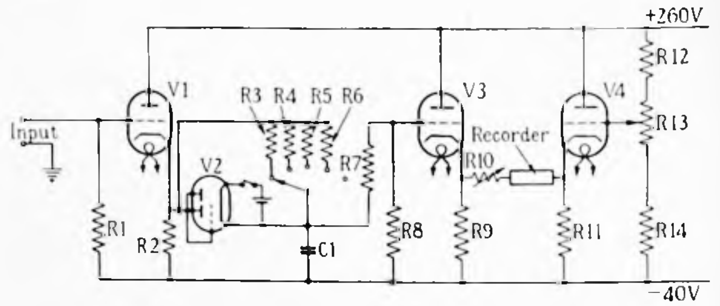

Fig. 11.—Circuit to allow the peak wind-speed during gusts to be recorded.

R1 ..	0·5 MΩ	R5 ..	1 MΩ	R9 ..	10 kΩ	R13	10 kΩ	V1 ..	EF91
R2 ..	10 kΩ	R6 ..	5 MΩ	R10 ..	10 kΩ	R14 ..	8 kΩ	V2 ..	DAC32
R3 ..	100 kΩ	R7 ..	100 Ω	R11 ..	10 kΩ			V3 ..	EF37
R4 ..	300 kΩ	R8 ..	50 MΩ	R12 ..	100 kΩ	C1 ..	10 μF	V4 ..	EF37

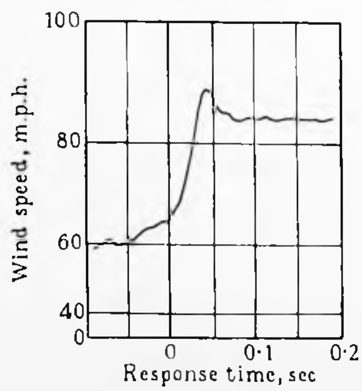

Fig. 12.—Section of chart to show the response of the new prototype anemometer.

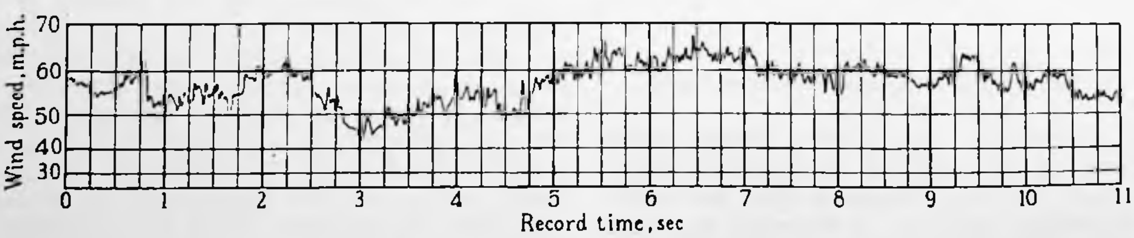

Fig. 13.—Record of the natural wind.

This record was obtained on Costa Hill in the Orkney Islands at 1203 hours on the 4th March, 1950. The mean wind-speed was about 60 m.p.h. from west south west, and the gusts were of moderate intensity.

plate. Thus the pressures on each side of the diaphragm will be kept equal, and changes of atmospheric pressure still will not be applied across the rubber sealing-diaphragm.

(5) ANEMOMETER FOR ANALYSING WIND COMPONENTS IN TWO HORIZONTAL DIRECTIONS

In addition to the information about wind speed in the horizontal plane which is provided by the anemometer described above, certain other details of the wind behaviour during gusts are required for the purposes of the wind survey. It is a matter of common observation that the wind direction, as indicated by a wind-vane, can change very rapidly under gusty conditions. This may affect the blades of a windmill, since a change in direction of the relative wind alters the force upon an element of the blade.

A modified form of the anemometer has therefore been built for indicating the components of the wind velocity in two horizontal directions at right angles. A skeleton diagram of the mechanical arrangements is given in Fig. 14. The same sphere and pivot arrangements are used as before, but the lantern frame has four pillars instead of three, and from the level of the pivot four wires are taken down to four flat cantilever springs. The movement of two of these (one of each of the opposite pairs) is detected by two transducers, which thus respond to deflections in two directions at right angles. Damping and limiting of the motion are effected by an arm which extends down from the lantern frame into an inner damping pot containing silicone fluid of suitable viscosity.

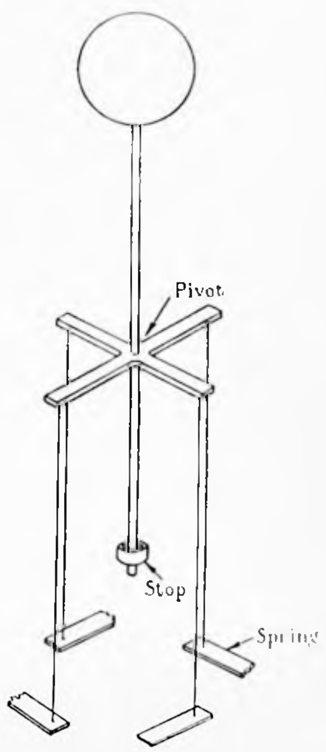

Fig. 14.—Diagram to show the principle of the anemometer for resolving the wind velocity in two horizontal directions at right angles.

The output of the transducers does not correspond directly to the two components of the velocity, since it is the force on the sphere which is resolved, and this depends on the square of the wind speed. Thus, the indications are proportional to $\sqrt{(V^2 \cos\phi \cos\theta)}$ and $\sqrt{(V^2 \cos\phi \sin\theta)}$, where θ is the angle of the horizontal component of the wind to one of the lines joining opposite pairs of wires in the anemometer. As with the previous anemometer, the interference of the arm and the anemometer body will affect the indication when the wind is not horizontal, and, as before, it is expected that the anemometer will indicate $V\cos\phi\sqrt{(\cos\theta)}$ and $V\cos\phi\sqrt{(\sin\theta)}$ (very nearly) when ϕ is less than 20°. A simple nomogram can therefore be used to convert the pairs of readings to pairs of horizontal wind components.

Since the controlling force is directly proportional to the deflection of the sphere, the calibration curve will be a parabola, and the time of response to gusts will be independent of the mean wind-speed.

(6) ANEMOMETER FOR MEASURING THE VERTICAL WIND-COMPONENT

To complete the analysis of wind behaviour during gusts, the vertical component of the velocity is required. Fig. 15 shows the skeleton arrangement of an anemometer which has been designed and built to give this information.

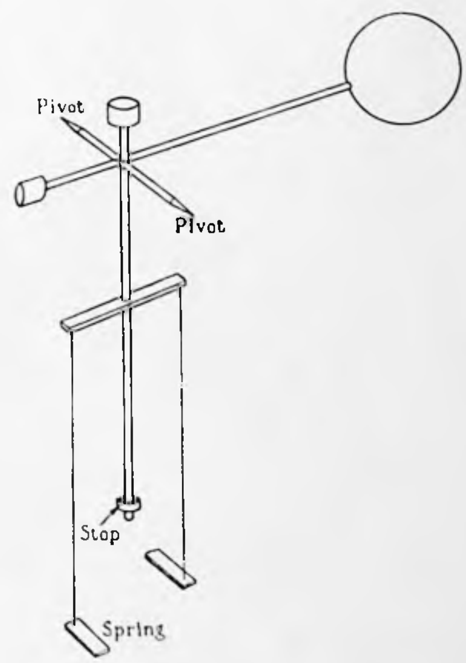

Fig. 15.—Diagram to show the principle of the anemometer for obtaining the vertical component of the wind.

The arm carrying the sphere is horizontal, and is carried on a shaft supported at each end by ball bearings. Thus the sphere can move only in the vertical plane. The moving parts are counterbalanced so that they are unaffected by forces due to gravity or to acceleration in any direction. Two wires connect the shaft assembly to two cantilever springs, one of which is provided with a transducer. Upward and downward movements of the sphere thus cause changes in opposite sense in the output voltage.

The anemometer is intended to be used with the arm perpendicular to the wind direction, but no arrangements have been made to secure this, as the tower on which it will be mounted is (for other reasons) designed to turn and follow the wind. Small changes in the angle between the arm and the wind are not expected to produce any appreciable error in the anemometer reading.

The calibration curve of this anemometer will be intermediate between a parabola and the curve obtained with the original type. The indication is again not directly proportional to the vertical component, and the horizontal component of the wind velocity must be known before the vertical component can be found. It is intended to mount one of these anemometers close to one of the type described in Section 5, so that all three components of the wind velocity may be found at a single point.

(7) ACKNOWLEDGMENTS

The authors wish to express their acknowledgments to the Director of the Meteorological Office for permission to view a photographic recorder developed by members of his staff, to Mr. L. F. G. Simmons of the National Physical Laboratory for his advice and assistance with the aerodynamical problems encountered in the design of the gust anemometer, to Messrs. Evershed and Vignoles, Ltd., for assistance with the problem of recording and to the Director of the British Electrical and Allied Industries Research Association for permission to publish the paper.

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Acknowledgement 3.11.51.

BRITISH ELECTRICITY AUTHORITY

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"BEEYAY, WESDO, LONDON"

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(Nr. Oxford Circus),
LONDON, W.1.

CMO
To see and file.
MC 12/11

Our Ref: C/RA/WTJA.
Your Ref: None.

30th October, 1951.

R. Stewart Slessor, Esq.,
83, Church Road,
Tredegar,
Mon.

Dear Sir,

Replying to your letter of 26th October it is correct that a considerable amount of investigational work has been done in Britain in the past few years on the subject of generation of electricity by wind power. There is not, however, so far as I am aware, any single book or similar source of information which summarises the results of this work.

Very briefly the investigations have been under two headings:-

(a) The survey of sites exposed to strong winds by the British Electrical and Allied Industries Research Association. In these tests the characteristics of the wind at a number of carefully chosen positions, mostly on the western side of the country, have been measured and recorded by suitable transportable instruments. The number of stations so explored is now fairly large and the object has in all cases been to discover the suitability of local conditions for the establishment of wind power stations of useful magnitude.

(b) The establishment of more or less permanent experimental generating stations. The first of these is at Costa Head, Orkney Islands, where a 100 kW plant has been installed by the North of Scotland Board. This machine is of a conventional propeller driven type. The second equipment will be installed by the British Electricity Authority at Mynydd Anelog, Caernarvonshire. This will also be of 100 kW capacity but of a novel design of French origin. The station is expected to be running in late 1952 or more probably/

probably early 1953.

I suggest that if this matter is of serious interest to you you might obtain further information from the Electrical Research Association, but you will no doubt recognise that it is not part of the Association's functions to provide public information services.

Yours faithfully,

Chief Engineer.

FG.

14

6

H.C.S.,

I have given more thought to the report at 2 and have discussed with S.P.H, who tells me that the unit cost of electricity is, at present, of the order of 8d and only one third of this represents fuel (the wind generating scheme is, in effect, a fuel saver). He hopes. of course, that the unit cost will come down with increased use of electricity (only about one seventh of the output is taken up at the moment) but, on the face of it, the capital cost of the wind generating equipment and the sinking fund which would be necessary to cover replacements, would be likely to consume any savings in fuel.

However, H.E. has emphasised that this project is a long-term one and there appears to be justification for going ahead with a wind survey which, I think, could be done at very small cost to the Colony.

This is sis of ... and interest.

S.P.H. is making a rough estimate of the cost per mile of power lines and switching gear which would be necessary to utilise the wind power and is providing me with graphs showing the diurnal and annual variation of the electrical load so that the nature of the wind survey required, can be decided on. Sappers' Hill is an obvious site, with a height above M.S.L. of 450 feet only 1 mile from the Power Station. Mount William is nearly twice as high but it is three miles from the Power House and is less accessible than Sappers' Hill. It may also be slightly sheltered from North West winds by Tumbledown Mountain and lacks the smooth contours of Sappers' Hill.

Met. Office observations indicate a mean wind speed approaching 18 m.p.h. with winds exceeding 15 m.p.h. for nearly 60% of the time. This suggests that Sappers' Hill site would produce a mean wind of the order of 22-24 m.p.h., with winds over 15 m.p.h. for about 75% of the time. As a start, I suggest that Sappers' Hill is "surveyed" and Mount William is kept in mind, in case Sappers' Hill does not produce enough wind. ✓

The "Integrator" recording anemometers used by the B.E.A. are not entirely suitable for meteorological purposes, because they do not record gusts, but the recording cup-generator anemometer to be used at Deception this year would appear to be entirely suitable for a wind survey and might well be bought by FIDS for subsequent use in the Dependencies. ✓ I think that we could get all the necessary information from the records of a cup generator anemometer and spot readings from two cup counter anemometers. The latter can probably be borrowed from Air Ministry, but the former cost about £100 each and take up to 18 months to obtain. Also, it would be very desirable to have two, since the instrument is in the nature of a prototype and a break-down could only mean a further 18 months delay.

I should, of course ask Air Ministry and ERA (through Mr Pickworth of Preece Cardew?) to confirm that these instrments would be adequate but, assuming that they concur, would H.E. agree to obtaining two cup-generator recorders (about £200) and two cup counter anemometers (probably on loan from Air Ministry, but costing only about £20 each)? I suggest that FIDS might buy the equipment and Colony either rent it or pay for any depreciation while the wind survey is being made. If approved, provision could be made in the FIDS estimates which will be drafted shortly.

C.H.
20.3.52

H.E.
P 14 submitted. This seems a worth while proposition, as FIDS can use the equipment subsequently in the Dependencies.
20/3

15

CS.
CMO

I have little doubt that we can give useful assistance in this experiment and as little doubt that it would meet with S of S' approval.

2. I have delegated the job to CMO and the Met. Service is part of the FIDS organisation. They will be able to employ the proposed equipment (if the authorities agree as to its suitability) in the field later and I have thus no objection to it being obtained from D'cies account.

2. We might now follow up p 8 and let Mr. Pickworth know that we are prepared to assist quite irrespective of whether we are able to ultimately install such wind-generating machinery b.f. it is still very much in the experimental stage, I take it.

X

MC 20/iii

CMO. Could you please put up a draft as in X/ & KIV for Dependencies Estimates.

21

H.C.S.
Draft (in so far as meteorological aspects are concerned) at back cover. HE may wish to include mention of the facts, put up by S.P.H., about initial & replacement costs? Also, perhaps, a "sound" Mr. Golding as to what will happen to the experimental equipment in Orkney & Wales when the experimental period is over?

2. Have noted for comp estimates.

G.B. 25.3.52

16

S P/H Pages 8 – 15

These pp. dont seem to have gone to you..
Have you anything to add?

31/3

HS: No Sir. I have a copy of the Technical Report and will keep in touch with CMO.

SBS. 2-4-52.

YE: Page (15)

Draft to Sir Pickworth S/C at cover. I do not think we need go into details of initial cost + replacement costs at this stage.

Admirable: thank you 2/4

IX/IV.

ACS. Draft to issue.

19/4

17.

GOVERNMENT HOUSE,
STANLEY, FALKLAND ISLANDS.
21st April, 1952.

Dear Pickworth,

8. Very many thanks for your letter CHP/ of 7th September, 1951, and for the most useful information contained therein.

My Chief Meteorological Officer is testing some remote recording wind equipment (obtained from the British Meteorological Office for experimental use in the Antarctic) which, he thinks, should be entirely suitable for making a wind survey. The detecting element of the wind speed recorder is a Short and Mason 3-cup generator anemometer of the type used in the Orkney Wind Survey, working in conjunction with an EVERSHED and VIGNOLES recording voltmeter. A specimen record is attached and I should be glad to know from Mr. Golding if this can be interpreted satisfactorily in terms of electricity generation. A cup counter anemometer to give the run of wind would be installed with the cup generator, both instruments being exposed at a standard height of 10 metres.

I would prefer to see the Meteorological Office equipment used for the wind survey (unless of course it is unsuitable) rather than the apparatus described in the E.R.A. reports, because the former can be put to normal meteorological use afterwards. The site which I propose to have surveyed first is a smooth-contoured hill 450 feet above M.S.L. and 350 feet higher than the surrounding terrain, lying within one mile of the power-house. There seems good prospects that it will yield a suitable site, since mean wind speed at the meteorological office (16? feet above M.S.L.) is 18 m.p.h. and winds exceeding 15 m.p.h. are experienced for 60% of the time.

Whether or not it is ultimately possible to instal unit generating machinery here, I am anxious to give all the help I can to assist in experiments.

Yours sincerely,

(Sgd) Miles Clifford.

Reply at 20.

C.W. Pickworth, Esq.,
Preece Cardew & Rider,
8 & 10 Queen Anne's Gate,
WESTMINSTER, S.W.1.

10/9/52
15/7/52
B.U.
30/5/52

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AIR MAIL

5th August, 1952.

OUR REFERENCE CHP/FKI

YOUR REFERENCE

Sir Geoffrey Miles Clifford,
K.B.E., C.M.G., E.D.
Governor and Commander-in-Chief,
Government House,
Stanley,
Falkland Islands.

Dear Sir Miles,

Wind Power Generation

P.20.

Further to my letter of the 7th June 1952 I enclose

---19 herewith a copy of the Association's Technical Report C/T108 on The Selection and Characteristics of Wind-Power Sites.

Yours sincerely,

C. H. Pickworth

Enclosure

CMO

METEOROLOGICAL FALKLAND ISLANDS OFFICE 8 SEP 1952

Returned by CMO 10/9/52

BV. 10/12/52

CdS

U.D.C. 621.311.24

THE ELECTRICAL RESEARCH ASSOCIATION

The Selection and Characteristics of Wind-Power Sites

by E. W. GOLDING, M.Sc.Tech., M.I.E.E., and A. H. STODHART

TECHNICAL REPORT C/T108
1952

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THE SELECTION AND CHARACTERISTICS OF WIND-POWER SITES

PREFACE

During the past three years a wind survey covering certain of the Orkney, Hebridean and Channel Islands, North and North-West Ireland and the western coastal districts of Great Britain has been in progress.

This report describes the methods used and results obtained and emphasizes the importance of such a survey, both for the selection of wind-power sites and for the part it plays in the study of aerogeneration as a whole. It may serve as a guide to organizations in other countries wishing to carry out investigations of a similar nature.

THE SELECTION AND CHARACTERISTICS OF WIND-POWER SITES

CONTENTS

THE SELECTION AND CHARACTERISTICS OF WIND-POWER SITES

SUMMARY

The report deals with the development, throughout its various stages, of a wind survey covering areas of the British Isles most likely to contain sites suitable for large-scale generation of electricity by wind-power. The methods by which these sites have been selected and the survey carried out, are described in some detail.

The results of the measurements are analysed and a comparison of wind flow at the sites is made. Estimates of the wind energy available and of the proportion of this which may be usable by an aerogenerator are given. Certain effects which may lead to discrepancies between estimated and actual outputs are considered.

A relationship, applicable to the British Isles, is obtained between annual mean wind speed and specific output.

(1) INTRODUCTION

The problem of the economic use of wind power for the large-scale generation of electricity divides itself into two main parts—(i) that of finding sites with sufficiently favourable wind characteristics, and (ii) the design and construction, at a low enough cost, of plant to give a good performance when erected on those sites.

The second part of the problem is complex, involving aerodynamic, mechanical, structural and electrical studies, which must take a considerable time to complete and which may lead to several different solutions if undertaken by independent groups of investigators. The selection of sites and the investigation of wind behaviour also have their difficulties but are, on the whole, more straightforward jobs with a rather clearer aim and a more restricted range in the methods to be followed. There are, moreover, sound reasons for tackling this part of the problem concurrently with, or even before, the attack on the second part : first, because unless it can be proved that an ample number of reasonably favourable sites exists it is pointless to consider the construction of wind-driven plant ; secondly, because the results obtained will certainly have a direct bearing on both the design and cost of such plant.

There is little, if any, doubt that any one of a dozen or more different types of aerogenerator, all technically satisfactory, could be developed to generate electrical energy. But the refinements of design needed to ensure economic success in generation on a large scale can be made only when adequate information on wind régime and wind behaviour is available. At the outset of the E.R.A. work on the subject this information was found to be lacking, at least in so far as it applied to sites likely to be suitable for the purpose in mind. The methods used to obtain it and the relationship of such studies to the other researches forming the concerted investigation of wind-power possibilities have been described in earlier reports.[1, 2]

The purpose of this report is to explain the matter more fully, to give an account of the results so far obtained and to interpret these results in such a way that they throw some light on the design requirements and probable performance of wind-driven generators which may be built to operate under the wind conditions to which they refer.

(2) THE REQUIREMENTS AND CHOICE OF SITES

In the earlier reports attempts were made to define the requirements of sites which would be satisfactory as locations for wind-driven generators. Although, in the main, the statements already made hold true, growing experience from an extensive wind survey points to the need for slight modifications.

Above all the site must, obviously, be windy ; expressing this more precisely, it must have an annual wind velocity duration curve of the right shape and area. It is now becoming clear that, at least for the similarly shaped hills in western coastal districts which have been studied, the duration curves are sufficiently alike in general form for the annual average wind speed to be accepted as a criterion. This is discussed more fully in Section 6.1.2, but it can be stated here that, taking into account generating costs in Great Britain and also the probable costs of construction of wind-driven generators, a site in this country should have an annual average wind speed of between 20 and 25 m.p.h. if its use is to be potentially economic.

It is necessary to emphasize that the actual constructional cost for wind-driven plant is still a matter of some uncertainty, an uncertainty which must remain until practical results, under actual operating conditions, are obtained following the considerable amount of research and development work on pilot plants and prototypes which is in progress. From the limited experience gained there appears to be no need at present, however, for drastic revision of the estimate of from £50 to £100 per kilowatt as the cost which might be achieved. If it were to prove possible eventually to build windmill plant at a lower cost or if, on the other hand, the fuel component of generating costs in steam power stations were to rise, then sites with even lower annual average wind speeds than 20 m.p.h. would be brought into the economic range.

A fairly steep, smoothly shaped hill clearly gives good results when it is well exposed, is free from screening by higher ground within a distance of 3 to 4 miles and particularly when it is near the coast. In the survey carried out so far the choice has usually fallen on hills with a maximum slope not exceeding about 1 in 3 and not further inland than 2 to 3 miles. Isolated hills or ridges have also been preferred to long ranges or mountain masses. Recently, however, to widen experience a few measuring installations have been made on sites of different shapes and rather further inland.

The high wind speeds at the summits of many of the hills chosen appear to confirm that steep, yet smooth, slopes accelerate the wind over the summit, and some evidence is accumulating that even steeper slopes might be used with advantage, provided the change of slope at the top is not so abrupt as to produce break-away of the wind with turbulent effects. Thus, while some very good results are being obtained the optimum shape of hill has not yet been determined. It may be that too much emphasis was placed, in the early stages of the survey, upon the advantage of a ridge, athwart the prevailing wind direction, as compared with an isolated hill of approximately conical shape. Some of the best results are being obtained on the latter, possibly because even the " prevailing " wind direction is not maintained for a long enough period in the year for the accelerating effect of a ridge across it to counterbalance the lack of acceleration with other wind directions. Thus, again, further experience must be gained before it will be possible to make any precise recommendation on the best general form of hill or relative dimensions of ridge.

Very windy hill sites are fortunately almost always devoid of trees, presumably because the wind conditions are too severe for the growth of anything higher than low scrub or heather. It is, indeed, noticeable that on a good hill even the heather or grass is clipped very short—seldom higher than 6 to 12 inches—which in itself acts as a rough guide to the probable suitability of the hill for wind power.

Occasionally it happens that on an otherwise suitably shaped hill there are precipitous outcrops of rock on the slopes. The precise effects of these have not been determined but it is reasonable to suppose that they will disturb the smooth flow of air over the hill so that the site for a generator or, at this stage of the investigations, for the measuring apparatus, should be as far away from such outcrops as possible.

The tops of some good hills are fairly flat and could probably accommodate several wind-driven generators, but the importance of space on the hill-top cannot yet be assessed accurately, for two reasons. First, the optimum size of such plant is not yet known and, secondly, there remains uncertainty about the spacing needed to avoid interference between adjacent wind rotors. Tentatively a horizontal spacing of 8 to 10 times the diameter of the wind rotor is being accepted as the minimum required, but investigation of this point appears to be necessary and will be undertaken.

The access to a site is a matter of importance since it has an appreciable effect upon the costs of erection ; a usable road or track with a solid foundation running close to the summit will always be a very favourable factor. The nature of the ground at the summit should also be taken into account as affecting the costs of plant foundations.

If separate generating units of only a few hundred kilowatts are in prospect the distances of their sites from the supply network must be considered carefully to avoid the possibility of connection costs forming an undue proportion of the total. If much larger units, or groups having a high total capacity, prove feasible the costs of connecting lines are, of course, less likely to be an embarrassment.

The possibilities of trouble from icing or from salt spray must also be taken into account. On the western seaboard of Great Britain icing may not present a difficult problem. So far failure of wind-measuring equipment has been attributed to icing only in one instance and that at an altitude of over 2,000 ft. Nevertheless, the possibility of trouble from this cause, as also from spray, cannot be ruled out until experience has been gained with wind-driven plant in operation.

(3) METHODS OF SELECTING POSSIBLE SITES

Wind being a natural phenomenon with which everyone is bound to come into contact without having any simple means of judging its precise intensity or constancy, it is perhaps inevitable that its characteristics should, like those of the weather, be subject to much exaggeration. No matter with which parts of the country we happen to be familiar we all imagine that we could, if the problem were put to us, select an ideal site for a windmill. But, in the main, one's experiences must be purely relative ; it is almost impossible to judge absolute values from casual observations under greatly varying conditions. Thus, while such experiences cannot be entirely discounted, it is clearly necessary to select such sites systematically, and the means of doing this are outlined below.

(3.1) Meteorological Records

The most obvious step to be taken at the outset is to examine long-term records of wind speeds made by the Meteorological Office. In this country we are fortunate in that the records for Great Britain and Ireland are fairly complete. Wind speeds at meteorological stations widely scattered over the country at such sites as aerodromes, farm institutes and coastguard stations have been measured continuously for many years, so that there is little difficulty in obtaining a general picture of the relative windiness of different districts. The records have been used by the Meteorological Office in the preparation of isovent maps which were included in an earlier E.R.A. Report W/T16.

These isovent maps, which are based on records obtained at 33 ft. above level open country, have been used as a guide in making the wind survey discussed later in this present report, the results of which have confirmed the information provided by them. In the windiest parts of the British Isles the annual mean wind speed at 33 ft. above ground is 17·5 m.p.h. ; at an altitude of 200 ft. in such districts this mean speed might well exceed 24 m.p.h. But the average annual wind speeds indicated by the isovents are, naturally, applicable only to the whole districts through which they run. Clearly they cannot, and should not, refer to the most windy places in those districts where the average wind speeds may exceed that for the surrounding country by as much as 50 or more per cent. The second stage in the selection of favourable sites is thus an inspection of the topography of the district.

(3.2) Study of Maps

It has been found advisable to choose for further consideration sites in a coastal area of, for example, 50 miles along the coast by 10 miles inland, by the use in the first place of a ½ inch to the mile map on which the high ground is coloured. Possible sites can thus be picked out very quickly. Following this the contours of the hills are studied from a 1 inch to the mile ordnance survey map. Usually hills which have precipitous faces, or which are screened from the direction of the prevailing wind or which, again, are indicated as being tree-covered or as having outcrops of rock are ruled out as probably unsuitable. The surroundings of the hills and their accessibility are, of course, also taken into account very carefully and isolated conical hills surrounded by flat ground and ridges athwart the prevailing wind are specially sought after.

(3.3) Inspection of Sites

However carefully selection is made from maps there is much to be gained by actual inspection of the site. Even a 1 inch to the mile map does not show the shape of the summit in sufficient detail to allow a judgment of the behaviour of the wind over it to be made. Larger scale maps such as 6 inches, or even 25 inches to the mile are obtainable for most districts but frequently these are not available for the remote hills which may be chosen. Again, these maps either do not show the contours at all or do so with too large intervals of height between them.

Inspection *at the summit of the hill* is very desirable. A misleading impression may be gained from the lower slopes ; ravines or rocky outcrops near the summit are not easily visible. Although it should be possible to judge the screening effect of surrounding hills solely from reference to maps giving their heights and distances it is certainly more convincing to make a decision on the spot. Another advantage of making the climb to the summit is that, if the approach is made from the windward side, one can, with practice, form a fairly accurate opinion about the gain in wind speed which the hill may give by noting the difference between the wind at the top and that prevailing on the surrounding low ground. With sufficient experience, indeed, a close approximation to the annual average wind speed can be made from such an inspection combined with long-term wind-speed data for the surrounding district.

Surveys made up to the present have usually covered coastal strips of between 50 and 100 miles in length and, in each case, from 6 to 10 hills have been chosen from a careful preliminary examination of relevant maps. It is interesting to note that in almost every case at least one of the chosen hills has been discarded after inspection on the site and has been replaced by an obviously better one which did not appear so attractive from the map.

It is important, also, to examine both the nature of the ground at the summit of the hill and the possibilities, in the shape of rough roads, or tracks, for transporting heavy equipment.

(3.4) The Technique of Site Selection : Laboratory Tests

While it is true that hill-top sites with high wind speeds can be chosen by the methods indicated in preceding paragraphs, these methods are based on simple assumptions regarding wind flow over hills which, though probably justifiable, are not sufficiently precise to ensure that the best possible positions for wind-driven plant will be chosen. Common sense and a certain amount of intuition at present form the basis of choice rather than a full knowledge of wind behaviour.

To obtain such knowledge and so to improve the technique of site selection, experimental studies in the laboratory can be made. These could take the form of wind-tunnel tests on models of hills of different shapes, but there is such a great difference in scale between the model and the hill that viscous effects in the air in the tunnel are likely to have a much more important effect than in practice. In the open air, molecular viscosity is probably negligible in effect and eddy viscosity, which will not be apparent from the tunnel tests, may be more important.

Instead of using a wind tunnel, which has the additional disadvantage of being costly, tests are being made on models, constructed in non-conducting material, placed in a tank containing an electrolyte. Alternating current is passed between two metal plates, on opposite sides of the tank, through water which well covers the model. The potential gradient in the water at different points over the model is measured. The gradient is proportional to the current density in the water and this, in turn, is analogous to wind velocity ; the equations for current flow in the tank and for air flow are the same if viscosity is neglected and if the air flowing over the hill is regarded as incompressible. These assumptions, together with the fact that no provision can be made to represent the increase of wind velocity with altitude, introduce errors which may be appreciable, but their order can be determined by comparison with the measured wind flow in particular cases and the method, which will be fully described in a later report, shows promise of giving information leading to improvements in the technique of site selection.

(4) DETERMINATION OF THE RELATIVE SUITABILITY OF SITES

It is clearly necessary, at the outset of a wind-velocity survey aimed at selecting suitable sites for wind-driven generators, to decide what is to be regarded as "suitable". Features affecting the costs of installation and connection to the network such as proximity to main roads and rail transport, the nature of the approach to the hilltop and the distance from load centres have already been mentioned and are, indeed, such obvious considerations that they require no further discussion. Measurements of wind velocity are made to enable an estimate to be formed of the probable annual output of energy from a generator designed to have certain fixed limits of operation. These limits have been chosen as follows :—

Cut-in point, i.e. wind velocity at which the generator begins to supply power to the network .. 17 m.p.h.
Rated wind velocity, i.e. velocity at which full rated output is given .. .. 30 m.p.h.
Furling velocity, i.e. wind velocity at which the plant is shut down to avoid damage .. .. 60 m.p.h.

It is also assumed that full output will be obtained for all wind speeds between 30 and 60 m.p.h.

Based on estimates of economic operation given in report Ref. C/T101 the classification of Table 1 can be made. The figures for specific output are obtained from the power duration curve for the site (derived from the velocity duration curve by cubing the velocities) after application of the operating limits just stated. (Values of specific output so obtained do not take into account variation of the efficiency of the plant when operating between cut-in and full output ; for this and other reasons discussed in Section 7, such estimates will be slightly erroneous but they are sufficiently accurate for classification purposes.)

Table 1

Specific output (kWh per annum per kW of installed capacity)	Classification	Designation
Above 4,500	Excellent	A
4,000 to 4,500	Very Good	B
3,500 to 4,000	Good	C
3,000 to 3,500	Fair	D
Below 3,000	Economic only when alternative generating costs are high.	E

It is to be understood that this classification applies, in the main, to operating conditions on the mainland of Great Britain with wind generators connected to a supply network and being in competition with steam-generated energy having a fuel component of generating cost around 0·4d/kWh. At the present stage of development, construction costs for wind-driven plant cannot be predicted accurately, but if a cost as low as £50 per kilowatt is found to be attainable the cost of wind-generated energy at a B class site will be about 0·25d/kWh. This figure will, of course, vary in almost exact proportion to the actual cost of construction. Table 2 shows the effect of specific output upon generating cost for three constructional costs and for capital charges at 8 and 10 per cent. per annum.

Table 2

Specific output (kWh/p.a./kW)	Generating costs at 8% p.a. capital charges and constructional costs of			Generating costs at 10% p.a. capital charges and constructional costs of		
	£50/kW	£75/kW	£100/kW	£50/kW	£75/kW	£100/kW
	d/kWh	d/kWh	d/kWh	d/kWh	d/kWh	d/kWh
4,750	0·20	0·30	0·40	0·25	0·375	0·50
4,500	0·213	0·32	0·426	0·266	0·399	0·532
4,250	0·225	0·337	0·45	0·281	0·422	0·562
4,000	0·24	0·36	0·48	0·30	0·45	0·60
3,750	0·256	0·384	0·512	0·32	0·48	0·64
3,500	0·274	0·411	0·548	0·342	0·513	0·684
3,250	0·295	0·442	0·59	0·369	0·553	0·738
3,000	0·32	0·48	0·64	0·40	0·60	0·80

For a generating cost not exceeding 0·4d/kWh the operating conditions must be those represented by figures above the heavy line.

(4.1) Preliminary Stage

The basis upon which the value of a potential wind-power site is judged is the annual velocity duration curve, i.e. the curve showing the number of hours in the year during which the wind speed is equal to or greater than any given value. In the preliminary investigation of a particular district this curve is plotted from measurements of hourly average wind speeds for heights of 10, 15 or 30 feet above the summits of the hills. The results are linked with the long-term wind régimes for the sites by simultaneous measurements at the nearest Meteorological Office station for which long-term records are available. By comparison it is possible to correct for any abnormality in the yearly average wind speed for the district surrounding the site.

The best sites in the district can usually be selected after about 12 months' duration of the preliminary stage measurements. After only 3 or 4 months it may be possible to eliminate some of the sites for which the results are well below those for the rest.

(4.2) Second Stage

This stage is concerned with fuller investigation of the wind régimes at the best sites. It consists of measurements of wind speed and direction at different heights above ground on the summit of the hill. As the information obtained should be made available to the designer of a wind generator which may be installed there it is desirable to make measurements up to heights corresponding to at least that of the hub of the machine.

Measurements of this kind are obviously more costly than those made in the preliminary stage but they are only necessary on selected hills on which there is some prospect of generating plant being built.

Details of the methods adopted and instruments used in both of the above survey stages are described in Section 5.

(5) WIND VELOCITY SURVEY

The survey now being made in Great Britain and Ireland has been undertaken because it obviously constitutes the first step towards any reasonably accurate estimation of wind-power potentialities in these islands, although the expressed interest of the electricity generating authorities concerned has led to its being rather more detailed than would be necessary for a general assessment.

The numbers of sites which have so far been covered by the preliminary stage survey are :—

Channel Islands	2
Eire	6
England	7
Northern Ireland	10
Scotland	15
Wales	10

On three of these sites second-stage measurements have been made, and on one a more advanced stage, including very comprehensive measurements to determine the behaviour of the wind in detail, has been reached.

It may be mentioned here, also, that close touch has been maintained with Électricité de France, whose research department has been carrying out a general wind-power survey for the past 4 to 5 years. The French results have been related to those obtained in this country, and measuring instruments have been exchanged in order to compare the two different methods of measurements employed.

It is clear that wind profile will be different for hills of varied shapes and for winds of different speeds and directions. It is difficult to generalize on theoretical grounds and actual observations are therefore essential.

(5.1) Methods Adopted

On first consideration it would appear to be a formidable task to determine the wind régimes on a sufficient number of hills, scattered over the whole of Great Britain, to enable the wind-power potentialities to be predicted with a useful degree of accuracy. A considerable amount of effort is certainly entailed, but the staff and financial provisions which could be made available for what is only a part—though an important one—of the wind-power investigations led, perforce, to the adoption of simplified methods. These will be described since in some respects they are unique and their description may assist others contemplating a similar undertaking.

The first measurements were made in July 1948 in the Orkney Islands primarily because the North of Scotland Hydro-Electric Board were interested in the possibilities of using the high winds —which are known to occur frequently there—as an auxiliary source of energy for the island network. Meteorological Office records showed that their observation stations down almost the whole of the west coasts of Scotland, Ireland, Wales and Cornwall had the highest annual average wind speeds in the British Isles, and it was thus planned to cover these districts when opportunities arose provided that the results of the Orkney measurements were sufficiently encouraging—as, in fact, they were.

In the earlier days of the survey a group of perhaps 8 or 10 hills, only a few miles apart, were chosen from maps and, after inspection, the best 5 or 6 of these were selected. After obtaining the permission of the owners of the hills (who, incidentally, were not always easy to locate probably because of the remote character and low value of the land concerned), instruments such as described in the following Sub-section 5.2.1 were erected on their summits. Arrangements for local observers to send back the records for analysis and inter-comparison were made at the same time. The aim, at this stage, was to find the best hill in each district and to compare their wind régimes so that recommendations could be made for the location of pilot plants of about 100-kW capacity.

Later, when a sufficient number of good sites had been found for any pilot plants which were likely to be built, and in the light of experience gained, the survey took on a rather changed character. It is now being made more extensive to obtain information on the variations of wind régimes on favourably shaped and exposed hills of different altitudes lying 20 to 50 miles apart, though still reasonably accessible and potentially useful for electricity supply purposes.

It is the intention to base on the results obtained an estimate of the total wind-power capacity which might conceivably be installed throughout the country if the technical and economic problems of construction and utilization are satisfactorily overcome.

(5.2) Installations

The installations made on the hills may be described under the two headings of "Instruments" and "Associated Equipment".

(5.2.1) Instruments.

The instruments used in the survey are :—

(*a*) Cup-counter anemometers reading run of wind, in miles, up to a total of 10,000 miles before repetition or, when modified, up to 100,000 miles.

(*b*) Cup-contact anemometers which close an electrical contact for each $\frac{1}{20}$ mile of wind flowing past the instrument.
(*c*) Recorders of either the photographic or moving-chart type for use with the cup-contact instruments. The photographic recorder records the miles of wind half-hourly, while the chart type gives a record of the time taken for each successive two miles of wind to pass the anemometer.
(*d*) Wind-direction indicators (second stage survey only).

Both types of anemometer used and the wind-direction indicators are of the standard pattern used by the Meteorological Office. The recorders have been developed for this particular purpose by E.R.A. and have already been described fully.[2, 3]

In the first preliminary-stage surveys, only cup-counter instruments, mounted on 10-ft. poles so that they could be read from the ground, were used. The object was to obtain, by means of cheap and easily erected equipment, a quick comparison between hills so that the best could be chosen.

On smooth hill-tops devoid of trees or rocky outcrops it was considered probable that measurements at this low height of 10 ft. would be sufficiently representative for purposes of intercomparison. Experience confirmed this and showed that, provided allowance can be made later for the increase of wind speed with height above ground, the results of such measurements can be accepted as a basis for the estimation of the wind régime at the site.

The original intention was to follow these simple installations by erecting on the selected hills 30-ft. masts carrying cup-contact anemometers run in conjunction with recorders of the moving-chart type located at the foot of the mast. As the work progressed it was found possible to shorten the time required for assessment of a site's potentialities and to save cost by, in effect, combining the two methods. Thus, for a group of hills in a particular district, recorder installations with 15-ft. or 30-ft. masts were made on the two or three sites which were expected to give the best results, and cup-counter instruments on 10-ft. poles were placed on the remainder.

It was soon found possible, by inspection, to pick out the best hills from a group and to place them in order of windiness sufficiently accurately in advance for the recorders to be installed where detailed wind régimes were most worth determining.

Analysis of the recorder results, giving hourly average wind speeds, enables the annual velocity-duration curve to be plotted. At the same time, the total run of wind, in miles, for a given period is obtained merely by adding the readings from successive chart records. Periodic readings (usually weekly) of the cup-counter anemometers provide only total flow—and hence, of course, average wind velocity over the period between any two readings.

Later still it became clear that the velocity-duration curves for sites over a wide range of country were so similar in shape (see 6.1.2) that the annual average wind speed could be accepted as a measure of the wind régime. In other words, the velocity-duration curve could be drawn with fair accuracy for any given value of the mean speed. Hence, in the most recent surveys, cup-counter instruments are used on most of the sites, with one or two widely separated recorders on others to keep a check on the wind régimes.

It is not yet possible to say whether this similarity of shape of the velocity-duration curves applies in other parts of the world as it applies in western coastal districts of Great Britain and Ireland.

Calculations of the frequency distribution in the British Isles of winds of different velocities[4] have been made and have been shown to agree well with measured values and the method adopted could be applied to sites abroad.

The probability is that several main forms of wind régime, each responsible for a particular shape of velocity-duration curve, exist throughout the world. In the British Isles, for example, what might be termed a North Atlantic régime prevails ; this probably extends as far north as Iceland and Northern Norway and south to at least the Brest Peninsula. Again, in Mediterranean countries a different régime, typical of that area, probably exists.

It may well be, too, that similarities occur between these large wind régime areas and that a South Atlantic régime, for example, affecting the more southern parts of South America and the Falkland and South Georgia Islands will be markedly similar to that pertaining to the North Atlantic. It is hoped that, provided sufficient information exists, actual comparisons of this nature will be made in the near future.

If such similarities in régime can be proved from initial trials with recorders giving hourly wind speeds, subsequent more intensive surveys for the purpose of preliminary assessment of site potentialities can be made by using cup-counter instruments to measure annual average speeds with a small number of recorders as a check.

It is perhaps worth mentioning that wind speed and direction at the principal Meteorological Office stations are often measured by Dines anemometers giving continuous chart records.[1] Analysis of these records provides ample data on the wind régime but is rather laborious. Apart from this, such instruments are not generally suited to extensive surveys, both because of their cost and of the work involved in establishing and attending to them. At other stations where meteorological observations are made such as, for example, at aerodromes both in this country and abroad, measurements of wind velocity are made at hourly intervals, or rather less frequently, by means of cup-generator anemometers giving instantaneous speeds. Also, at most lighthouses, estimations of the wind strength, using the Beaufort scale, are made at regular intervals throughout the day. An experienced observer can estimate wind force within the limits of the scale quite accurately. Instantaneous measurements of this kind are certainly useful in giving a general indication of the windiness of a site, but cannot be utilized for the estimation of wind régime in connection with wind-power possibilities.

(5.2.2) **Associated Equipment.**

(i) *Preliminary Stage.* The equipment needed in addition to the instruments themselves is, of course, mainly for their support and protection.

In designing this equipment the following facts should be borne in mind :—

It must be robust and weatherproof to withstand gales up to 100 m.p.h. or even more.

Ease of erection on different sorts of ground is important.

The equipment should be light and easily handled for transport over rough ground.

Simplicity in design is an advantage since maintenance may have to be done by unskilled local observers.

The principal items are :—
(*a*) Poles.
(*b*) Guy wires.
(*c*) Strainers.
(*d*) Stakes.
(*e*) Tools and ancillary gear.
(*f*) Shelters.

The form of construction usually adopted is shown in Fig. 1. Two sets of three guys are used, attached to angle-iron stakes driven into the ground at distances approximately equal to the height of the pole and spaced 120° apart as accurately as possible. The guy wires should be of 7 × 20 gauge galvanized iron wire for the 10-ft. poles and 7 × 15 gauge for the 30-ft. poles. Strainers to take tensions of up to 3 cwt. for a 10-ft. pole and about 10 cwt. for a 30-ft. pole are used, these being initially almost fully extended to allow tightening of the guys as they stretch with time. In soft ground the stakes should be at least 3 ft. long, driven in to almost their entire length. Alternatively the double-picket anchorage system may be used as shown in Fig. 2. On some sites the ground is too rocky to allow of driving to an adequate depth and it may be necessary to resort to laying the stakes horizontally with loose, heavy rocks piled on their ends, taking care that the guy wires do not chafe against the rock. Included in the kit of tools should be a 14-lb. hammer for stake-driving, and an effective pair of wire cutters. Particularly if cattle or sheep run on the hill, care should be taken to bury waste scraps of wire and other litter which might be dangerous to the animals if they picked them up while grazing.

Initially, wooden poles about 2½-in. diameter were used and these were sunk in the ground a few inches with their butt resting on rock or on a flat stone. Later it was found better to use a sectionalized steel, or aluminium, tubular pole with a flat plate at the base and flanges, drilled to take shackles, at the top and middle of the pole. The 30-ft. poles can conveniently have light steps welded to them so that they can be climbed for attention to the instrument. It is sufficient to drill the bottom section of the 10-ft. poles at heights of 1½ ft. and 3 ft. from the ground so that ¾-in. steel bars can be pushed through to act as steps ; this is to facilitate reading the cup-counter instruments in bad weather. The pole sections may be screwed into one another or may be held together by sleeves or bolted flanges at the joints. Alternative forms of construction are shown in Fig. 3.

If recorders are to be located at the summit of the hill they can be housed in strong wooden boxes held down with stakes or rocks or, more conveniently, in metal household coal bunkers turned on their sides ; the lid acts as a shelter when the recorder is being serviced (see Fig. 4).

(ii) *Second Stage*. As already stated in Section 4.2, this stage is normally entered into only when the final selection of a site for an actual aerogenerator installation has been made.

In designing the measurements mast, which should, if possible, be of a height similar to that proposed for the aerogenerator tower, the four considerations specified at the start of Section 5.2.2. should again be borne in mind with, perhaps, additional emphasis on the need for using cup anemometers and recorders designed for wind speeds exceeding 100 m.p.h.

The type of installation adopted (Fig. 5) while not, perhaps, very rigid, has the several advantages of being comparatively light, easy to assemble and erect—even with unskilled labour—and sufficiently strong to withstand several years' use under severe weather conditions.

The mast, which is of 16-gauge galvanized steel, comprises two main cigar-shaped members, coupled to each other by a universal joint and held upright by guy wires. Each cigar is composed of five tapering tubular sections which are joined together by driving one into the other. The derrick for hoisting the mast consists of one cigar-shaped member identical with those used in the mast itself.

The completed assembly is 66 ft. high, the lower cigar being 30 ft. 6 in. and the upper 35 ft. 6 in. long. Originally only eight guys were used, four of which were attached at the top of the mast and four at the centre. This was insufficiently rigid and, under severe gale conditions experienced on one occasion, vibration of the mast, transmitted to the anemometers, resulted in the shearing of the anemometer main shafts and subsequent destruction of the complete cup assemblies. To counteract this effect four extra guys were added at the centre of each cigar member. Steel trays 4 ft. × 2 ft. with long hairpins attached, buried to a depth of 4 ft. 6 in., form the guy anchorages.

At the centre and top of the mast on the latest installation, platforms 6 ft. long are erected on either side (Fig. 5 (*b*)). These are firmly strutted to avoid lateral movement in high winds. If necessary, they may also be guyed to the main anchorages.

Anemometer mountings are provided at the ends of the platforms a foot or so above handrail level. This duplication of instruments is desirable for two reasons : first, it ensures that whatever the wind direction, at least one anemometer at each height will be free from possible interference of the wind flow by the mast and, secondly, that in the event of unserviceability, readings at both heights will continue during the inevitable lapse of time between discovery of the fault and replacement of the instrument. At the top of the mast itself the wind-direction indicator is mounted (Fig. 5 (*c*)).

For climbing purposes, a light angle-iron ladder is attached to the mast. The lower 6 ft. of this is readily detachable and is removed when the installation is complete and in working order. This ensures, to some extent, against the possibility of interference with the equipment.

Before erection the electrical wiring is bound firmly to the mast by means of hose-pipe clips at intervals not greater than 2 ft. A multicore polythene-insulated cable with p.v.c. outer covering has been found most suitable. At the base of the mast a weatherproof junction box is provided from which connection is made to the recording apparatus.

Since this apparatus is necessarily somewhat more complex than in the preliminary survey and since, owing to the number of anemometers in use, large-capacity batteries are required, some accommodation must be provided. This takes the form of a hut—10 ft. × 8 ft. is about the minimum useful size—which may be used as both store and workshop during the assembly and erection period.

(5.2.3) **Erection.**

(i) *Preliminary Stage*. The installation of measuring equipment on hills can be simplified considerably by using a proved technique.

In the first place, when the installations form part of a general survey, choice of an erection team and an assessment of the time required are important. Table 3, based on experience in Great Britain and Ireland, may be used as a fairly accurate guide.

When the height to be climbed from the nearest approach point on the road is 1,000 ft. or more it is usually necessary to locate the recorder—or a counter and battery if only the aggregate run of wind is to be measured—near the base of the hill to facilitate attention weekly by a local observer. This means that a twin cable (field telephone wire will suffice) has to be run down the hill from the anemometer to the recorder, hence the increased time required for installation. The cable may have to be buried for some portions of its run to reduce the possibility of damage by animals.

With high or long climbs an extra man is useful to assist in carrying the equipment. A frame and harness, as used by hikers, has been found to be a most useful piece of gear for transport of heavy loads, by man power, up rough hillsides. The maximum convenient load per man is 50 to 60 lb. for climbs of up to 1,000 ft. For higher climbs 40 lb. per man is sufficient. It is sometimes worth while exceeding these loads to avoid a second climb but the rate of climbing is reduced. Since such installations have frequently to be made in very bad weather, provision for protective clothing must be made in estimating the magnitudes of the loads to be carried.

Incidentally, it is a wise precaution to carry a map and compass on ascents of high hills since clouds, or hill fogs, often descend unexpectedly and cause confusion. An altimeter has also been found useful, particularly in locating the highest point on the hilltop.

(ii) *Second Stage*. It is unlikely that the complete equipment necessary for this stage will be carried manually by the survey party to its site. The use of a tractor and trailer or, in crofting districts where such a machine may not be readily available, some local labour to assist the erection team will almost certainly be necessary (see Fig. 6).

It is also convenient to employ local labour for erecting the hut, excavating the guy anchorage footings and assisting in hoisting the mast.

The survey party itself need not consist of more than three men, who will assemble the mast and platforms, fit the guys and electrical wiring and finally repaint all ungalvanized ironwork, bolts, etc. Given reasonable working conditions this should not take more than about ten days.

For the actual erection, which, in the case of the tubular steel mast, consists of pivoting the completed assembly about its base by means of hoisting tackle attached to the derrick-top, up to 12 men may be needed for perhaps two or three hours. After erection, when the guys have been adjusted and tightened, the instruments may be mounted in their respective positions and connected up and the wind-direction indicator orientated.

Two or three days should then be allowed for completing connections to the recorder, checking the operation of the anemometers and briefing the person who will be responsible for the maintenance of the equipment. Care should be taken to ensure that the newly erected mast is sufficiently far from the existing 10-ft. pole installation to cause no interference of wind flow at the latter.

The charging of batteries often presents a difficult problem and it may be advisable in some cases to instal a small petrol-driven plant for this purpose. The alternative of a small wind-driven plant seems attractive at first, but experience has shown that these are not normally designed to withstand the severe conditions they will undoubtedly encounter at such exposed sites.

Table 3

Height of hill above sea level, feet	Height of climb from nearest approach road, feet	Type of installation	Number of men required	Time to be allowed, days*
500	500	Cup-counter anemometer with 10-ft. pole	2	⅓
		Cup-contact anemometer with 30-ft. pole. Recorder at summit	4 or 5	1
1,000	500	Cup-counter anemometer with 10-ft. pole	2	⅓
		(*a*) Cup-contact anemometer with 30-ft. pole. Recorder at summit	4 or 5	1
		(*b*) Cup-contactor anemometer with 30-ft. pole. Recorder at foot of hill	4 or 5	1½
—	1,000	Cup-counter anemometer with 10-ft. pole	2	½
		As (*a*) above	5	1½
		As (*b*) above	5	2
1,500	500	Cup-counter anemometer with 10-ft. pole	2	⅓
		As (*a*) above	4 or 5	1
		As (*b*) above	4 or 5	1½
—	1,000 to 1,500	Long-term cup-counter with 10-ft. pole	2 or 3	¾
		As (*b*) above	5	2
2,000 and over	1,000	Long-term cup-counter with 10-ft. pole	2	½
		As (*b*) above	5	2
—	1,500 to 2,000	Long-term cup-counter with 10-ft. pole	3	1
		As (*b*) above	6	2

* This does not include time for travel to the base of the hill.

(5.3) Organization

It is usually quite out of the question for E.R.A. staff to visit survey sites, after the installation is complete, except for maintenance purposes when a fault develops. This, fortunately, is infrequent, especially with the cup-counter instruments which, if well lubricated with grease at the outset, will run for an average period of six months without attention. Recorders may require some attention every two or three months. Thus, for readings from the instruments and for weekly changing of the recorder charts, local observers have to be recruited. Some of these are members of the staff of local electricity authorities but much more often they are people living near the hills and willing to assist in obtaining records. It is a surprising fact that little difficulty has been experienced in finding such local observers even in very

Table 4. WIND SURVEY SITES AND RESULTS

No.	Site		Altitude above sea level, feet	Height of instrument above ground, feet	Type of instrument	Date of installation	Duration of observations, months	Estimated long-term annual average wind speed		
	Name	District						Miles per hour	Metres per second	Kilometres per hour
1	Bignold Park	Kirkwall, Orkney	130	35	A	9–7–48	37	14·8	6·6	23·8
2	Costa Hill	Orkney Mainland	500	10	A	10–7–48	37	25·0	11·2	40·2
(3)	Vestra Fiold	Orkney Mainland	430	10	A	11–7–48	7	23·0	10·3	37·0
(4)	Dolgarrog	Caernarvonshire	1,390	30	B	22–3–49	13	17·0	7·6	27·4
(5)	Mynytho Common	Caernarvonshire	600	10	A	29–3–49	21	18·0	8·0	29·0
(6)	Holyhead Mtn.	Anglesey	430	10	A	1–4–49	24	19·0	8·5	30·6
7	Mynydd Mawr	Caernarvonshire	524	30	B	5–4–49	27	25·0	11·2	40·2
(8)	The Lizard	Cornwall	50	10	A	14–5–49	21	14·5‡	6·5	23·3
(9)	St. Agnes Beacon	Cornwall	629	15*	B	17–5–49	21	22·0	9·8	35·4
(10)	Tregonning Hill	Cornwall	615	30	B	18–5–49	12	21·0	9·4	33·8
(11)	Watch Croft	Cornwall	827	10	A	19–5–49	6	20·0	8·9	32·2
(12)	Carn Bean	Cornwall	665	10	A	19–5–49	12	17·0	7·6	27·4
(13)	Carn Brea	Cornwall	657	30	B	24–5–49	21	22·0	9·8	35·4
14	Mynydd Castlebythe	Pembrokeshire	1,137	10	A	24–8–49	23	19·0	8·5	30·6
15	Foel Eryr	Pembrokeshire	1,537	15	B	25–8–49	23	25·0	11·2	40·2
(16)	Mynydd Kilkiffeth	Pembrokeshire	1,096	10	A	26–8–49	3	16·0	7·1	25·8
17	Rhossilli Down	Gower	633	15	B	30–8–49	23	24·0	10·7	38·6
18	Mynydd Anelog	Caernarvonshire	628	10	A	15–11–49	20	26·0	11·6	41·8
(19)	Les Landes	Jersey	250	10	A	10–1–50	12	16·0	7·1	25·8
20	Downan Hill	Ayrshire	348	10	A	25–4–50	15	22·0	9·8	35·4
21	Pinbain Hill	Ayrshire	734	15	B	26–4–50	15	23·0	10·3	37·0
22	Torr Mor	Mull of Kintyre	1,358	10	A	1–5–50	15	25·0	11·2	40·2
23	Cnoc Moy	Kintyre	1,463	15	B	2–5–50	15	24·0	10·7	38·6
24	Macrihanish	Kintyre	100	30	A	7–5–50	15	12·0	5·4	19·3
25	Brecqhou	Channel Islands	150	10	A	1–6–50	14	20·0	8·9	32·2
26	Divis Mtn.	Belfast	1,574	30	B	5–9–50	11	21·0	9·4	33·8
27	Slieve Gullion	Co. Armagh	1,894	10	A	7–9–50	11	24·0	10·7	38·6
28	Chimney Rock	Co. Down	2,152	10	C	7–9–50	11	26·0	11·6	41·8
(29)	Evish Hill	Co. Antrim	1,100	10	A	11–9–50	10	17·0	7·6	27·4
(30)	Big Collin	Co. Antrim	1,163	10	A	12–9–50	10	17·0	7·6	27·4
31	Carnanmore	Co. Antrim	1,253	10	A	12–9–50	11	23·0	10·3	37·0
32	Knocklayd	Co. Antrim	1,695	30	B	14–9–50	11	22·0	9·8	35·4
(33)	Binevenagh	Co. Londonderry	1,260	30	C	16–9–50	10	18·0	8·1	29·0
34	Mullaclogha	Co. Tyrone	2,088	10	C	19–9–50	10	23·0	10·3	37·0
35	Dooish	Co. Tyrone	1,100	30	B	21–9–50	10	19·0	8·5	30·6
36	Leahan	Co. Donegal	1,418	30	B	23–9–50	10	22·0	9·8	35·4
37	Slieve Tooey	Co. Donegal	1,515	30	C	25–9–50	10	25·0	11·2	40·2
38	Bloody Foreland	Co. Donegal	1,038	30	B	27–9–50	10	27·0	12·1	43·5
39	Crocknafarragh	Co. Donegal	1,707	10	A	27–9–50	10	23·0	10·3	37·0
40	Ardmalin	Co. Donegal	362	10	A	28–9–50	10	17·0	7·6	27·4
41	Blue Stack Mountains	Co. Donegal	2,219	10	C	1–10–50	10	22·0	9·8	35·4
42	Firle Beacon	Sussex	718	10	A	26–4–51	3	—	—	—
43	Mynydd Rhiw	Caernarvonshire	990	15	A	16–5–51	3	21·0	9·4	33·8
44	Cruachan Treshnish	Isle of Mull	704	10	A	12–6–51	1	—	—	—
45	Ben Tangaval	Isle of Barra	1,092	10	A	14–6–51	1	—	—	—
46	Easaval	South Uist	800	10	A (L.T.)	16–6–51	1	—	—	—
47	Chaipaval	Isle of Harris	1,203	10	A (L.T.)	19–6–51	1	—	—	—
48	Ben Geary	Vaternish, Isle of Skye	929	10	A	22–6–51	1	—	—	—
49	Meall an Fheadain	Ross-shire	663	10	A	25–6–51	1	—	—	—
50	Dunan Mor	Sutherlandshire	523	10	A (L.T.)	26–6–51	1	—	—	—

NOTES ON TABLE 4

Column 1. Sites numbered in brackets are those at which the measuring instruments have now been removed.

Column 2. The Lizard is a Meteorological Office station. Bignold Park and Macrihanish are one-time Meteorological Office stations at which measurements have been discontinued.

Column 5. * Changed to 30 ft. in January, 1950.
" Height above ground " has been used in preference to the term " effective height " used by the Meteorological Office. This latter term is defined as the height at which an anemometer would record an equal wind velocity in a situation free from obstructions. Since nearly all the sites shown are open it has not been practicable to give a value for the " effective height " for each exposure.

Column 6. Type A = Cup-counter anemometer reading up to 10,000 miles of wind.
Type A (L.T.) = Cup-counter anemometer fitted with a long-term counter to read up to 100,000 miles of wind.
Type B = Cup-contact anemometer with chart recorder.
Type C = Cup-contact anemometer with counter.

Column 9. ‡ The long-term averages have been estimated by comparison of the observations with long-term averages for the nearest Meteorological Office stations. Where gaps occur in this column the observations have been interrupted or have been of too short duration to form the basis of reliable long-term estimates.

A " Type A " instrument was installed at the Lizard merely to compare its readings with those of a Dines anemometer at the Meteorological Office station there. The average annual wind speed of 14·5 m.p.h. is actually the long-term value for this station at a height of 33 ft. above ground, height above sea level 315 ft.

Column 10. 1 metre per second = 2·237 m.p.h.

Column 11. 1 kilometre per hour = 0·6214 m.p.h.

The last two columns have been given to facilitate comparison with records for sites abroad.

Fig. 1.—10-ft. pole installation on Cruachan Treshnish, Isle of Mull.

Fig. 2.—Double-picket anchorage.

Fig. 3 (a).—30-ft. pole installation—Divis Mountain, Northern Ireland.

Fig. 3 (b).—30-ft. lattice tower installation—Chapel Carn Brea, Cornwall.

Fig. 4.—Coal-bunker housing recorder for 15-ft. lattice tower installation—St. Agnes Beacon, Cornwall.

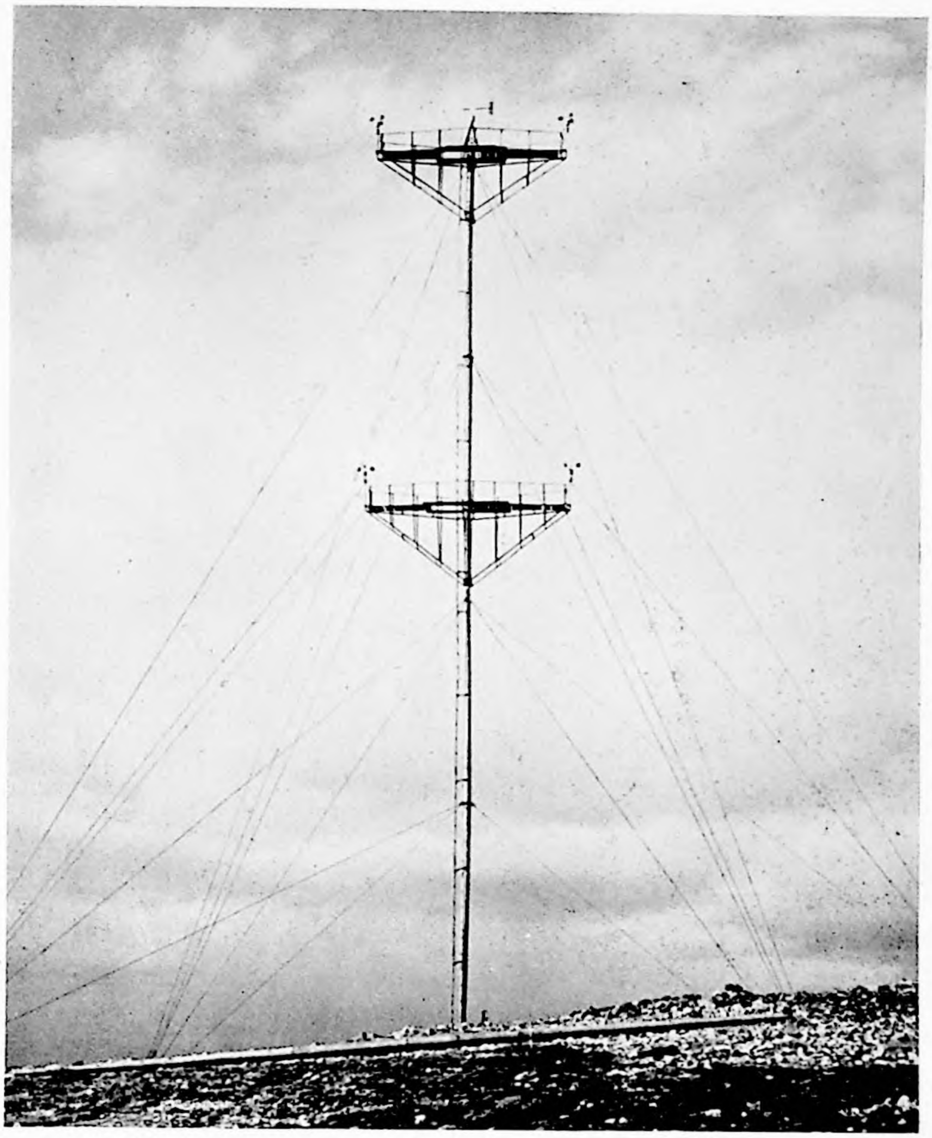


Fig. 5(a).—66-ft. tubular steel mast installation—Mynydd Anelog, North Wales.

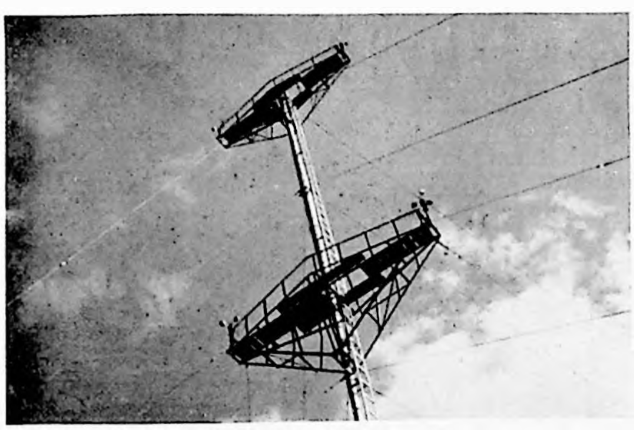


Fig. 5(b).—66-ft. mast at Anelog, showing guys and platform construction.

Fig. 5(c).—66-ft. mast at Anelog, showing wind-direction indicator and anemometer mountings.

Fig. 6(a).—Hauling equipment to the site—Costa Hill, Orkney.

Fig. 6(b).—Hauling equipment to the site—Mynydd Anelog, North Wales.

Fig. 6(c).—Carrying equipment on horse-back to the site—Slieve Tooey, Co. Donegal.

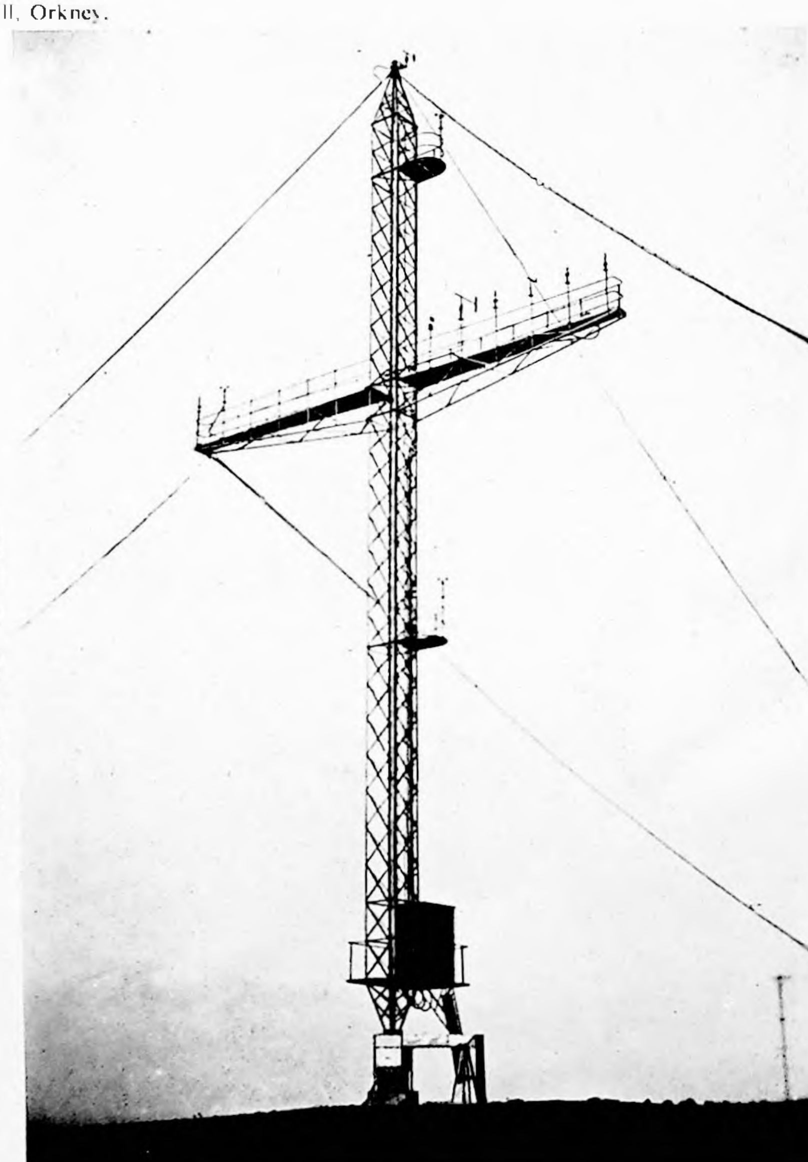


Fig. 21.—120-ft. mast—Costa Hill, Orkney

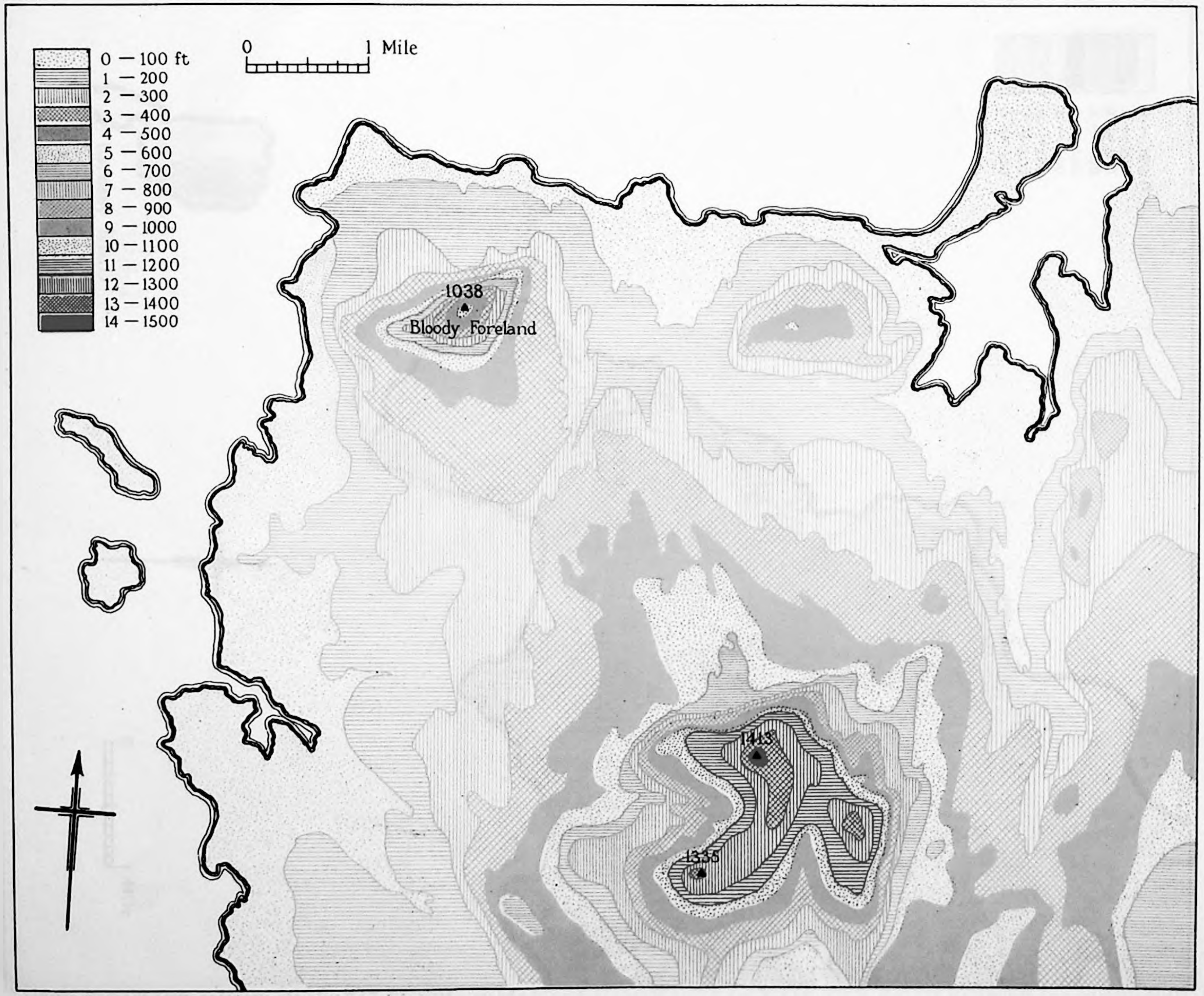


Fig. 10 (a).—Contour map, North-West Donegal.

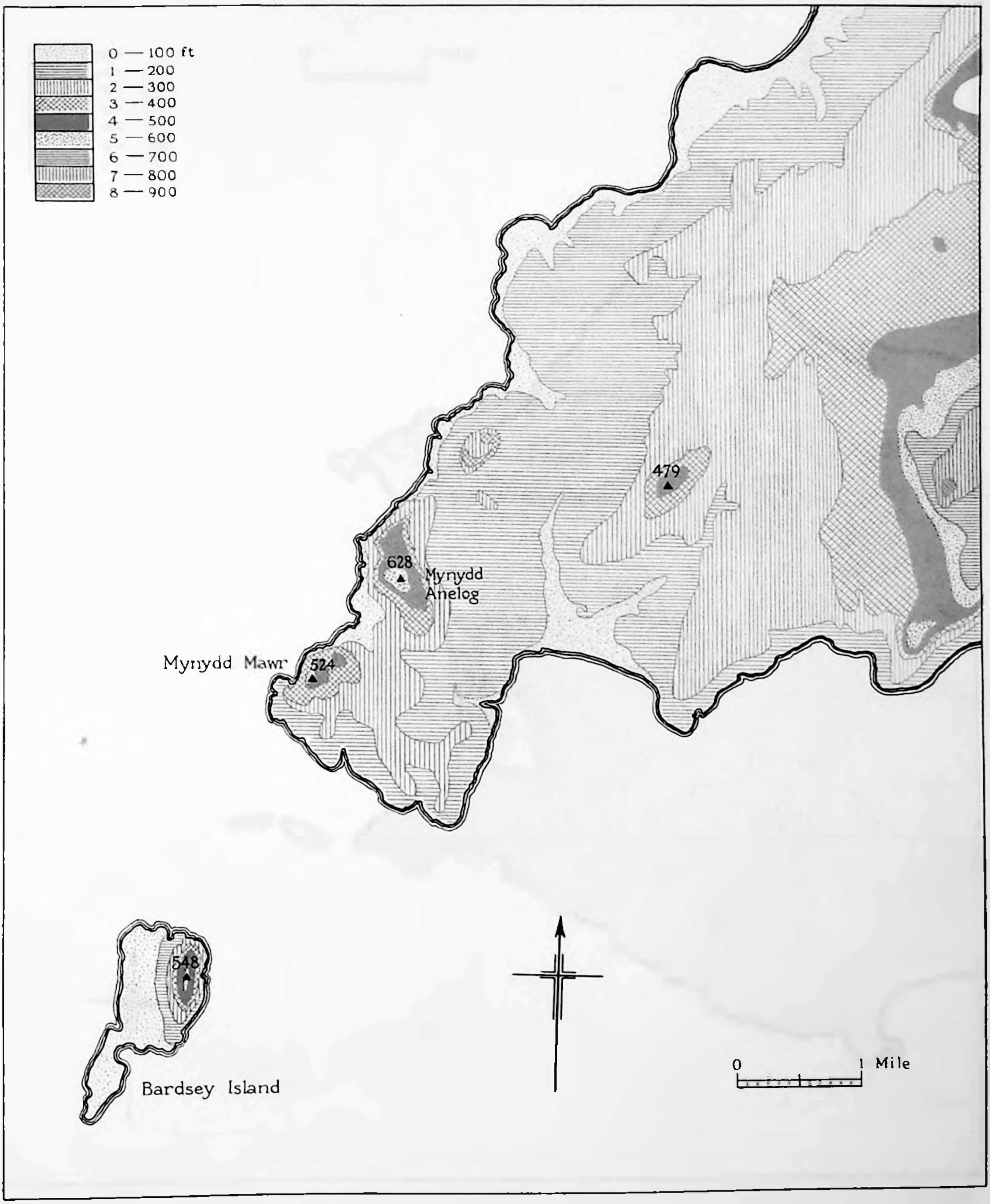


Fig. 10 (b).—Contour map, Lleyn Peninsula, Caernarvon.

Fig. 10 (c).—Contour map, West Gower Peninsula.

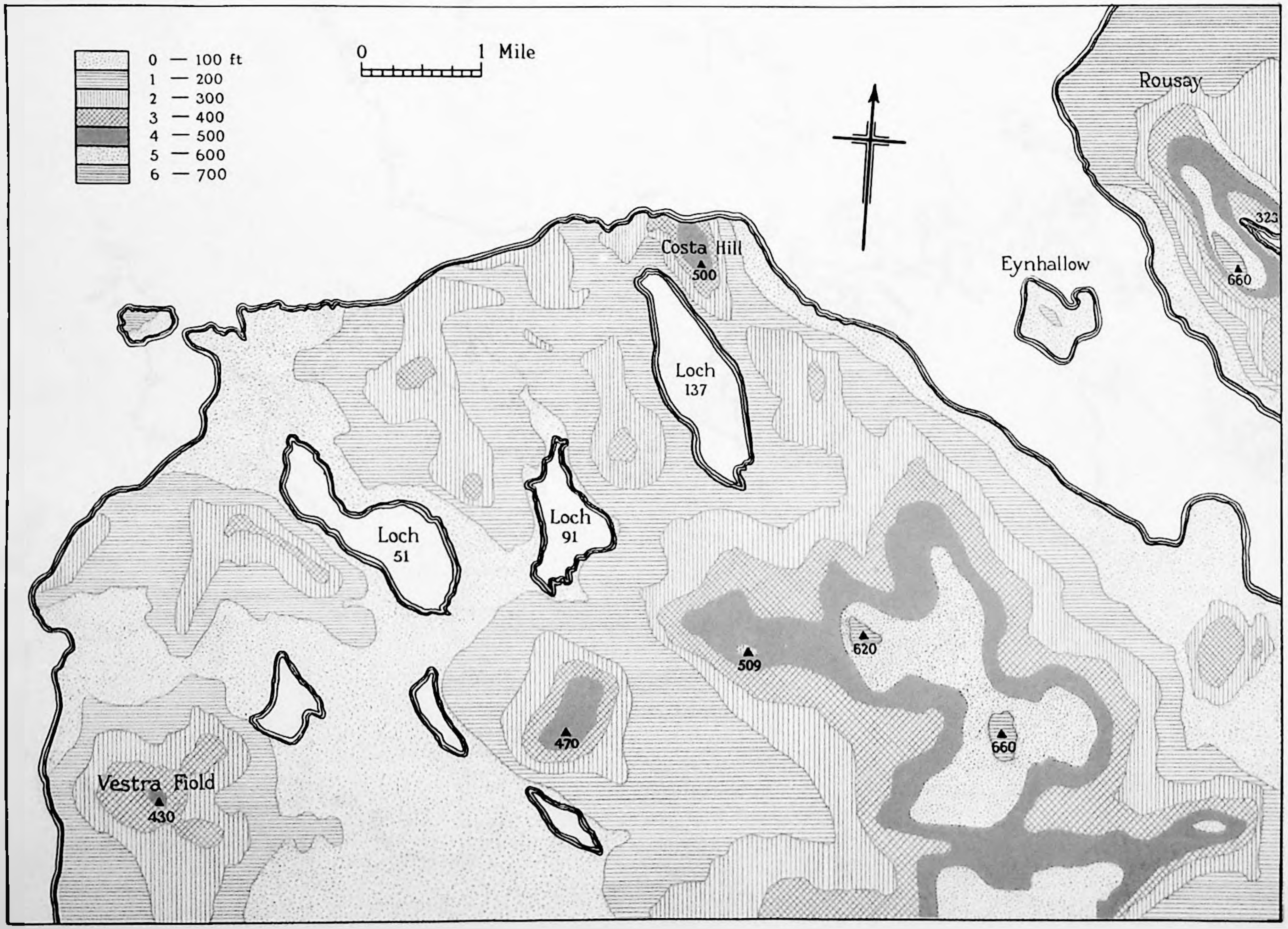


Fig. 10 (d).—Contour map, North Orkney Mainland.

Fig. 7.—E.R.A. wind survey sites.

remote districts ; farmers and their families, shepherds, postmen, coastguards, water supply maintenance men and the like have occasion to climb the hills at intervals and have been found most helpful. The reading of a cup-counter instrument—which has merely a cyclometer dial—is a very simple matter and arrangements are made for readings to be made approximately weekly and sent to E.R.A. headquarters monthly. Chart changing and other attention to recorders is a rather more skilled job but an hour's tuition, accompanied by a simple " instruction sheet ", has been found quite adequate in most cases.

Maintenance and the changing of films on the photo-recorder had, until recently, been carried out by a member of the staff of an electricity supply authority. On the latest installation, however, a local man has successfully taken on this quite responsible task.

The investigators would like to acknowledge with gratitude the help which they have received from the local observers who, for a very small monthly payment or, in some cases, without payment, have steadily and conscientiously carried on this recording work under difficult conditions, particularly on rough and high hills in winter. Their work has been essential to the success of the survey.

(6) RESULTS AND THEIR ANALYSIS

The wind data obtained as a result of the survey obviously contains many thousands of figures. For the purpose of this report these have been reduced to usable proportions and in the following sections and tables only the significant information is shown and analysed.

(6.1) Preliminary Stage

A list of the measuring sites installed up to the end of July 1951, together with some details and dates of the installations, is given in Table 4.

In all cases the total run of wind, in miles, at the site has been measured and the average wind speed obtained therefrom. The values are given as " estimated long-term averages ". This means simply that allowance has been made for the wind speed in the district concerned being greater or less than the long-term average during the period of the observations. Such a figure is more realistic than that which would be obtained by dividing the measured run of wind by the duration of the period of measurement, especially as these periods are of different lengths and do not coincide in time.

In view of the scanty knowledge at present available regarding the vertical wind gradient at hill sites it has not been possible to correct the figures given in the table to a value applicable to a common height above ground.

Continued field measurements and laboratory experiments may eventually enable such corrections to be made.

The measurements have been discontinued at some sites which have proved, after a short time, insufficiently windy to be worth studying further, at least in the early stages of wind-power development. Sometimes, however, it has been found advisable to continue readings at less windy sites, from which records have been continuously reliable, in order to have a check upon better sites nearby at times when their anemometers are unserviceable. There appears to be a sufficiently constant relationship between the wind velocities on adjacent hills for gaps in records of not more than a few days' duration to be filled by estimation without introducing any appreciable error.

(6.1.1) Analysis of Results.

It will be noted from Table 4 that, out of 47 hill sites (i.e. after excluding Meteorological Office stations) 25 are already known to have long-term annual average wind speeds exceeding 20 m.p.h. and there is little doubt that a further seven sites will be found, from future observations, to have wind speeds of the same order.

Eight sites already have been proved to have average speeds of 25 m.p.h. or above and this number will almost certainly be increased when the records already started become more complete with time. It must be emphasized that the sites chosen do not by any means represent the only favourable hills in the districts concerned ; in some instances they are merely representative of a group of hills. This is particularly true of those in Orkney, Donegal and the West of Scotland where many equally good hills probably exist. Clearly it would be wasteful at this stage of the work to instal measuring instruments on all possible sites, since wind régimes on adjacent hills of similar shapes are nearly enough identical.

The distribution of the sites already used is shown in the map of Fig. 7 ; the stretches of coastline not yet covered by measurements will be included in surveys to be started in the near future. On the map, sites 2, 7, 15, 18, 22, 28, 37 and 38 have the highest wind speeds (to date). Sites 42, 44 to 50 are those which have not yet been studied for a long enough period for estimates to be made of their wind speeds. It is interesting to note that the seven especially good sites are well separated and cover Orkney, North Wales, South Wales, Kintyre and Donegal.

(6.1.1.1) Total Wind Flow.

As already explained, cup-counter anemometers merely provide readings (usually weekly) of the integrated run of wind, in miles, while the cup-contact anemometers used with recorders give the run of wind during each hour or even for shorter periods. By addition of the hourly values the latter also give an integration of the miles of wind during a lengthy period so that the records from the two types of instrument can be compared by graphs showing miles of wind plotted against time. Fig. 8 shows the

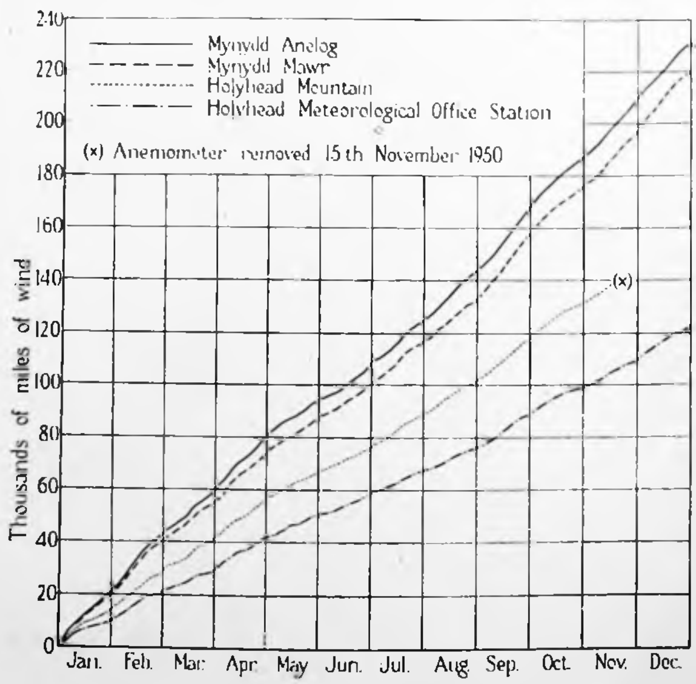


Fig. 8.—Run of wind, North Wales, 1950.

results for a group of hills in North Wales compared with that for the nearest Meteorological Office station at Holyhead during the same period of time, while in Fig. 9 curves of wind flow over hills in different parts of the country, but for the same period, are compared.

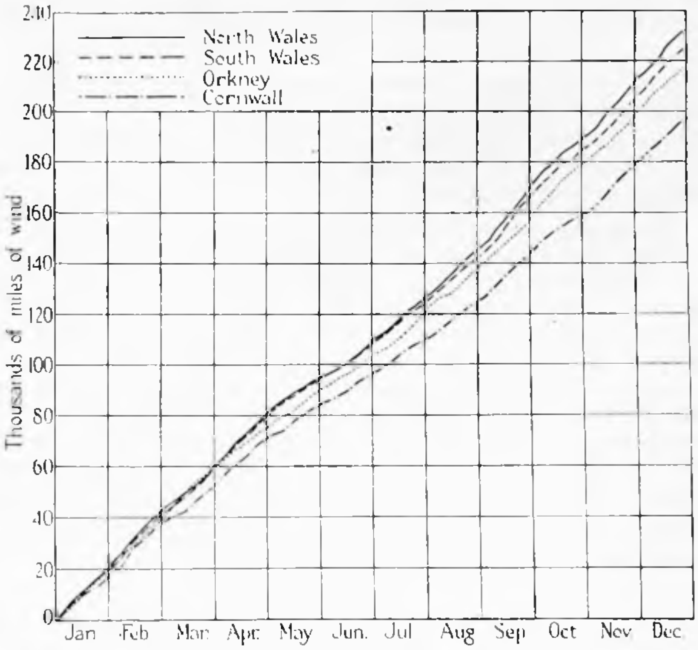


Fig. 9.—Run of wind at best sites, 1950.

Note, in Fig. 8, both how consistently some hills show a higher wind flow than others and also how great an increase—up to 85 per cent.—is obtained at the best hills on the flow at the local Meteorological Office station. Examination of such curves, plotted for at least one year, leaves little doubt as to the superiority of some sites over others.

When comparing hills situated in a particular district it becomes apparent, within a fairly short period of the commencement of the readings, which of them is likely to be the windiest. In the comparison of widely separated sites, however, at least one year's readings must be studied before their relative windiness can be assessed.

It is interesting to compare the shapes and exposures of some of the most favourable sites which have so far been found. Four of these are shown in Fig. 10 which gives, for each hill, its position in relation to the sea and to the nearest high ground and also its contours in detail. Note that in no case is the summit of the hill more than 1½ miles from the coast ; that at least three miles separates each site from ground of the same height as its summit, and that all these hills, although perhaps not the highest in their particular vicinity, stand out amongst the surrounding countryside and do not form part of a hilly or mountainous mass.

(6.1.1.2) **Velocity/Duration Curves.**

While wind-flow curves are sufficient for an assessment to be made of the order of windiness of a group of hills the wind régimes, as expressed by velocity/duration curves, are necessary for the estimation of energy potentialities. These are plotted from recorder charts in the following way :—First the wind flow, hour by hour, is noted from the chart and these hourly average wind speeds are filled in on tables of which Fig. 11—for Mynydd Mawr covering the period December 9–16, 1950—is an example. The totals at the bottom of each column are of daily run of wind for use in plotting the run of wind graphs already discussed. The numbers of hours in the year during which each wind speed, at 1 m.p.h. intervals, exists at the site are then reckoned and finally the velocity/duration curves are drawn as in Fig. 12 which shows curves for three of the same sites as those for which wind-flow curves were given in Fig. 9. Here it is important to note how similar in shape are these curves of velocity duration in spite of the inevitable differences in shape, exposure and altitude of the hills and of their wide distances apart.

STATION : MYNYDD MAWR DATE RECEIVED 20–12–50
REF. 60

Dec.	9th	10th	11th	12th		13th	14th	15th	16th
mdnt.	—	49	40	49	mdnt.	18	22	33	60
1	—	53	40	44	1	17	18	43	52
2	—	49	40	43	2	15	19	48	60
3	—	50	39	39	3	11	26	51	66
4	—	39	38	35	4	9	32	56	60
5	—	35	36	34	5	8	32	52	57
6	—	30	41	30	6	8	32	56	53
7	—	23	38	30	7	14	32	59	57
8	—	21	37	25	8	18	29	58	55
9	—	26	43	24	9	23	29	55	53
10	—	34	42	23	10	26	53	47	54
11	19	41	56	27	11	28	47	53	62
12	21	44	56	26	12	28	46	47	62
13	21	38	57	28	13	33	42	50	59
14	22	33	50	21	14	39	35	44	51
15	30	35	54	25	15	42	26	48	56
16	34	36	60	32	16	46	20	44	54
17	38	33	63	30	17	46	12	47	58
18	40	35	71	29	18	43	5	50	—
19	42	38	60	14	19	42	6	51	—
20	44	36	57	7	20	42	3	50	—
21	49	36	58	18	21	39	5	55	—
22	46	33	55	11	22	35	18	58	—
23	46	38	51	15	23	31	27	62	—
Total	452	885	1,182	659		661	616	1,217	1,029

Fig. 11.—Weekly summary sheet, showing mean hourly wind speeds.

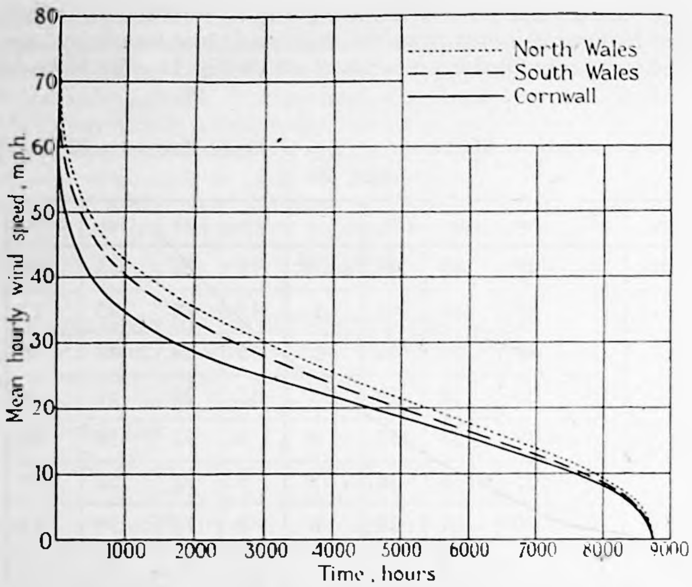


Fig. 12.—Velocity-duration curves for best sites, 1950.

(6.1.2) **Interpretation of Results in Terms of Probable Energy.**

For a given area swept by a windmill rotor, and for a given air density, the power in the wind is proportional to the cube of the wind speed.

$$P \text{ (in kW)} = 0.0000053\, AV^3,$$
$$\text{where } A = \text{swept area, ft.}^2$$
$$V = \text{wind speed, m.p.h.}$$

The air density, taken as 0·08 lb./ft.^{3}, is included in the constant. Thus, to estimate the probable annual output of energy by a wind-driven generator located on any particular site it is first necessary to draw the curve of (wind velocity)^3 against time. This is called the power/duration curve.

A power/duration curve typical of an excellent site (annual average wind speed 26 m.p.h.) is drawn in Fig. 13 together with the velocity/duration curve (shown dotted) from which it is derived. It is inconceivable that an economic wind-driven generator can be built to extract all the annual energy in the wind swept by its rotor, so that operating limits of wind speed must be imposed. These limits cannot yet be fixed precisely and, indeed, they will certainly vary with the type and detailed design of the plant, with its cost of construction, with the wind régime itself and with the generation costs by alternative means of energy production with which the machine is likely to be in competition.

Nevertheless, the order of the operating range is known and, for purposes of energy estimation in comparing sites, it has been

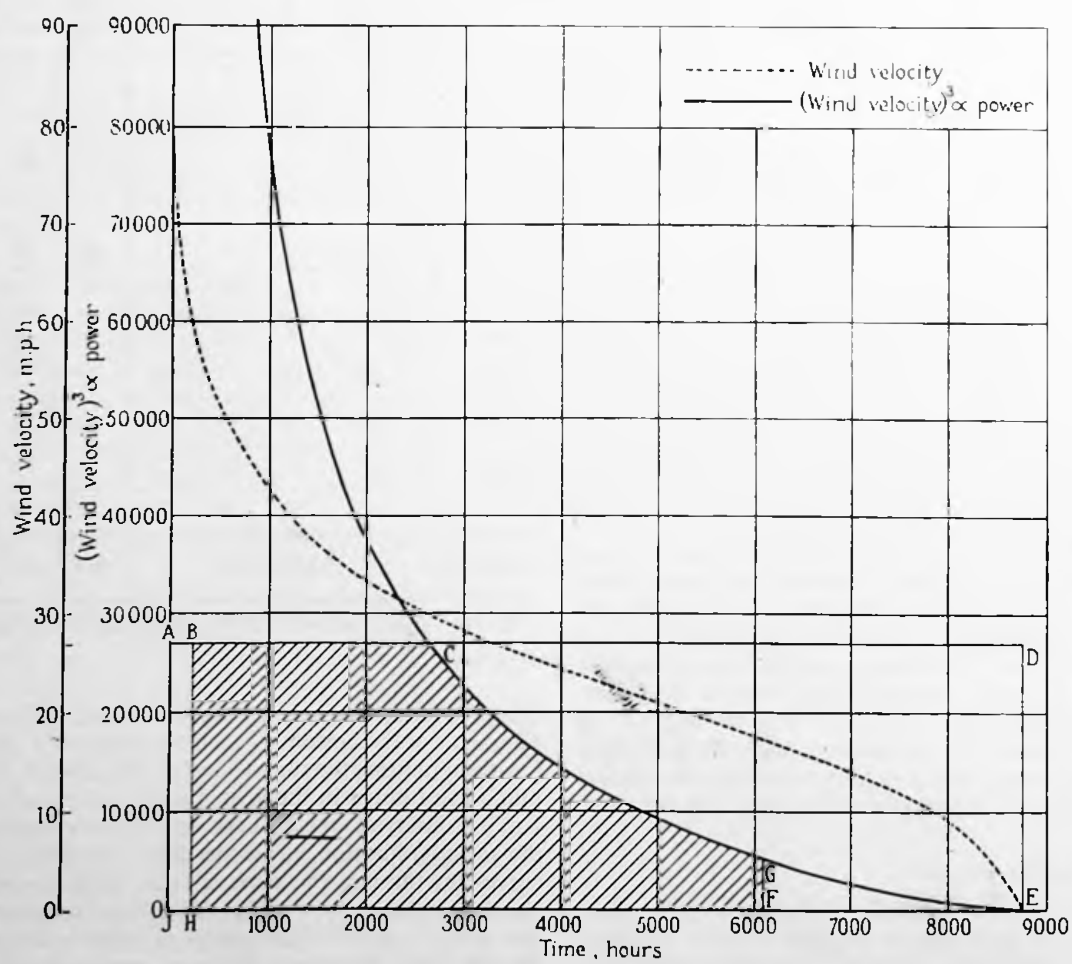


Fig. 13.—Velocity- and power-duration curves typical of an excellent site.

usual to assume, as already mentioned in Section 4, that full output will be produced with a " rated wind speed " of 30 m.p.h. and above up to 60 m.p.h., after commencing to generate output at about 17 m.p.h.

The annual energy output is thus represented in Fig. 13 by the shaded area if it is assumed, as it may be with very little error (see 7.3.1), that the " overall power coefficient* " of the set remains constant over the operating range from cut-in at 17 m.p.h. to full output at 30 m.p.h. At the cut-in point the power being generated must be just sufficient to supply the no-load losses of the plant, which may be of the order of 15 per cent. of the full output, so that the ratio of power at the rated wind speed to that at the cut-in speed is roughly 100 : 15. The " specific output " of the plant, expressed in kWh per annum per kilowatt of capacity, is calculated by multiplying the ratio (area BCGFH)/(area ADEJ) by 8,760 which is the number of hours in a year.

Reduction of the rated wind speed has the effect of increasing the specific output, and the variation in this value, for different operating ranges, with the power/duration curve of Fig. 13 is shown in Table 5. At the same time, the cost of construction, for a given kW capacity, must rise as the rated wind speed is reduced and economic design must take into account both of these effects.

Table 5

VARIATION OF SPECIFIC OUTPUT WITH OPERATING RANGE OF WIND SPEEDS

Operating range			Specific output, kWh/annum/kW
Cut-in speed, m.p.h.	Rated speed, m.p.h.	Furling speed, m.p.h.	
24	45	60	2,000
21·5	40	60	2,600
18·5	35	60	3,400
17	30	60	4,400
13	25	60	5,500

In an attempt to correlate the annual average wind speed at a site with the specific output obtainable from plant erected on it the latter has been determined for a large number of sites for which the velocity/duration curves (and hence the power/duration curves, by cubing velocity ordinates) are known. The results are given in Table 6 in which values of specific output for three rated wind speeds, namely 30 m.p.h., 25 m.p.h., and 20 m.p.h. are shown. The three corresponding cut-in speeds have been taken as 17 m.p.h., 13 m.p.h. and 10 m.p.h. respectively and in each case a furling speed of 60 m.p.h. has been assumed. Sites with annual average wind speeds less than 20 m.p.h. are all Meteorological Office stations, and those with higher speeds are sites studied during wind surveys.

The values of specific output plotted against average wind speed are shown in Fig. 14 from which it can be seen that the individual points all lie very close to the mean curves. This is especially true for the highest rated wind speed. There is a little scattering with the 20 m.p.h. rated wind speed due to variations of shape of velocity/duration curves having the same average value ; there is less variation between the higher portions of the curves which enter into the output calculations with the 30 m.p.h. rated speed.

More points will be added on these graphs as time passes and sufficiently long-term records are obtained from further wind survey sites, but there is already a clear indication, as suggested in 5.2.1, that the *annual average wind speed for any site can be*

Table 6

Site	Annual mean wind speed, m.p.h.	Specific output (kWh/annum/kW)		
		Rated wind speed		
		30 m.p.h.	25 m.p.h.	20 m.p.h.
Mawr (1950)	25·3	4,420	5,520	6,070
Costa	24·6	4,350	5,400	6,200
Rhossilli	23·7	4,000	4,960	5,930
Mawr (1949)	23·5	4,000	5,100	6,000
St. Agnes (1950)	21·7	3,600	4,850	6,050
St. Agnes (1949)	21·0	3,300	4,300	5,600
Bell Rock	18·0	2,550	3,700	4,850
Lerwick	17·6	2,425	3,530	4,790
Butt of Lewis	17·6	2,300	3,500	4,600
St. Ann's Head	16·2	2,100	3,000	4,100
Stornoway	15·6	1,900	2,900	4,040
Scilly	15·4	1,850	2,800	4,000
Tiree	14·9	1,750	2,700	3,800
Kirkwall	14·7	1,560	2,550	3,730
Southport	13·7	1,350	2,100	3,100
Fleetwood	12·9	1,150	1,700	2,800
Plymouth	11·2	800	1,400	2,200
Eskdalemuir	11·0	800	1,450	2,350
Cranwell	9·9	650	1,200	2,050
Aberdeen	9·7	340	750	1,600
South Shields	9·6	530	1,050	1,870
Yarmouth	9·4	450	900	1,600
Birmingham	8·8	195	620	1,350
Catterick	7·1	250	500	1,000
Leicester	6·2	60	200	550

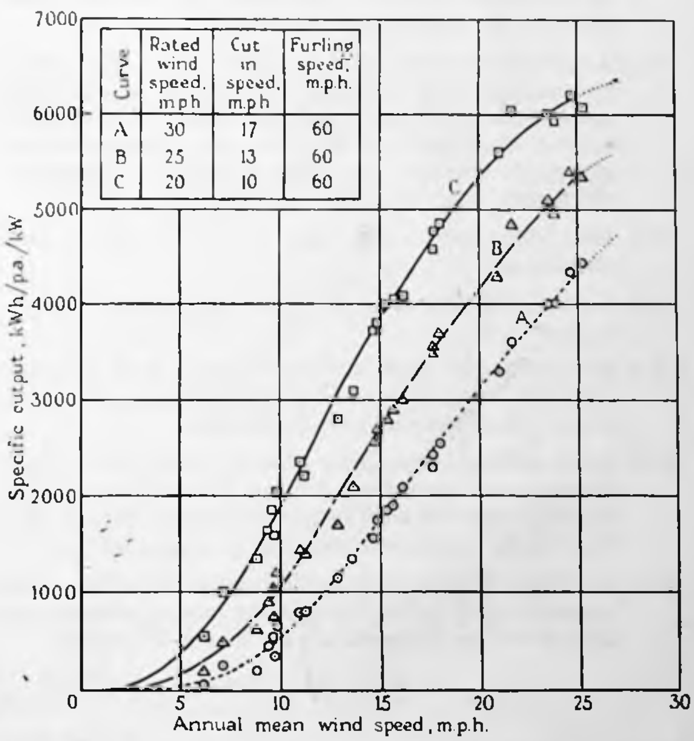


Fig. 14.

• Overall power coefficient = $\frac{\text{electrical power output}}{\text{power in the wind}}$.

The " power in the wind " is taken as that which would exist, in the circle swept by the wind turbine, if the machine were not present. The use of the term " efficiency " for this ratio is to be avoided since the " input " to the turbine is not ascertainable—some of the column of air, of cross-section equal to the swept area, flows round the outside of the windmill disc so that the power in this air cannot be reckoned as input.

accepted as a measure of the potential specific output. This is very important because, if it can be confirmed, it will lead to a great simplification in carrying out surveys and in estimating the potentialities of sites.

Before dismissing Table 6 it is worth noting that, if a rated wind speed as low as 20 m.p.h. were usable without involving an excessive cost of construction for the wind power plant, even sites with annual average wind speeds of no more than 15 m.p.h. could give specific outputs of 4,000 kWh/kW. The best site so far discovered in the survey, namely Bloody Foreland in County Donegal, has an estimated long-term average wind speed of 27 m.p.h., which, from Fig. 14, implies a specific output of 4,800 kWh/kW with a rated wind speed of 30 m.p.h.

(6.1.3) Conclusions to be Drawn from the Results.

While the wind survey is well advanced it is not yet complete either in extent or duration. The most obviously windy districts and shapes of hills have been studied first ; other parts of the country, which may also be sufficiently windy, and hills of different exposures and contours remain to be dealt with. Nevertheless, enough information is now available for the following conclusions to be drawn with some confidence :—

(i) The Meteorological Office isovent maps (see Ref. W/T16, Fig. 11) form a very useful guide in the selection of windy sites.

(ii) In many coastal districts sites can be found having annual average wind speeds between 50 and 100 per cent. higher than that for the surrounding district.

(iii) At least on the west coasts of Great Britain and Ireland, an annual average wind speed of over 22 m.p.h. corresponds to a specific output of 4,000 kWh/kW or more for a rated wind speed of 30 m.p.h., the velocity/duration curves for different sites being so similar in shape that the former figure is a good indication of output.

(iv) Hills within one to two miles of the sea are the most promising.

(v) Conical hills may be as good as ridges athwart the prevailing wind.

X (vi) The altitude of a hill summit is not in itself a reliable criterion, hills only a few hundred feet high often being as good as others well over 1,000 feet.

(vii) After sufficient experience of wind surveys the annual average wind speed for a hill can be estimated with fair accuracy from the site inspection alone but the hill must be climbed—estimates from maps are not reliable.

(viii) In Great Britain and Ireland good hills have bare summits. Any hill having trees or bushes growing near the top can be dismissed at once as not favourable.

(6.2) Second Stage

To date, installations for the second stage survey have been set up at the three sites listed below.

The installations at sites 1 and 2 were, in all ways, identical. Since, however, they presented some difficulty in maintaining the instruments, due to the lack of any means of climbing the masts, it was considered advisable to modify later installations. The first of these is installed at the remaining site, Mynydd Anelog.

The methods of recording at the three sites are almost identical, but at Anelog an extra counter has been added, making, with the timing counter, six in all so that simultaneous recording of run of wind at all four positions on the main mast and on the 10-ft. pole can be made.

(6.2.1) Results.

The aim of the second stage survey is fundamentally to provide further information concerning the wind behaviour at aerogenerator sites. Although some overlapping may occur, it is convenient to classify this information under three main headings as referring to (i) wind régimes, (ii) vertical wind gradient, and (iii) wind direction. These will be dealt with individually in the following paragraphs.

(i) As in the preliminary survey the velocity/ and power/ duration curves are drawn from the record charts on which mean hourly wind speeds are entered.

Completed annual curves are available only for Costa Hill and for the years 1949 and 1950. Although the two years were climatically dissimilar—1949 was abnormally windy during the winter and calm during the summer whilst in 1950 the reverse was true—little difference is apparent from the respective wind régime curves and the mean annual speeds varied only slightly. Actual figures for the two years are 24·9 m.p.h. and 24·8 m.p.h. respectively.

(ii) When considering vertical wind gradient it is first necessary to define a minimum period of time to which the value applies.

Obviously, with gusty winds, the gradient will vary from instant to instant but, when a method of recording run of wind at half-hourly intervals is used, only average values will be obtained. Since, also, wind velocities are only normally tabulated at hourly intervals, hourly mean wind speeds at different heights are most conveniently used for the purpose of comparison. Graphs showing the relationship between mean hourly wind speeds at different heights over Costa Hill and Vestra Fiold are shown in Figs. 15 (*a*), (*b*), (*c*) and (*d*). It is clear from these that the vertical wind gradient is not only greater at the latter but also is far more constant. These two hills are of similar height and are sufficiently close to each other (only seven miles of lower country lies between them) to be affected initially by identical wind conditions. They are, however, completely different in

Table 7

Second Stage Survey Sites

Site	Height of anemometers above ground, feet	Height of wind-direction indicator above ground, feet	Type of installation*	Date of installation	Duration of observations, months
1 Costa Hill	35(2) 66(2)	66	D	25–11–48	32
(2) Vestra Fiold ..	35(2) 66(2)	66	D	16–12–48	7
3 Mynydd Anelog ..	35(2) 66(2)	66	D	17–4–51	3

* Type D—Cup contact anemometer and remote-reading wind direction indicator with photographic recorder.

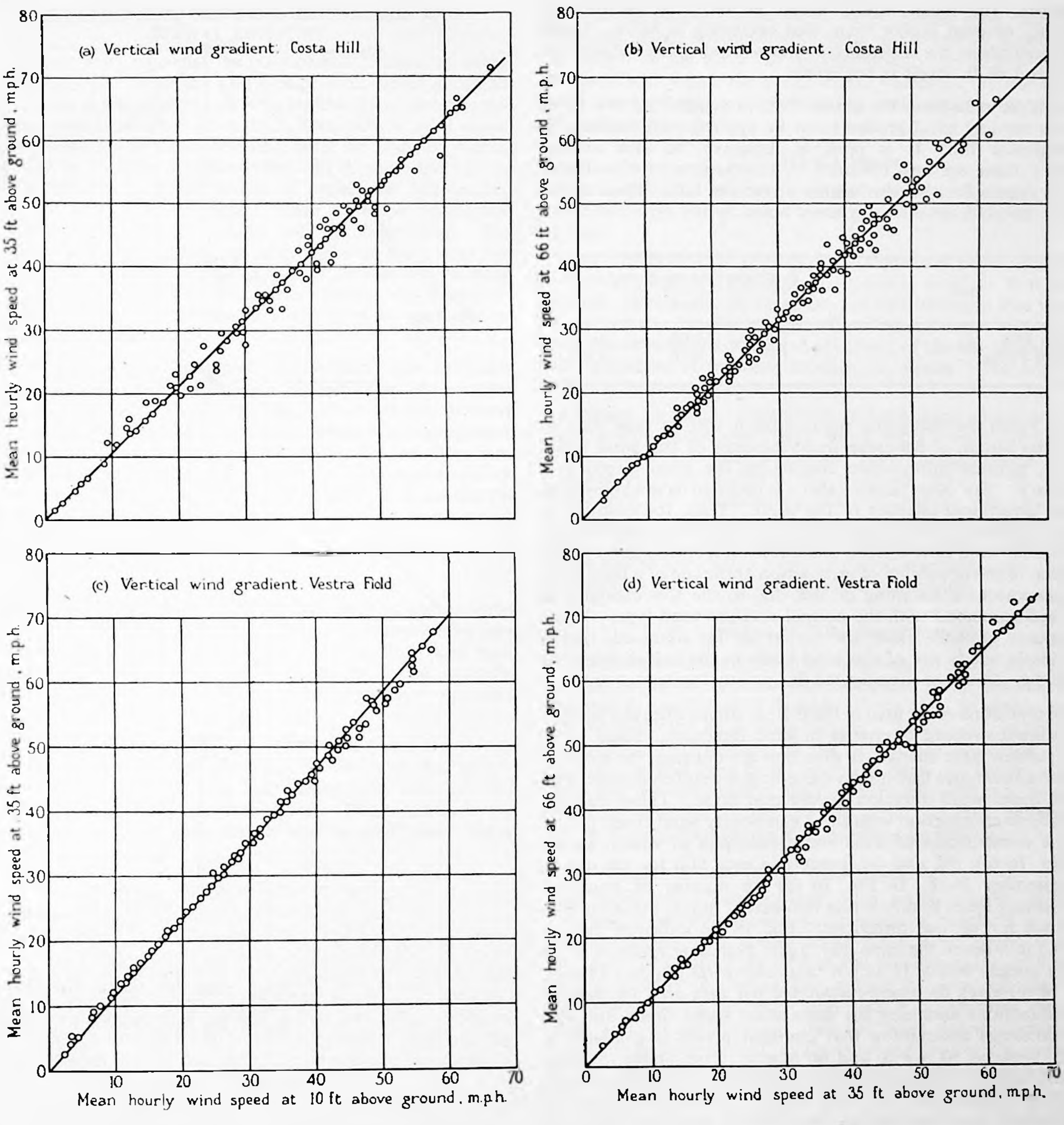


Fig. 15 (a) and (b).—Vertical wind gradient—Costa Hill (35 ft.—10 ft. and 66 ft.—35 ft.).
(c) and (d).—Vertical wind gradient—Vestra Fiold (35 ft.—10ft. and 66 ft.—35 ft.).

shape and, since the wind velocity gradient over a hill-top is dependent largely on the slope of the hill, a ready explanation of the dissimilarity between the two graphs offers itself. Vestra Fiold is flat-topped and has only a gentle slope away from the summit ; consequently, little acceleration of the wind occurs whatever its direction and the vertical wind gradient therefore remains sensibly constant at a value not greatly different from that existing over level country in coastal areas. At Costa, on the other hand, the comparatively steep slopes cause some acceleration of the wind but this acceleration is obviously appreciable only at levels near the ground, which results in a decreased value for the vertical wind gradient. Furthermore, owing to the effectively shallower slope as the wind tends to blow along the ridge rather than across it, the acceleration and, consequently, the wind gradient will vary with wind direction.

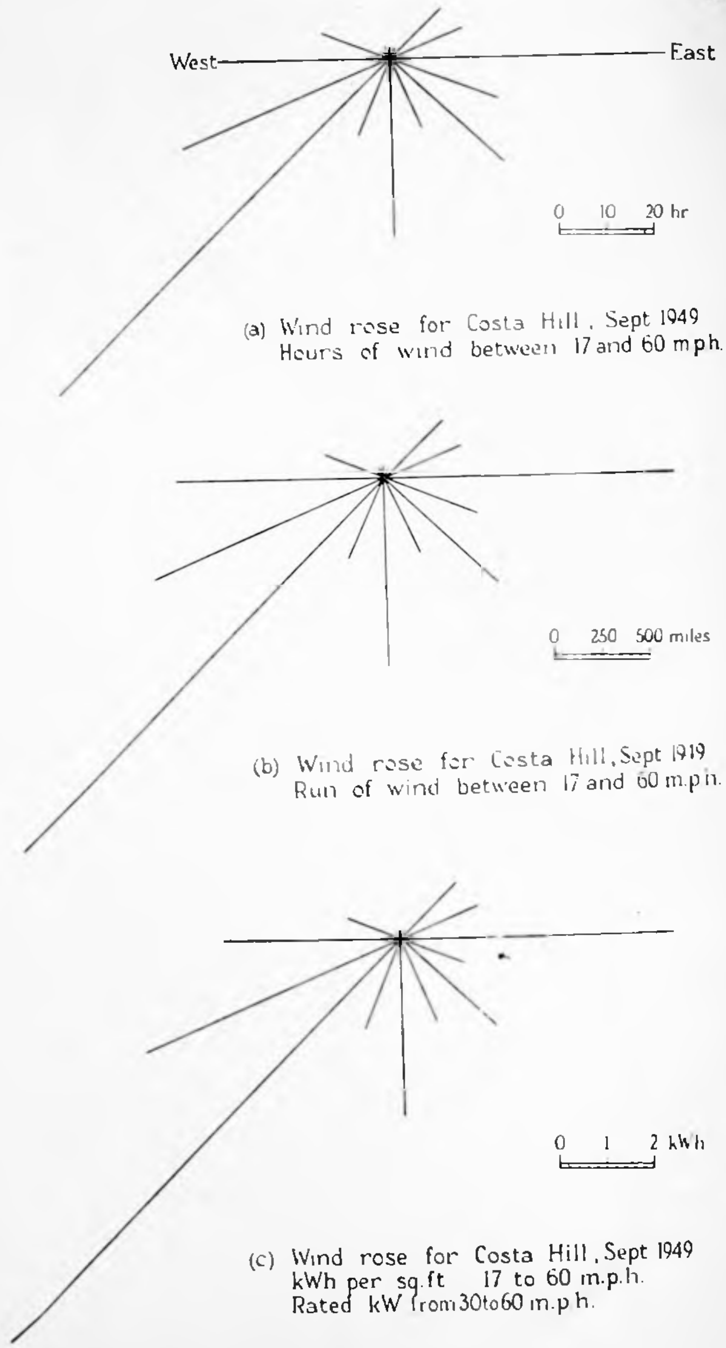
From the limited results so far obtained this phenomenon seems to occur also at Mynydd Anelog where, owing to abnormal acceleration of the wind near the ground, with certain wind directions, the mean hourly speed at 10 ft. is occasionally equal to, or even higher than, that occurring at 66 ft. Under these conditions the difference in mean wind speed between the 35-ft. and 66-ft. levels is negligible.

It will be seen from the above that, in general, no one figure for the vertical wind gradient can be applied with accuracy to a particular hill. It is possible, however, to give average values : these are best obtained by comparison of run-of-wind curves drawn for various heights above the hill. These values for the two Orkney sites are given below.

Site	Comparative run of wind at		
	10 ft.	35 ft.	66 ft.
Costa Hill	1·0	1·06	1·11
Vestra Fiold	1·0	1·18	1·25

(iii) From the foregoing paragraphs it will be seen that, in order to obtain a complete understanding of the wind speed figures, parallel information concerning the wind direction is necessary. For other reasons also it is useful to have a knowledge of the directional changes of the wind. Thus, for example, if it can be shown that at a certain site a very high percentage of the annual wind flow is from one direction, consideration might be given to the possibility of installation at the site of a fixed-head aerogenerator—a tempting project due to the low capital cost involved compared with the normal rotating-head type. While it appears unlikely, from the results so far obtained, that a sufficiently windy site of this kind exists in the British Isles, the possibility should be investigated during any foreign survey.

The type of recorder used in the E.R.A. survey does not provide a continuous record of change in wind direction. Since, however, sudden large changes in direction are unusual, the mean of the two consecutive half-hourly recordings is a sufficient indication of the mean wind direction during that hour. These readings are used in conjunction with the mean hourly wind speed figures for the construction of wind roses, examples of which, shown in Figs. 16 (*a*), (*b*), and (*c*), apply to Costa Hill for the month of September 1949. In Fig. 16 (*a*) the number of hours of wind having mean hourly values between 17 m.p.h. and 60 m.p.h. is shown for various directions. Fig. 16 (*b*) indicates the run of wind in miles in the same way, again excluding winds of mean hourly speeds below 17 m.p.h. and above 60 m.p.h. Finally, Fig. 16 (*c*) gives the energy available per unit area for various wind directions assuming the same wind speed limits but with the additional assumption that constant power is available at speeds between 30 m.p.h. and 60 m.p.h. The labour involved in constructing a diagram of this nature from the photographic record is considerable but since, in its proportions it does not differ widely from the two previous figures, sufficient indication of the energy distribution may be obtained from them to obviate the necessity for its construction.



(a) Wind rose for Costa Hill, Sept 1949
Hours of wind between 17 and 60 m.p.h.

(b) Wind rose for Costa Hill, Sept 1949
Run of wind between 17 and 60 m.p.h.

(c) Wind rose for Costa Hill, Sept 1949
kWh per sq.ft 17 to 60 m.p.h.
Rated kW from 30 to 60 m.p.h.

Fig. 16 (a, b and c).

(6.2.2) Conclusions.

The scope of the second-stage survey is yet too limited to enable conclusions, applicable to all wind-power sites, to be made. Certain inferences may nevertheless be drawn. These are listed below :—

(i) At a good site no great improvement of the wind régime over that found from the preliminary survey is likely.

(ii) The vertical wind gradient above a hill is dependent on its shape. In general, the steeper the slope in any direction the nearer to unity will be the wind gradient with winds from that direction, i.e. the less will the wind speed increase with height above the hill-top.

(iii) Sufficient indication of the energy available at a site from winds of various directions can be obtained from a wind rose showing the times for which these winds prevailed.

(iv) It is improbable that a high percentage of the energy available at any satisfactory site in the British Isles will be provided by winds from any one direction.

(7) RELATIONSHIP BETWEEN ESTIMATED AND ACTUAL OUTPUTS

It is undoubtedly true that the only certain method by which the output of a particular size and type of wind-driven generator on a given site can be determined is to build it there and measure the annual energy which it provides. The 100-kW pilot plants now being installed on Costa Hill and, later, on Mynydd Anelog (sites 2 and 18 of Table 4 respectively) will be subjected to very full tests (see 7.4) from the results of which the relationship between estimated annual output, from previous wind-speed measurements, and actual output will be determined. The interpretation of these results, as will be shown later, may not prove easy but they will, at least, provide a definite link between prediction and performance which may enable the figures of estimated output, such as those in Table 6, to be corrected to actual realizable values.

In spite, however, of the uncertainties which must inevitably be attached to any estimations from the results of anemometer measurements such as those described, wind velocity surveys remain a very important part of the investigations on windpower. Even though values of specific output obtained from them may later prove erroneous it seems unlikely that the errors will be large and, in any event, they must prove useful in assessing the relative potentialities of sites. The sources of the errors which may arise are discussed below.

(7.1) Wind Distribution

A cup anemometer measures the wind speed at the point at which it is located. The instruments used in the survey have been installed at heights above ground of 10, 15 or 30 ft. and their hourly readings have been used in determining the velocity/duration curves upon which, through the derived power/duration curves, the energy estimations are based.

In following this method it is implied that the mean hourly wind speed is the same at all points of the windmill disc as it is at the anemometer. Now it is well known that normally the mean wind speed increases with height above ground, the formula applying to an open site on level ground inland being

$$V = kh^{0.17}$$

where h = height above ground

V = wind velocity

k = constant.

Thus, the mean wind speed at a height of 150 ft. above level ground will be about 1·3 times the speed at 30 ft. At coastal sites the correction factor for height will be less than for inland sites, varying with exposure to a minimum factor of 0·7 of the inland factor when the surroundings of the site are seven-tenths or more open to the sea.

On a hill-top site the factor will be affected by the shape of the hill and will be less for a very sharp ridge than for a flatter one. While, in general, precise information on the increase of wind speed with height above hill-tops of different shapes is lacking, such observations as have been made up to heights of 120 ft. indicate that at a good site the increase from 10 ft. above ground up to this height is not likely to exceed 20 per cent. (i.e. factor 1·2) as shown in 6.2.1.

The variation of mean wind speed horizontally will again depend upon the configuration of the hill-top, but unless the summit is very peaked it is probably negligible.

The mean wind speed over the area swept by a wind-turbine having its axis of rotation at a height around 100 ft. is thus likely to be greater, by perhaps 10 to 20 per cent., than that measured by the anemometers. It is not, however, certain that the output of the plant will be correspondingly higher because the speed with which the blades adjust themselves to the varying wind speed which they meet during their rotation must affect the output.

(7.2) Wind Direction

The direction of the wind, over the hill-top, in both the vertical and horizontal planes must also affect the output of a wind turbine.

Considering first the vertical plane, there may be an inclination to the horizontal of a few degrees, especially at 10 to 30 ft. above ground. Again, the shape of the hill will influence this inclination at greater heights and its effect upon output will depend upon the mounting and degree of coning of the blades and upon their quickness of response to changing winds. The net effect is thus at present unpredictable.

Changes of wind direction in a horizontal plane will not affect a cup anemometer ; their effect upon a wind turbine will depend upon their rate of change. Slow changes which can be followed by reorientation of the machine, through its yawing mechanism, are unimportant, but fast changes will mean that the plane of rotation of the windmill rotor is not normal to the wind. This will cause some reduction of output which should not be serious except in a very gusty wind when the rapid changes in direction may be of considerable magnitude.

(7.3) Variation of Wind Speed with Time

There can be no doubt that its variations of speed with time is the feature of the wind which introduces most uncertainty in attempts to predict what fraction of the total available energy may be extracted by a wind turbine. The effects, which must be considered in relation to the design characteristics of the machine, depend very much upon the rates of change of wind speed and are extremely difficult to estimate with any precision especially when the changes are very rapid. It may, perhaps, be best to discuss them under two headings as follows.

(7.3.1) Changes in Mean Hourly Wind Speeds.

In estimating energy output from measurements of mean hourly wind speed the power/duration curve, obtained by cubing speed ordinates and taking some rated wind speed such as 30 m.p.h., is assumed to be like the full-line curve in Fig. 13. Having already discussed the effects of non-uniform wind distribution in 7.1 we may here take it as uniform over the swept area. Consider also that the wind speed during each hour remains constant at the value measured by the anemometer ; changes within the hour will be considered in the next sub-section. The available power in the wind which can be utilized by the wind turbine will then vary as indicated by the power/duration curve up to the rated wind speed after which, if the governing mechanism is perfect, the power will be limited so that the machine extracts an amount corresponding to its full output.

In energy estimations made earlier in the report the overall power coefficient (C_{op}) of the wind-driven plant was assumed constant over the whole operating range up to the rated wind speed after which it is, of course, artificially reduced by the governor. In practice this will not be so ; the blade pitch will probably remain fixed until full output is reached, and this will cause a fall in the fraction of the available power which is extracted at lower wind speeds. Again, the efficiency of the generator will fall with diminishing output.

Thus the duration curve of *output power* from the generator will not be exactly proportional to the power/duration curve obtained by cubing wind speeds. The latter may be used with sufficient accuracy for estimations of specific output when comparing the potentialities of different sites, but further consideration must be given to the question in attempting to predict the actual performance of an aerogenerator. If the coefficient C_{op} were constant for all wind speeds the curve of output would be of the same shape as the power/duration (curve A of Fig. 17 (*a*)), the ordinates of the latter being merely reduced in the ratio C_{op} : 1.

The coefficient is likely, however, to vary with wind speed as show in Fig. 18, which is drawn from information given in the United States War Production Board report.[6] The dotted curve in this figure shows the variation of the ratio

$$\frac{C_{op}}{(C_{op} \text{ at rated wind speed})}$$

In Fig. 17 (*b*), curve 1, derived from these ratios, gives the values of the correction factors to be applied to corresponding ordinates of the curve A above. Their application leads to curve B of Fig. 17 (*a*). This is the curve of output/duration which would be obtained from an aerogenerator with the given characteristics of C_{op}.

In the example taken, maximum C_{op} occurs below rated wind speed so that the correction increased the output, at wind speeds a little below the rated value, to something greater than that corresponding to the value of C_{op} at rated wind speed. But this increase is obtained at the expense of output at rated wind speed. For a design in which maximum C_{op} corresponds to full output the curve of correction factor would be that marked II in Fig. 17 (*b*). This gives a higher value of maximum output, but the output for wind speeds below the rated speed falls away more quickly.

In designing an aerogenerator for a given power output and rated wind speed it is possible to allow for the fact that C_{op} at full output is considerably less than unity by increase of blade length, but the reduction of output resulting from a falling C_{op} at low wind speeds must be accepted.

It would appear at first sight that, since, at a good site, between one-half and two-thirds of the total annual energy may be obtained from winds having speeds above the rated value it is best to design for maximum C_{op} at full output. The power output curve then takes the form of C in Fig. 17 (*a*) where the annual loss of energy due to part of the curve lying below curve B is small. If, however, the rotor size is increased slightly in order to give the same output at a given rated wind speed in both cases, i.e. if curve B is made coincident with C in the initial, straight part of the curve and the power ordinates over the remainder are proportionately increased, then the difference in the area under curves B and C become considerably more marked. This difference in area represents increased annual energy output in

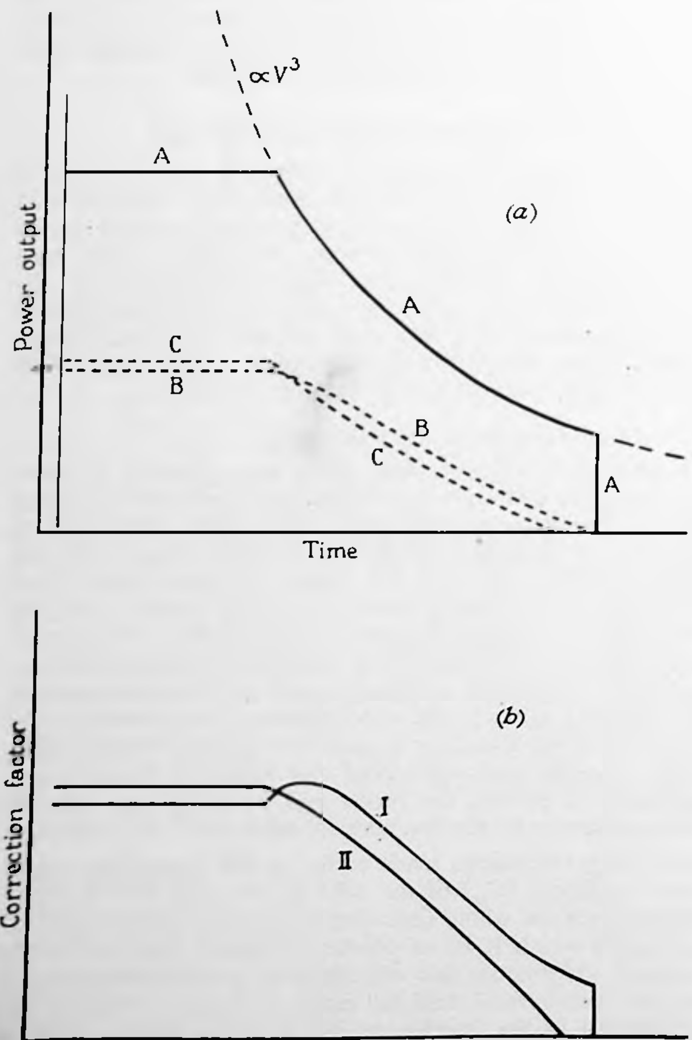


Fig. 17 (a) and (b).—Power output curves and correction factors.

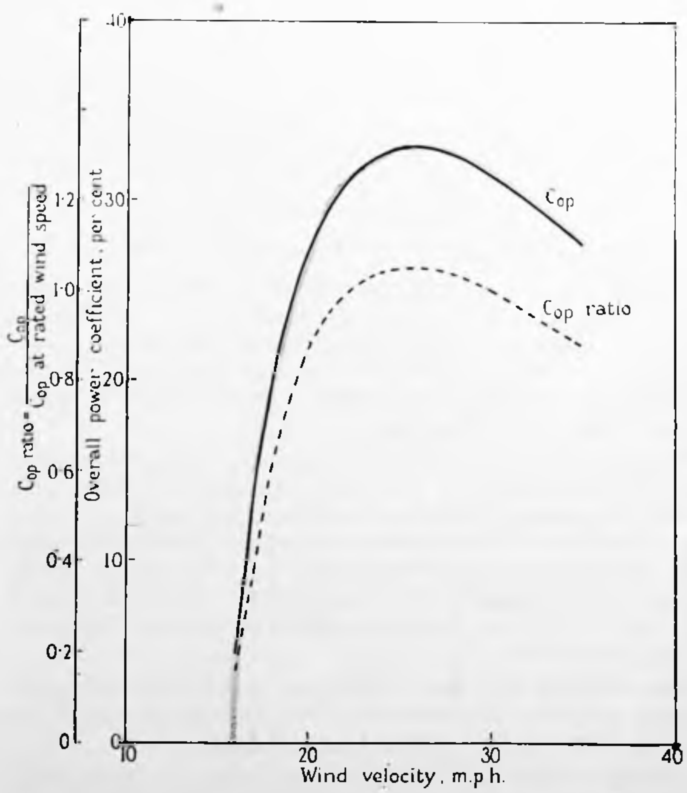


Fig. 18.—Curve of overall power coefficients.

case B and if, therefore, the annual income deriving from it is greater than the appropriate proportion of the increased blade and allied costs arising from the larger blade dimensions required, an economic advantage will be gained by designing for maximum C_{op} at a wind speed of less than the rated value.

(7.3.2) **Changes During the Hour.**

These must be dealt with according to their relative rates of change, but all are supposed to occur within the hour so that they are covered—as far as a cup-anemometer can record them—by the readings of mean hourly wind speeds.

(*a*) *Slow changes.* These are, in this case, changes in speed which are slow enough (taking at least 5 to 10 seconds) for the wind turbine control gear to follow them, so that the power output *at any moment* is that corresponding to the wind speed at the moment as given by the power output curve (taking into account the C_{op} of the machine).

On first consideration it would appear that no error in estimation of the actual output would arise from this cause. But this is not so ; it has to be remembered that such estimations are made from mean hourly speeds and, as will be shown, the energy output for an hour with a varying wind is different from that corresponding to its mean value. Again, this output is not even constant for a given mean value but varies according to the detailed behaviour of the wind during the hour.

A factor K_e, called the "energy pattern factor", has been introduced by some investigators to relate actual and apparent output. This is defined as

$$K_e = \frac{\int_0^T v^3 dt}{T\left[\frac{1}{T}\int_0^T v\, dt\right]^3} = \frac{\text{Actual energy in time } T}{T\,.\,V_A^3}$$

where V_A = mean wind velocity during time T

and v = instantantaneous wind velocity.

Usually T is one hour but it can, of course, be given any value. For infinitessimally small values of time $K_e = 1$ and for periods up to one hour it will not greatly exceed unity, but if longer periods are considered it may lie between 1 and about 4 depending, as it does, solely upon the shape of the wind-velocity curve during the time considered. (The "cube-factor"

$$K_c = \frac{\sqrt[3]{(\text{Mean of the cubes of wind speed})}}{(\text{Mean wind speed})}$$

is sometimes used. Clearly $K_c = \sqrt[3]{K_e}$).

When the overall power coefficient of the plant is taken into account the portion of the power curve between zero and full output may, in fact, approximate more nearly to the parabolic than to the cubic form. Then K_e may approach the value

$$\frac{\int_0^T v^2 dt}{T\left[\frac{1}{T}\int_0^T v\, dt\right]^2}$$

but, although this will be less than before, it still exceeds unity.

The result is that when the wind speed during an hour, although varying, remains within the limits of cut-in point and rated wind speed the energy output will be rather higher than that calculated from the mean hourly wind speed but, in practice, the increase is not likely to be more than a few per cent.

When the curve of available power in the wind is corrected for losses in the aerogenerator as in 7.3.1 the resulting curve of output will be neither cubic nor parabolic in shape. Thus, energy pattern factors, although they are convenient as an indication of a general effect, are artificial and their use in energy calculations may give misleading results.

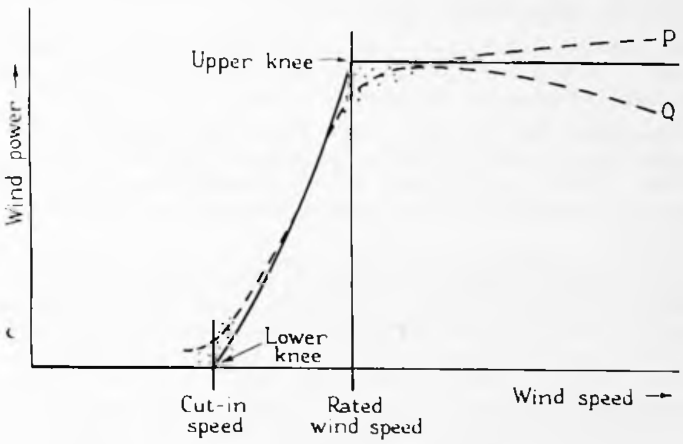


Fig. 19.—Power curves for steady and fluctuating winds.

To consider the effect of slowly fluctuating winds more precisely it may be better to follow a rather different method of approach :—

Consider the power output curve for steady winds as given, full line, in Fig. 19. When wind speed v, and power P, are varying with time the mean value of v is

$$\bar{v} = \frac{\int_0^T v\, dt}{T}$$

and of P,

$$\bar{P} = \frac{\int_0^T P\, dt}{T}$$

These expressions can be written

$$\bar{v} = \frac{\int_0^T v\frac{dt}{ds}\,.\,ds}{\int_0^T \frac{dt}{ds}\, ds}$$

and

$$\bar{P} = \frac{\int_0^T P\frac{dt}{ds}\,.\,ds}{\int_0^T \frac{dt}{ds}\,.\,ds}$$

s being the length of the power curve along which the operating point is moving. Clearly, ds/dt is the rate of movement along the curve and its inverse, dt/ds, corresponds to a weighting of the curve according to the time spent in the element of length concerned.

If these expressions are compared with those used to find the position relative to the axes of the centre of gravity of a curve with a variable mass ρ per unit length we find that they are identical, $\frac{dt}{ds}$ corresponding to ρ.

If each small element ds of the curve is given a weight proportional to the time during which the operating point remains in it, then the centre of gravity of the curve gives the mean wind speed and mean output during the period.

In general, therefore, this point will lie above the power curve where it is concave upwards and below it where it is convex upwards. The flatter the section of curve traced out in the period considered the nearer is the point $\bar{v}, \bar{P}$, to the curve for steady winds. This confirms, of course, that the "energy pattern factor" is only very slightly greater than unity over most of the operating range between the cut-in and rated wind speeds.

There is a more important effect—which might be called the "knee effect" but which is explained by the same reasoning as above—when the mean hourly wind speed happens to coincide (or nearly so) with either the rated wind speed or with the cut-in speed. Assume that the power is rigidly controlled to full output for all higher wind speeds immediately the rated value is reached and, at the lower limit, that immediately below the cut-in speed the power becomes zero. In other words, the curve of power plotted against wind speed has two sharp discontinuities or "knees" as shown in the full-line curve of Fig. 19. Then, when the wind speed during the hour oscillates about the mean hourly values, (*a*) rated wind speed, or (*b*) cut-in speed,

Case (*a*): The energy during the hour (i.e. the mean power) is less than the full output corresponding to rated wind speed;

Case (*b*): The energy during the hour, and hence the mean power, is greater than zero—which corresponds to cut-in wind speed.

These effects are due to the flattening of the power curve above (in case (*a*)) and below (in case (*b*)) the point concerned. Thus, in case (*a*) increases in wind velocity above the mean hourly value do not increase the power output, which remains constant at its full value, whereas decreases in velocity reduce the output so that the net effect is a reduction in the power to something below the full-load value although the mean hourly wind speed is equal to the rated wind speed.

For similar reasons the power will be higher than zero when the wind speed oscillates about the cut-in point.

The magnitudes of these power losses or gains depend upon the amplitudes of the wind speed oscillations which occur during the hour and will thus never be exactly the same for any two hours. A number of hours during which the average wind speed is equal—or nearly so—to rated wind speed will thus give a cloud of points, all *below* the power curve drawn for steady winds, as shown in Fig. 19, if their individual outputs are plotted. In the same way, each hour in which the wind speed averages exactly the cut-in speed will provide one point in a cloud lying *above* the steady-wind power curve.

Thus, for the reasons just discussed, the curve obtained in actual operation, when the wind will certainly oscillate about the mean value during each hour, will be a distortion of the theoretical power curve for steady winds. This is illustrated by the dotted curve in Fig. 19, which suggests that the overall loss in output, if any, due to these effects may not be large.

(*b*) *More rapid variations.* In the preceding paragraphs we have dealt with the slow variations of wind speed during each hour—slow enough for the control gear of the machine to follow them. Consider now—although this may be rather hypothetical—rather faster variations which, while slow enough to overcome the inertia of the machine, cannot be followed completely by the control gear unless its operation is almost instantaneous.

Then, two effects, both of importance only or mainly when the mean wind speed is above the rated value, may occur. The first relates to the heating of the machine. Thus, in a gusty wind the r.m.s. value of the output current, as this varies during gusts owing to sluggish control of blade pitch, will be greater than the mean output current (then at its full-load value). To avoid overheating, the output may have to be reduced below the full-load value unless, perhaps, forced cooling—which should be easy to provide—were employed. With large sets these output fluctuations are very undesirable and the design of the machine should be such that they are reduced as far as possible so that the effect may not be very important.

The second effect—again a reduction of output to something below the full load—may occur when the mean wind speed is above rated wind speed. This is due to the controls reducing output, to avoid excessive stresses, more quickly when the wind suddenly rises than when it falls ; by cutting off the "peaks" and leaving the "valleys" relatively unaffected a net reduction in output might occur. This case, again, may be hypothetical but, if not, the actual power curve for winds above rated speed, instead of being flat, may thus lie between two limits such as those marked P and Q in Fig. 19. The mean power for any given mean hourly speed will depend on the gustiness.

The importance of neither of the above effects, in influencing the annual energy output, can be estimated precisely without an exact knowledge of the rate of response of the control mechanism of the machine. They may not introduce insuperable difficulties but, nevertheless, present yet another problem for the designer of wind-driven plant.

(*c*) *Very rapid variations of wind speed.* These high-speed gusts are likely to be far more important from the point of view of the stresses or vibrations which they set up than for their influence on output. They are not likely to be large in amplitude, nor will they occur uniformly over the swept area, and the inertia of a large-capacity machine is probably great enough for them to have negligible effect on the output. Nevertheless, they will change the aerodynamic conditions at each blade section.

(7.3.3) Errors in Measurement of Wind Speed.

As already stated, cup anemometers, of either the counter or contact type, are used to measure the wind flow and hence to give the average wind speed hourly or over longer periods. The readings of these instruments thus form the basis for estimations of the energy output obtainable at a wind power site. Those used in the wind surveys described have been of the standard Meteorological Office type the calibration curve of which, obtained from wind tunnel tests,[6] shows that their error does not exceed 0·5 m.p.h. for steady wind speeds up to 80 m.p.h. When properly maintained these anemometers retain their calibration remarkably well even when exposed to very rigorous conditions on a hill-top.

With the chart recorder used to record, by dots on the chart, the passage of each two miles of wind past the anemometer there is the possibility of error due to departure of the chart speed

Table 8

ANEMOMETER READINGS*

Costa Hill, 10.00 hours 18–8–51 to 10.00 hours 19–8–51

Type of anemometer	Mean hourly wind speeds (m.p.h.)																							
Dines	32	31	29	36	43	41	46	47	46	45	49	47	46	40	41	42	38	35	32	33	30	25	19	19
Cup-Contact ..	33	31	30	36	43	42	46	48	46	45	49	47	46	40	42	41	38	35	32	33	30	24	19	19
Balsa Wood Windmill ..	33	32	29	37	42	42	46	48	47	45	49	48	45	40	42	41	38	35	32	33	30	23	20	19

* All anemometers sited at 80 ft. above ground.

from its design value of three inches per hour. The drive for the chart is, however, a standard eight-day clock movement and in normal running such errors should be quite negligible.

It has sometimes been stated that, in gusty winds—especially those of high average value—the Robinson three-cup anemometer tends to over-read. Recent tests in which a comparison with a more sensitive anemometer has been made, suggest that it does not over-read to any significant extent. In the cup-counter instrument which merely integrates the wind flow over a lengthy period the effect will be to give a total which is somewhat too high. With the cup-contact anemometer and recorder the hourly speeds above the rated wind speed are reckoned as producing only the same output as the rated wind speed (because of the control mechanism which spills excess wind) so that if over-reading does occur in high winds its effect upon the estimation will be negligible.

The actual error in reading, being dependent upon the rate of rise and duration of the gust, cannot be measured directly, but a comparison of hourly average wind speeds measured by a cup anemometer with those measured both by a Dines anemometer and a windmill-type anemometer subjected to the same wind has been made. A few of the results, covering, in this case, a continuous 24-hour period, are shown in Table 8.

It will be seen that in no instance does the hourly mean wind speed measured by the cup anemometer vary by more than 1 m.p.h. from that given by either of the other instruments. Actually, the agreement between the instruments was closer than appears from the table, in which the figures are given only to the nearest mile per hour.

An indication of the gustiness of the wind during this period is provided by the Dines anemometer chart, Fig. 20.

It is thus safe to conclude that the measuring instruments may be left out of consideration when assessing the possible differences between estimated and actual energy outputs, the effects discussed in the preceding sub-sections being largely of unknown, though almost certainly greater, magnitudes.

(7.4) Investigations Planned to Test the Importance of Various Effects

During the early stages of the operation of a prototype or pilot-type aerogenerator it is essential that a full investigation of the performance of the plant in relation to wind behaviour should be made. While a detailed account of such an investigation lies outside the scope of the present report it is useful, especially as the meteorological measurements involved form the final stage of the wind survey, to describe briefly the arrangements which have been made to study the effect of wind variations on the output of an actual 100-kW pilot plant.

This plant is sited at Costa Hill, Orkney, and its performance is to be related to wind behaviour, details of the latter being provided by instruments mounted on a mast (Fig. 21) some 80 yards from the aerogenerator tower. In its main dimensions this mast resembles the aerogenerator arrangement in that the height of its cross-arms corresponds to the height of the turbine hub and, furthermore, the swept circle of the blades is represented by the two platforms, one at 50 ft. and the other at 110 ft. above ground, and the extremities of the two cross-arms, which are each 30 ft. long. The diameter of the circle swept by the turbine is 60 ft.

Since the 120-ft. mast will rotate through 360° it can be made always to face the mean wind direction and will consequently imitate the movement of the aerogenerator head.

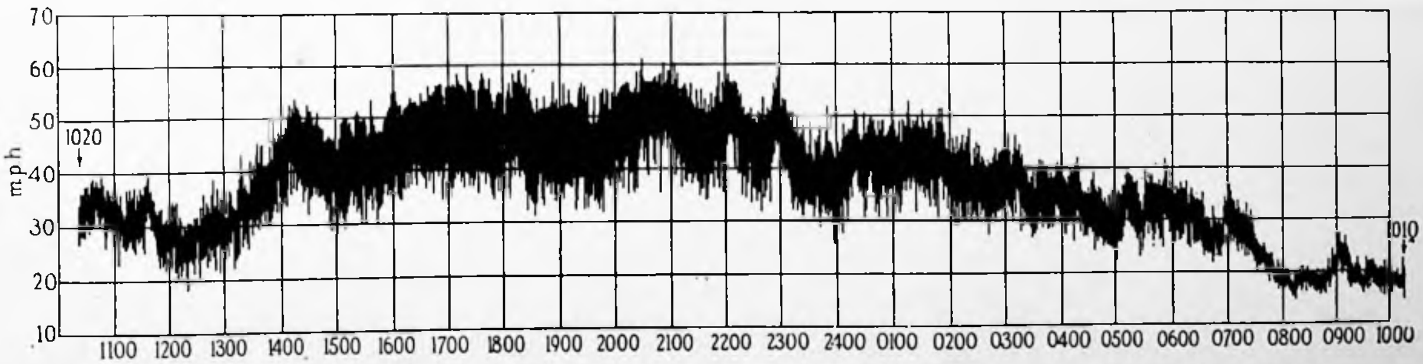


Fig. 20.—Dines anemometer chart for Costa Hill—18th August, 1951, 10.20 hr.—19th August, 1951, 10.10 hr., B.S.T.

Gust anemometers mounted at the four points representing the swept circle of the blades will indicate the range of the instantaneous variations in wind velocity over the swept area and, during steady winds (which have been found to occur quite frequently for short periods of time), readings from them may be related to instantaneous values of power output from the generator. Other types of gust anemometers mounted on the tower cross-arm will measure the lateral components of the wind (i.e. the wind direction) and its vertical component.

Cup anemometers at various heights will provide information on the average vertical wind gradient and on the wind régime applying to the aerogenerator. Comparison between energy estimates made from the power/duration curve for the site and actual energy produced by the machine during the same period will then be possible.

Measurements of temperature at different heights will enable a comparison of gustiness at different temperature lapse rates to be made.

(8) CONCLUSION

In the report the methods used in making a wind velocity survey and in employing the results to form a reasonably reliable estimate of wind-power potentialities at representative coastal sites have been described. Some details have been included for the guidance of others who may wish to undertake a similar survey, but it is not suggested that these methods could not be improved upon. Indeed, until information upon the actual energy output is obtained, from tests upon wind-driven generators located at some of the sites studied in the survey, even the accuracy of the estimates based on such wind measurements must remain open to some doubt.

Nevertheless a survey of this kind is clearly essential as a preliminary to the establishment of wind-driven plant ; without it neither the possible economy of wind-power utilization nor the design requirements for the plant can be determined. Test data from installed generators may indicate the need for corrections to be made to the energy estimates but will not invalidate the results of the survey.

The effects discussed in Section 7 point to the need for further investigation of wind behaviour on typical sites, especially when these are to be the location of wind-power installations. Such investigations are being made in Orkney and in North Wales and will be reported upon later when completed, but they fall outside the scope of the present report which has dealt mainly with the more extensive preliminary work that will always form the first experimental stage in wind-power research in any country.

Apart from the information which has been gained on wind régimes in Great Britain and Ireland, perhaps the most outstanding feature of this survey is the comparative ease with which it has been possible to carry it out. This is not to say that it has been made without considerable cost or without efforts, which have indeed been rather strenuous at times, on the part of the investigators. But, at the outset, the task of covering so large an area of rough country to gain data which must be fairly accurate if it is to be useful, certainly appeared much more formidable than, in fact, it has proved to be. The first attempts were, of course, rather laborious and had to be made with very little guidance from any previous experience; but they were educational and, as experience was gained, the survey became simpler ; a technique was established and a routine followed. If the suggestions made in Section 5.2.1 for basing a survey mainly on measurements of wind flow by cup-counter anemometers prove practicable, those in the future should be simpler still.

(9) ACKNOWLEDGMENTS

Naturally, investigations such as those reported upon cannot be undertaken merely by one or two investigators ; team work, supported by local collaborators, is an essential feature of them. The authors' gratitude to the latter has already been expressed earlier in the report and they wish here to acknowledge also, with no less gratitude, the valuable help they have received from several of their colleagues, particularly from Mr. H. H. Rosenbrock who has made a study of the influence, upon the performance, of the effects mentioned in 7.3.2, and who is mainly responsible for the testing programme, involving use of the 120-ft. mast at Costa Hill, and from Messrs. J. R. Tagg, E. D. Gardner and others who took an important part in the establishment of the survey stations and the analysis of the results.

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20

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20 NOV 1952

BY AIR MAIL

7th June, 1952.

OUR REFERENCE CHP/FKI

YOUR REFERENCE

Sir Geoffrey Miles Clifford,
K.B.E. C.M.G. E.D.
Governor and Commander-in-Chief,
Government House,
Stanley,
Falkland Islands.

Dear Sir Miles,

Wind Power Generation

17. I was interested to receive your letter dated 22nd April, and forwarded an extract from this to Mr. Golding of The Electrical Research Association, together with the specimen chart which you enclosed.

21. I am now enclosing an extract from his reply, which you will see states that the apparatus you suggested is probably satisfactory for the purpose of determining data needed to assess wind power possibilities. I, therefore, suggest that you should go ahead with the investigation, using this equipment, even though that suggested by the Association would probably yield results which are easier to analyse.

I had previously been told that the Association were issuing a further report describing their survey methods and results. On enquiry, I am informed that this is now in the final printing stage, and should be published during the next three or four weeks. I have asked them to let me have a copy as soon as it is available, which I shall forward to you.

Yours sincerely,

C. H. Pickworth

CS. Bu mpt 19

Enclosure

OAG

CdS

Pl. pass to CMO and S/PH Mc. 12/IX

EXTRACT FROM ELECTRICAL RESEARCH ASSOCIATION LETTER
DATED 4TH JUNE. 1952.

"The method of wind speed measurement described in your letter of 13th May, using a cup-generator anemometer and a recording voltmeter, is probably satisfactory for the purpose of determining data needed to assess wind power possibilities. The main difficulty is in analysing the record to obtain the velocity duration curve for the year. This curve is essential. One needs to take from the recorder chart the hourly wind speeds and, with so broad a band, these values are subject to some uncertainty since they have to be estimated hour by hour from the mean height of the record. It is, also, a laborious job. That is why we have used a recorder giving the miles of wind-run in each hour from which the hourly wind speeds are easily obtained. The cup-counter anemometer mentioned is likely to give a more reliable value for the mean wind speed over a period of time when the measured run of wind (in miles) is divided by the time.

The recorder chart with cup generator anemometer gives apparent values of maximum wind speeds which, while useful as an indication, are not very accurate since the response of both anemometer and voltmeter recorder are involved in the measurements.

There appears to be some misunderstanding about the equipment which we use in our surveys. The anemometers (apart from those for gust measurements, which we do not use in surveys but only for gust measurements on one or two potential sites for wind generators) are standard Meteorological Office pattern. Our impulse recorders are at least as useful as the recording voltmeter for general meteorological purposes.

The site described in your letter should certainly give some interesting results and may be satisfactory as a power site."

CMO
S.P.H.
20-21 passed to you accy
29.11

16
H.CS

19-21 Seen try.

The report 19 adds little to the earlier one at 2 but confirms that we will get sufficient information from the proposed cup generator recorder and cup counter anemometers. X on p 24 of the report is interesting in that it confirms my belief that Sappers Hill will be as good a site as any in the vicinity. S.P.H. is providing some data on cost of power lines and I gather from him that this is likely to be about £2-3000 per mile i.e. a large proportion of the capital cost of the figure of £50 per kilowatt at P1 of report at 2 is correct. This high cost of power line might well rule out all other sites (the Sappers Hill site would require about 2500 yds of line i.e of the order of £4000, which compares with about £5000 for the cost of an aero generator). However, the above should await S.P.H's more detailed figures for power line cost.

2. X on 21 is not strictly true. We need instruments for met purposes which record gusts and the impulse recorder used by ERA will not do this. (In fact we have one at Deception working alongside the anemometer generator and it is not as reliable as the latter, apart from the fact that it cannot measure gusts). The reduction of records from the anemometer generator is no problem - it is done regularly for the "Dines" in Stanley which produces a similar record.

3. We expect the equipment in the 2nd or 3rd charter vessels and hope to install it before the winter ⊙

G.H.
17.12.52

H.C.S./

With reference to S.M.O's comments @ 20 it is difficult to give any accurate estimate for overhead power line costs, however basing my figures on costs in 1944-50 the cost per mile for a 3.3KV line of sufficient capacity for Stanley would be in the region of £1,500 excluding labour, to arrive at any real estimate I would need more information of the equipment necessary at the generating end and the receiving end. One point that should be noted is that in the UK when these sets are installed they run in parallel with mostly steam, water, and a few diesel plants all connected on to a bus bar of infinite capacity. Here however in the event of a wind generator coming in on load the machine in the Power Station already running would have to shut down if we are going to save fuel, I have a vision of shutting down and starting up several times in an evening perhaps; all very bad for the machine, maximum wear always taking place on starting.

X If you so desire, knowing our problems here I could discuss with Consultants and put the picture as I know it to them when I return to the UK in March.

[signature] 17-12-52.

Y.H./

To see from 15.
Until C.M.O. has obtained his statistics the financial implications of wind generation cannot be examined - and then it will be a matter for the 'consultants' - but I think S/P.H. suggestion at X above should be implemented in order that P.C.&R. should have as much dope as possible.

[initials] 29/12

I agree - pse ask S.P.W. to act accordingly.
[initials] 30/12

84

S/P.H.

Your minute at X on p.23.
I shall be glad if you will arrange to discuss with [redacted] Preece Cardew & Rider

[signature] 30/12

H.E.S.

Yes Sir.

[initials] 2-1-53

B.U. ~~31/3/53~~ 30/6/53 for H.E.'s return

C.M.O. (22)

Is the equipment installed yet?

[initials] 4/6

H.E.S.

No Sir. We have the cup-counter anemometers but still await the recording voltmeters — there is a

X| long delay in the supply of these. I am keeping the matter in mind but cannot, at present, say how soon we shall be able to go ahead.

[signature] 5.6.53.

H.E.

(20)

Pse see et seq: to (24). [initials] 10/6

X who could ask? K.I.V. [initials]

M.E. 10/VI

If C.M.O. Above. Can you get a delivery date? [initials] 13/8

B.U. 1 month. [initials] 11/6

B.U. 11/7/53

H.C.S.

The recording voltmeters arrived in the last FITZROY. We now have the necessary instruments, a steel tower & fittings, and Mr. Mercer is enquiring about wire to link the anemometer with the recorder. We shall expose two instruments:

1) Cup-counter anemometer – which records miles of wind on a dial like a cyclometer – we'll have to climb the tower periodically to read it.
2) Cup-generator anemometer — which records on a recording voltmeter at a distance. I would *like* the recorder at the Met. Office, where I can keep an eye on it, but if we can't get enough wire we may have to accept a location nearer the site – like the Power House perhaps?

I have visited Sapper Hill and selected the site – on the summit beside the concrete look-out hut. If P.W.D. could lay the foundations (four holes about 2 feet square and 1½ – 2 feet deep) – I can provide the base plates for setting in the concrete, dimensions and so on – Supt. P. & T. says we can run the wire on his telephone poles where necessary – and I'll get my staff to erect the 30-foot tower, instal and connect the instruments and so on. We may have to wait for quiet weather to put up the tower – it may be rather dangerous in strong winds – but we'll go ahead as soon as possible after the foundations are set. If you approve would you seek Supt. of Works comments, pl.

D.Mc
ACMO
15/7/53.

Yh. Be see above. I will discuss x/ with A.S. as this seems a possible task for P.W.D. handymen. (of whom there are, at present, 3 : we could plead an additional burden on S/W at this time).
[illegible] 16/7

Seen: I would like to assist this small piece of research [illegible]

Mc 16/vii

36

A

A S/F (25)

Pse arrange with A/CM for P.W.D. handyman to help him with the installation.

17/7

A/CMO.

B

above for your comments please. I have no objection to Browning assisting with this task which amounts to less than a day's work for 2 men in the operation of laying the concrete.

17/7

C

A.S/F.,

The difficulty is not in laying the concrete but in obtaining, and transporting to the summit of Sappers Hill the necessary sand, shingle, cement, water, base-plates, tower sections and so on. It was because we have no facilities for doing this that I suggested P.W.D. should undertake to lay the Base, and that F.I.D.S. staff should erect the tower and link up the instruments. This seemed fair enough since this is really a Colony commitment and the Colony was being expected to do only part of the work. However, if H.E. approves, I suggest P.W.D. should obtain and transport the necessary materials to the site and F.I.D.S. handyman or Met. staff do <u>all</u> the work.

I have the recording voltmeter on test now and it appears to be working satisfactorily.

D. Mer
21. 7. 53.

A/C.S.

D.

Pl. see B & C above. The transport of materials is the main chore and makes P.W.D. assistance essential. The rest we can manage.

20/7.

A/CMO.

To you for action at E please.

24/7

E.

A S/F Pse discuss direct with D/W

23/7

HCl
Have discussed with W McNaughton and PWD
Will arrange transport

AGL
29/7/53

[initials]
30/7

S/CS.

Anything to report?

[initials]
30/9.

BU 30/9.

HCS I am awaiting news from W McNaughton to say
when he is ready

AGL 1/10/53

A/CMO.

S..

[initials]
2/X.

HCS.
I have told S. of W. that I am ready as
soon as he is & we get a break in the weather. I
am at present testing with 3 miles of wire on
the instrument. I will keep in touch with S of W.

[signature]
2/10/53

HCS/

S..

[initials]
5/10.

BU. 1 month

[initials]
5/10

H.C.S.

I regret to have to report two snags:

1). I have just discovered that we do not have a wind tower in stock for this project. I was assured by my Acting Senior Assistant three months ago that we had, but when I asked him to produce it the other day, he reported that the boxes contained something else! Evidence suggests that he was not alone in his belief, but I have pointed out to him that it was up to him to be <u>certain</u>, and there is no excuse to offer. He has been unusually busy, and I suppose I should accept some measure of blame for not having made a personal inspection – it never struck me as necessary. A wind tower is on order and may arrive by the end of the year.

2). Tests made with three miles of wire on the recording voltmeters have <u>not</u> been successful. The resistance of the wire reduces the effectiveness of the record, and the same is true even when the length of wire is reduced to one mile. I am not very happy about tampering with the instruments themselves (they cost over £50 each), and I don't think the purchase of special wire for the purpose would be justified (even if we were sure it would work).

However, I am determined to get some results without further delay, and I have therefore decided to start (as E.R.A. did at home) with short steel masts 10-15 feet high. I have therefore installed two anemometers in this way on the very summit of the hill, and put the recorder in a weather-proof, locked box in the concrete look-out hut — a relic of the war. The installation will be visited each Monday morning by a member of my staff who will read the cup-counter anemometer, put more ink in the recorder and wind the clock. Tests made at the Met. Office over several weeks indicate that the instrument should operate quite satisfactorily unattended for at least 8 days; we may need to make more frequent visits in winter.

I think we may get some very interesting results.

A

I spent last Thursday afternoon on top of the hill when there was a gale blowing in Town — up there it was almost impossible to stand. Gusts of wind seemed to try to pluck one off the hill — I think there must have been at least a 30% increase over the wind in Stanley.

H.E. has asked to be kept advised.

Dillon
A.C.M.O.
26/10/53.

B

Y.E./
To see from (28)

[initials] 2/11

A/CMO

C

Thankyou. We discussed yesterday and I suggested that the wind-tower at Base D could be brought back for this purpose; it is of no real use at Port Lockroy, as I understand?

MC 8/XI

D

H.C.S.

Noted thank you. I am examining the Port Lockroy position and will see whether we could get the tower out. From a purely meteorological point of view it certainly has little value.

Dillon
3/11/53.

31

J.E. To see 30 D.

[signature] 5/11

A/CMO

Let me know early please as it will be necessary to include in J.B's sailing orders: alternatively S/P&T may have a spare tall mast which he can let you have - he seems to have an absolute forest of them up there and there are more to come!

MC. 6/XI

Y.E. [direct to save time].

I have discussed with Lenton and Marchmont who know the position at Port Lockroy. They assure me that, if the wind tower was removed, it would have to be replaced by a steel mast for radio purposes. This would be difficult to erect on a rocky site and would waste the labour and material which went into the erection of the tower — including a large amount of concrete. On consideration, I think the tower should be left (A.S/F agrees in principle) and I will put up proposals for Port Lockroy in a Met file.

I approached S.P&T. before & he has no masts which could be climbed regularly & this is essential. In the meantime we are getting good results with our short masts.

[signature] ACMO

A/CMO as in margin [signature] 9/11

Noted, agree [signature] 9/XI

CO

Original issued
from 1398

9th August, 54.

3 in 1398

Sir,

I am directed to refer to your letter of the 27th of July, 1954, and to state that Government is prepared to contribute up to £100 towards the cost of this survey.

2. Though not wishing to make this contribution in any way conditional it is requested that Mr. Walker should direct his attention also to the possibility of wind generation.

3. Government has for some years been making investigations into the possibility of large scale wind generation for Stanley and is working in co-operation with Mr. E.W. Golding of the British Electrical and Allied Research Association and, though the practical method of wind generation in the Camp would probably be by means of small units for individual settlements, it is suggested that it would be useful for Mr. Walker to have a talk with Mr. Golding before he sails.

I am,
Sir,
Your obedient servant,

See 40

(Sgd) C. Campbell
COLONIAL SECRETARY.

The Manager,
Falkland Islands Company, Limited,
STANLEY.

CC/VP

33

21st August 54

Dear Sir,

You have been giving us assistance, for some time past, in organising a wind survey of potential sites, near Stanley for generation of electricity from wind power. The correspondence was first started by Sir Miles Clifford, through Mr. C.M. Pickworth of Preece, Cardew and Rider (Consultant Engineers).

See 8, 17, 20

2. For the last three months, we have had a recording anemometer, at 30 feet, and two cup counter anemometers, at ten and twenty feet, operating on Sapper Hill (450 feet). Already, there is good evidence of a "Putnam Effect" but records will be maintained for at least twelve months and full details will then be sent to you.

3. I am writing now, on behalf of the Government, to ask your assistance in a different, though related, matter. This is the provision of electricity at the numerous isolated farm settlements in the Falklands. These number about thirty and each consists of from five to twenty houses. Their requirements of electricity are quite small and about ten kilowatts per hour for twelve hours a day will satisfy the majority. The settlements are scattered over the entire area of about 4618 square miles, most of them being on the two main islands West and East Falkland; but about a third are scattered on small islands several miles from the "mainland". The cost of carrying electricity from Stanley by a grid system would be prohibitive and I should think quite unjustifiable in view of the small use to be made of it.

4. The only alternative would appear to be for the farms to provide their own individual units to supply themselves with power and this probably means that it is outside your province? I have therefore written to Dr. E.A.E. Galley, Director of the Colonial Research Council, Imperial Institute London; because I understand that he has some contact with Enfield Cables, who have an interest in the production of an aero generator of about eight kilowatts. The local farmers, through their Sheep Owners Association, are also making enquiries about small independent hydro units and arrangements are being made with a private firm, Gilbert, Gilkes and Gordon Ltd., to send out their representative (Mr. Walker) to examine the possibilities. Government are making a small contribution to the cost; although it is doubtful whether hydro sites can be found at any but a few farms, and the suggestion has therefore been put that Mr. Walker should also have in mind the using of wind power. Unfortunately nothing is known here about Mr. Walker's firm and it may turn out that he is only concerned with hydro machinery. In that event, he may not be very sympathetic towards utilisation of wind power. However, he is being asked to contact yourself and Dr. Galley before leaving the United Kingdom and I would be most grateful if you can give him any assistance in your power.

5. A copy of my letter to Dr. Galley is enclosed.

Yours faithfully,

C.A. Howkins

Chief Meteorological Officer.

Mr. E.W. Golding, M. Sc. Tech., M.I.E.E.
The British/and Allied Industries Research Association.
Electrical

34

FIDMS 100/54/25 21st August 54

Dear Sir,

I am writing to enquire whether you can advise on any modern applications of wind power to electricity generation.

2. I should explain that we are already conducting a wind survey of a hilly site near Stanley, to see whether a wind generator of the order of 2-300 kilowatts could be used in conjunction with the existing diesel plant which supplied the town. This survey is being done in conjunction with the British and Allied Electricity Research Authority (Mr.E.W.Golding).

3. However, the outlying settlements, scattered across the Falklands have rather a different requirement which I imagine may be somewhat outside Mr.Golding's province and it is in this connection that I am writing to you. This matter first arose as a result of a private letter from the manager of a local firm of general merchants (Mr.Rowe of Estate Louis Williams) to Enfield Cables Limited. The latter replied that they would soon have available an 8 kilowatt wind generator and suggested that you should be contacted about the precise requirements of this Colony. Mr. Rowe therefore handed the matter over to me to persue.

4. The average settlement is from five to twenty houses and requires electricity for lighting, a limited amount of domestic power and occasional power for small workshop machines, automatic sheep shears etc. A plant producing about 10 kilowatts would, I imagine, be ideal for the majority of the settlements provided that it could be linked with some easily maintained storage unit, so that the power can be available at times when there is insufficient wind to produce electricity. Most houses already have wind-chargers such as those produced by "Lucas" or "Wir-charger" and there is usually someone at each settlement with a practical turn of mind. However, there is rarely anyone with a knowledge of electricity, so that equipment must be robust and capable of running for long periods without expert maintenance. No doubt arrangments could be made for an annual overhaul of equipment by having a trained man to tour the various settlements.

5. I have no detailed information about winds at the various farms but, judging from our records at Stanley, winds over the Falklands probably exceed ten knots for more than two thirds of the time, the average speed being about 15-16 knots in open locations. There is no significant annual variation, but diurnal variation is well marked in the summer months, and night-time winds are 20% less than the daily average at Midsummer. The wintertime diurnal variation is small. However, most settlements would have little use for electricity after 9.30 p.m. in the evening, until daybreak, Summer or Winter; so that the reduction in wind energy during the Summer nights is not so important as it would at first seem. Therefore, as a working guide, I would say that the farms require a generator which could supply about ten kilowatts from a wind speed of ten knots, coupled with a storage plant which could stand a drain of up to ten kilowatts per

/ hour for about .....

hour for about six hours.

6. Also, I understand that the local Sheep Owners Association are approaching the firm of Gilbert, Gilkes and Gordon Ltd., with the object of having various farms surveyed for hydroelectric sites. Personally, I doubt whether hydrogeneration is feasible except at a small number of farms. Many settlements are in low lying country and good streams, which maintain a steady flow throughout the year, are uncommon. However, I understand that a Mr. Walker of the above firm may pay a visit to the Falklands early next year. Government are making a small contribution to the cost of his visit and have asked that he should if possible, keep in mind the generation of electricity from wind power. He has therefore been asked to contact you before leaving the United Kingdom. I do not know whether Mr. Walker's firm is concerned solely with hydro-electric plants and therefore whether he will be prepared to consider wind power. If he will do so, it may be possible to combine the two ideas by converting surplus kinetic energy from wind into potential energy, by pumping water to a height, and using this to operate a small hydro-generator. If the latter can be built so as to take advantage of an existing stream, then a good supply of electricity might be obtainable continuosly.

7. I know nothing about the technicalities of electricity generation but venture to offer the following idea for your comments. The wind generator made by Enfield's French associates Ateliers et Chantiers de France, should be used to produce hydrogen by electrolysis. This gas should be stored in cylinders and used as fuel to drive a simple internal combustion gas engine (viz the engines powered during the war by gas from coke burners). The size of the hydrogen storage plant should be sufficient to cope with the average requirements when wind power is not available, but exceptional cases (e.g. during unusually long periods of calm) should be covered by providing the gas engine with a carburetter for paraffin. The gas engine would drive an alternator to produce the electricity. No doubt the aero generator could be automatically switched off as soon as the hydrogen storage was filled, and, if designed in this way, it should be possible to seal both the aero generator and hydrogen plant so that no inexperienced person could tamper with it. Most farms would have someone capable of running a simple internal combustion engine and, if a fault developed in the aero unit, then the power could be maintained by paraffin fuel until an experienced man could reach the farm. A ten kilowatt gas engine with alternator would probably cost something of the order of £500. The aero generator and hydrogen plant might cost twice this amount but, against this, twelve hours running per day on paraffin would cost at least £200 per annum. Maintenance on the entire plant should be small.

8. I appreciate that this sketchy information is quite inadequate for a proper investigation but I would be glad to supply details if you are in a position to help. The Colonial Secretary is aware that I am writing to you, so that my approach to you is a demi-official one, and if you are able to help in this matter, further correspondence from this end will reach you through the Colonial Office. Meanwhile, I shall be most grateful for any assistance you can give to Mr. Walker, if he approaches you.

Yours faithfully,

G.A. Howkins

Chief Meteorological Officer.

Dr. R.A.E. Galley Ph.D. D.I.C. F.R.I.C.
Director of Colonial Products Research Council,
Imperial Institute,
London S.W.7.

36

FIDMS 100/54/27 21st August 54

Dear Sirs,

Mr. Rowe of Estate Louis Williams, Stanley, has handed me your letter SC/JB of 24th March and the accompanying pamphlet illustrating an 8 kilowatt wind plant manufactured by your French Associates Ateliers et Chantiers de France.

37

2. I am at present making a wind survey of the Stanley area (in conjunction with the British and Allied Electricity Research Authority) to see whether a wind generator of the order of 2-300 kilowatts could be used, along with the existing diesel plant, to supply the town of Stanley.

3. However, the equipment which you mention in your letter to Estate Louis Williams would appear to be ideal for most of the scattered sheep farms in the Falklands. These small settlements of from five to twenty houses require lighting, a limited amount of electrical power for domestic purposes and occasional power for small machines such as sheep shears. Hence, equipment producing something of the order of ten kilowatts may well suit most farms, provided that it is linked with some means of storage, so that the power can be available at times when there is insufficient wind.

4. I have no detailed information about winds at the various farms, but, judging from our records in Stanley, winds over the Falklands probably exceed ten knots for more than two thirds of the time, the average being 15-16 knots. There is no significant annual variation but diurnal variation is well marked in the summer months and averages 50% (maximum over minimum) at Midsummer. However, this lack of wind energy is not so important as it would at first seem to be, because most settlements would have very little use for electricity after 9.30 p.m. until daybreak Summer or Winter.

5. I am writing to Dr. R.A.E.Galley, as you suggest, but would welcome any information which you may have about plant of the order of ten kilowatts. You will, of course, appreciate that, personally, I am only concerned with the technical aspects and that any orders which may be placed as a result of our tests in Stanley would be dealt with through the Crown Agents for Overseas Administrations and Governments. Requirements for the outlying settlements are, strictly speaking, a matter for the farmers themselves who will no doubt approach you through their Association and any local agent which you may appoint. However, I have no doubt that Government would take a keen interest in anything which is likely to meet a general need such as exists for electricity at almost all settlements.

Yours faithfully,

G.A. Howkins

Chief Meteorological Officer.

Enfield Cables Limited,
Victoria House,
Southampton Row,
London W.C.1.

37

COPY

Ref:
Ours SC/JB
Yours 1053/1481-Q

Enfield Cables Limited,
Victoria House,
Southampton Row,
London W.C.1.

24th March 1954.

Estate Louis Williams,
General Merchants,
Port Stanley,
Falkland Islands.

Dear Sirs,

Wind Power

We regret to note that your interesting letter of October 29th has not yet been dealt with. Perhaps this is because we have had very little which we could usefully add to the information already sent.

Quite recently, however, we have had a long discussion with Dr. R.A.E. Galley, Director of the Colonial Products Research Council, and we think he would be quite pleased to hear from you about your energy problems in order that he may advise you, the Crown Agents, and the Colonial Office, as to the priority which is to be given to the development of new sources. May we suggest that you write to him at the Imperial Institute, London S.W.

Meanwhile, we enclose a leaflet which illustrates an 8 kilowatt wind plant manufactured by our French Associates, Ateliers et Chantiers de France. Selling rights for these plants in the British Commonwealth are vested in us and in about twelve months they should be available at a reasonable price.

Yours faithfully,
for ENFIELD CABLES LIMITED

(signed) S.Chaplin,

Associate Director.

ius

FALKLAND ISLANDS AND DEPENDENCIES

METEOROLOGICAL SERVICE

With the Compliments

of

The Chief Meteorological Officer

Cooking by Windmill

by D. H. Middleton.

To the best of our knowledge and belief, an "Eighty-four" Cooker is the first gas appliance in the world to be operated by Hydrogen which has been produced from water with power generated by a windmill.

The Hydrogen is produced at Prae Wood, St. Albans by Enfield Cables Ltd. in an exhibition which displays a wide range of machines and processes all operating successfully on fuel or power created by hanessing the winds.

Throughout the ages, man has sought to convert the force of the wind into mechanical power but the few remaining windmills derelict in this country testify to the uneconomical and inefficient results hitherto achieved.

Now a new principle is being applied, and although an enormous amount of research and experimental work remains to be done, practical results have already been achieved.

The conventional method employed in the past was to have some form of mechanical transmission direct from the shaft of the windmill. The Enfield project bears no relation to this, its success arises from the application of the well known principle of centrifugal force.

If an object is tied to the end of a piece of string and swung round and round, the string will remain taut. Should, however, the knot become loose, the object will be thrown off with considerable force; in fact, by the action of centrifugal force.

To apply this principle, a hollow tower has been built, to the top of which a hollow propeller is fitted, the latter being revolved by the wind just as the old fashioned windmill was.

At the tips of the propeller blades, on the edges which are not facing the wind, there are air outlet holes. As the propeller revolves, centrifugal force throws out the air from these holes in exactly the same way as it would our object if the knot in the string became loose.

When the air is thrown out, more air moves up the hollow tower into the propeller to replace that which has been ejected and is in turn thrown out through the holes. This process is continuous and the up-draught in the hollow tower reaches a tremendous velocity.

This high velocity air stream is utilized to rotate an air turbine built into the lower part of the tower. The turbine shaft is coupled to a generator which converts the wind power into an electrical power supply.

Having obtained electricity at a negligible operating cost, it becomes a comparatively simple matter to apply it to a wide range of electrical, mechanical and chemical operations and processes.

One of them on show at the exhibition is the separation of water into hydrogen and oxygen, the hydrogen being used to drive a gas engine and also as fuel for the operation of a converted "Eighty-four" Cooker.

This conversion was the result of a dinner at which Lord Verulam, the Managing Director of Enfields told Mr. Kenneth Davis the story of this new project. Mr. Davis arranged for Central Laboratories in Birmingham to make new burners of similar power for the otherwise standard cooker.

The cost of power produced by this new type windmill is calculated to be a farthing per kilowatt hour as compared with the cost of nearly a halfpenny per kilowatt hour for electricity generated by the orthodox coal-burning steam generating plant.

The possibilities of this new form of wind power utilization are so great that the British Electricity Authority have taken the initiative in supporting the Enfiled project. They visualise the erection of a number of large wind-power generators in suitable spots as an economic and therefore valuable means of feeding cheap electricity into the national grid system.

Those of us without town gas who prefer the advantages of cooking with gas will perhaps have a windmill on our house-tope!

YE The answer for the F.! when peak runs out — or before ?

2/10

Copy for C30

4

COPY

40

Original filed
in 1398

20th September, 54.

Sir,

32A

I am directed to refer to my letter No. 1398 of the 9th of August, 1954, and to your letter of the 10th of August, 1954, on the subject of the hydro-electric survey and to state that it would be appreciated if Mr. Walker could also have a talk with Dr. R.A.E. Galley of the Colonial Products Research Council, particularly as the latter is more concerned with small scale wind generating units. Both he and Mr. Golding have been advised that Mr. Walker may be getting in touch with them.

I am,
Sir,
Your obedient servant,

(Sgd) C. Campbell

COLONIAL SECRETARY.

The Manager,
Falkland Islands Company, Limited,
STANLEY.

C/VP

No.100/55/6

It is requested that, in any reference to this memorandum the above number and date should be quoted.

MEMORANDUM.

2nd March 1955

H.C.S.,

Stanley.

C.M.O.

Stanley, Falkland Islands.

SUBJECT :- Hydro-Electric and Wind Survey

I saw Mr. Walker of Gilbert Gilkes and Gordon on Saturday, 12th February and the following points are of interest:-

1. Mr. Walker explained that, although he is the London Manager of the above firm, he is acting as an independent advisor during his visit to the Falklands and therefore will make a point of not pressing his firm's products. He has already acted in this capacity several times elsewhere.

2. He confirmed that the Murrel would be surveyed as a potential source of hydroelectric power for Stanley and stated that transmission lines of up to six miles or so should be quite economical provided that the power source was adequate.

3. He emphasised that he was no expert on wind power, but he had been able to get a good deal of information from Mr. Golding who was probably the only person in the United Kingdom who could claim to be expert in this field. Mr. Golding was very interested in a comprehensive wind survey of the Falklands because he was working on a theory that surveys for a particular place could be applied to other areas in the same latitude. He would therefore like to have the Sapper Hill work repeated at a number of different positions in the Falklands.

I stated that Government would probably find it too expensive to instal recorders but thought that a number of cup counter anemometers (costing about £20 each) might be considered.

4. Mr. Walker was very interested in the Sapper Hill records - especially in the apparent gain in wind speed due to the height and shape of the hill- and asked that we should send our results to Mr. Golding immediately, without waiting to complete a years operation. I undertook to send these as soon as possible (though we are very pushed at the present time).

5. Mr. Walker stated that, although he found the wind research interesting and thought that it may eventually prove successful as a fuel saver in large grid systems; he did not think that it was likely to be a commercial proposition as a source of small amounts of electrical power for many years. He also had personal doubts about the figures of £50 to £70 per kilowatt claimed in Golding's article and thought that the actual production costs might well be several times this figure. He also suggested that the novel design of the French generator would probably be discarded for a simpler well-tried mechanism if the equipment was put into production.

Mr. Walker is therefore satisfied that, where the water power exists, there is no cheaper or more effective way of producing electricity. The equipment has been well tried (some small plants have operated for 50 years or more with hardly any maintenance). The simplest installation is used where there is always enough flow to cope with the maximum loads but, a slightly more complicated method can be used if the flow is capable of dealing with the average load. In the latter case a small dam is built and the flow is automatically diverted into this when the electrical load falls below average. ...

/6. Mr. Walker ....

6. Mr. Walker will also look out for those cases where a combination of water and wind power might be practicable i.e. by having a wind mill to pump water from a low point back to a higher reservior when the supply of water is inadequate. One snag in this is that areas where water power is available are almost always low-lying parts and are frequently sheltered by hills so that they would be generally unsuitable for wind mills.

7. Mr. Walker will also look for potential wind generating sites and provide a list of these on return to Stanley. The most promising of these could perhaps be surveyed by Government, using the cup counter anemometers mentioned in paragraph 3. (It might be reasonable to expect the Farm in question to contribute towards the cost of the equipment.)

8. Mr. Walker is intending to visit the Met. Office and the Power House on his return to Stanley and will want to discuss the whole question of generators for Stanley with S.P.H. - especially the economics of producing electricity from diesel fuel.

G.A. Hoskins

Mr H. wd like file back pl.

C.no. Thank you - most interesting & we will await developments. I presume you are keeping SPW informed.

8/3

C.no. Seen thank you.

[signature]

10-3-55.

DMS 100/55/13

MEMO[RAN]DUM.

...c is requested ...t, in any refer-...ce to this memorandum the above number and date should be quoted.

17th August ...

Chief Met. Officer.

Stanley, Falkland Islands.

Hon. Colonial Secretary.

SUBJECT :- Preliminary Report on Sapper Hill Wind Measurement.

Copy of Preliminary Report on Sapper Hill Wind Measurements attached for filing. Copies are being sent to Mr. E.W.Golding E.R.A. and to Dr. Galley of Colonial Research Council.

2. Grateful to know if you approve suggestions for further work in Section I. of Report i.e. to install Cup contact anemometers at four or five places in the camp. The equipment will cost about £10 per station, for the basic measurements but it would be desirable to spend a further £25 at one station to get more detailed information - a total cost of from £75 - £100 for first cost, including installation, and about £25 per annum to observers for taking the readings.

3. This could be provided in Colony estimates under Head VIII (b) 3 ?

C.A. Howkins

Sie pe.

The Falkland Islands Company, Limited.

53A

(INCORPORATED BY ROYAL CHARTER 1851.)

REGISTERED 1902.

TELEPHONE: WHITEHALL 6077/8.
TELEGRAMS: "FLEETWING, PICCY, LONDON"

120, PALL MALL,
LONDON, S.W.1.

31 OCT 19

WHY/TFW

29th August, 1955

O. R. Arthur, Esq., C.M.G., C.V.O.,
36, Argyll Road,
London, W.8.

Dear Sir,

I recently had a most interesting meeting with Mr. Walker of Messrs. Gilbert Gilkes & Gordon, and Mr. Golding of the Wind-power Research Station. Mr. Golding informed me that Messrs. John Brown & Co., had now developed their wind-power generator to such an extent that they were in a position to accept orders for 250 kilowatt type and he thought prices would be in the region of £100 per kilowatt. I advised him that a generator of this size was, of course, too large for our requirements but it might possibly be of interest to the Falkland Islands Government and as you were at home I thought that you might care to see the enclosed 53B. extract from the magazine "Engineering." I understand that if you wish to make any further enquiries, Sir Stanley Rawson, the Vice Chairman of John Brown & Co., would be very pleased to meet you and discuss the matter.

From figures supplied by Mr. Howkins from the instruments on Sappers Hill, Mr. Golding is of the opinion that this site should provide a high enough average wind speed to drive a machine of this size, though he qualified his opinion when he learned from Mr. Walker that the readings obtained only cover a period of one year.

My Father is at present on holiday but I thought that in view of your presence in this country you might be interested to learn of the foregoing.

Yours faithfully,
For the FALKLAND ISLANDS COMPANY LIMITED

Secretary.

WIND-DRIVEN GENERATOR ON COSTA HEAD

OPERATIONAL EXPERIENCE AT VERY EXPOSED SITE

Costa Head in the Orkneys is one of the windiest and most exposed places in the British Isles. Because of the wind it is eminently suitable as a site for a wind-driven electric generator, but because of the exposure the conditions for construction are formidable. In spite of the difficulties, the 100-kW plant shown in Fig. 1 has been erected there by John Brown and Company (Clydebank), Limited, Carlisle-street, Sheffield, 4, for the North of Scotland Hydro-Electric Board. The plant has been running in parallel with the Diesel generators on the island at various times over the last year; because the plant is largely experimental, however, there have been continual modifications in the light of field experience, and operational running has not been continuous. John Brown and Company are now working on a design for a 250-kW wind-driven generator and experience gained from the first machine will greatly reduce constructional and operational problems in the second.

The Costa Head windmill has been designed to give an output of 100 kW with a rated wind speed of 35 m.p.h. The height of the triangular-section steel tower is such that the centre of the rotor is 78 ft. above the ground, and swept diameter of the three-bladed rotor is 50 ft. The nacelle mounted on top of the tower, shown in Fig. 1 and diagrammatically in Fig. 2, carries the three-bladed rotor, step-up gearbox with clutch, and electric generator; in addition, it carries the pilot windmill, yawing vane, and control gear, which together position the blades appropriately in relation to the wind and keep the rotor shaft turning at the correct speed. The output from the generator is 3 phase, 415 volt, and is fed through slip rings and cables running down the side of the tower to the transformer shown at the foot of the tower. From there the output is fed to the main distribution network of the island through the 11-kV line also shown in Fig. 1.

TOWER AND FOUNDATIONS: DESIGN FOR HIGH WIND LOADING

To withstand the exceptionally high winds—gusts sometimes exceed 125 m.p.h.—great attention has been paid to the construction of the tower and its foundations. For a depth of 6 ft. below the surface the ground consists of soft rock. An excavation 6 ft. 9 in. deep was made at each of the three points where the legs of the tower stand, and from the bottom of each excavation eight holes 4 in. in diameter and 6 ft. deep were drilled in hard rock at an angle of 20 deg. to the vertical, equally spaced on a 3 ft. 9 in. square. Mild-steel rods 1 in. in diameter and 9 ft. long were grouted into these holes, and the excavation was then partly filled with concrete, giving a block 6 ft. square at the base and 4 ft. square at the top by 2 ft. 6 in. thick, the top being 4 ft. 3 in. below ground level. A steel plate 2 ft. square by 2½ in. thick was fixed to the block, the mild-steel rods acting as foundation bolts, and the leg of the tower was firmly cleated to this baseplate. More concrete was poured in to cover the plate and to case the tower leg to above ground level, and finally the hole was filled in with some of the excavated material.

The tower is constructed from steel angle sections, galvanised after fabrication. It is triangular in section, the width of each side being 24 ft. at the base and 7 ft. 10½ in. at 66-ft. level. The total height from the ground to the seating for the bull-gear is 71 ft. 6½ in. There are two platforms, both clearly visible in the illustration, and a built-in steel ladder for access to the nacelle. The cables carrying the generator output to the transformer can be seen running down the leg of the tower nearest to the control room.

NACELLE: FIXED AND FLOATING BEDPLATES

The nacelle and its mounting are shown in section in Fig. 2. It is mounted on a pintle shaft to allow the windmill to be yawed round to suit the direction of the wind. The windmill head is supported by the bull-gear, a large and heavy steel casting fixed to the seating on the top of the tower. The bull-gear casting forms the housing for the bearings in which the pintle shaft and hence the whole windmill head rotates. The pintle shaft itself is a hollow steel casting 4 ft. long, 13½ in. outside diameter at the centre and tapering towards each end, with a wall thickness of 1 in. To the pintle shaft the fixed bedplate is rigidly attached.

The fixed bedplate is a welded steel framework 18 ft. 5 in. long by 4 ft. wide. At the windward end are containers for ballast weights, which help to relieve the bending stress in the pintle shaft; this bending stress is also relieved by four sets of rollers running on the flange of the bull-gear, one of which can be seen in Fig. 2 at the forward end of the bull-gear. At the centre of the fixed bedplate are the bearing housings for the journals of the floating bedplate (the bearing housing is shown in Fig. 2 as "rocking centre of floating bedplate").

The floating bedplate is also a welded steel framework, and supports the hub and blades, gearbox, and generator. The whole floating bedplate can move in a vertical plane about the rocking centre, but its movement is restrained by the main springs, auxiliary coil springs and auxiliary transverse spring. The effect of this mounting is to reduce the transmission of vibration and shock from the rotor to the pintle shaft and tower; the combination of springs cushions any relative movement there may be between the fixed and floating bedplates.

In Fig. 6 the hub and gearbox are shown being lifted into position during the construction of the windmill. The bottom half of the nacelle is in position, and the top half can be seen lying on the ground in front of the tower. Erection could only be carried out while the wind allowed, and raising the heavier items was the most difficult part of the job.

LIGHT WOODEN BLADES

The propeller hub consists of a central boss to which are welded three short hollow flanged arms, to each of which is bolted a tubular extension piece. From the centre of the boss to the fixing point for each blade is 8 ft., and with blades 17 ft. long this gives a swept circle of 50 ft. diameter. The blade spars are made of compressed laminated wood, the ribs of spruce, and the skin of $\frac{3}{32}$-in. mahogany ply covered with plastic coating and painted; the weight of each blade is about 150 lb. At the point of attachment to the hub is a high-tensile steel fitting. Each blade fitting is attached by quickly detachable fork joints with taper-pins to a universal joint with needle-roller bearings. These give the blades freedom to "cone" and "drag" when up to speed ("dragging" is the movement of the blades about their root fittings in the plane of rotation, and "coning" is the movement of the blades about their root fittings towards and away from the tower).

The point of attachment is shown in Fig. 3, which also shows the damping gear which operates in the drag plane. The coupling through the two universal joints and the shaft at the bottom left of Fig. 3 gives the blade freedom to draw out and to move in the coning plane, but movement in the drag plane is controlled by the damper. The blade itself acts as a damper in the coning plane. When the machine is shut down, draw-out springs pull back the root fittings about 2 in., thereby causing a shaped part of the universal joint shank to seat on a hollow rubber cuff in the end of the hub arm, thus restraining the universal joints and holding the blade steady. Because the blades are held in this fixed position by springs and because the seating is rubber, there is a certain amount of freedom to move if the winds are very strong. In the winds at Costa Head this provision has been of great value.

The drive from the hub is transmitted through a step-up gearbox, weighing 2 tons, which operates with an input speed of 130 and an

Fig. 1 The 100-kW generator on Costa Head consists basically of a triangular-section steel tower, a control room at the base of the tower, and a nacelle containing the step-up gearbox and generator. The generator output is transformed to 11 kV and fed into the Orkney mainland distribution network through the overhead line.

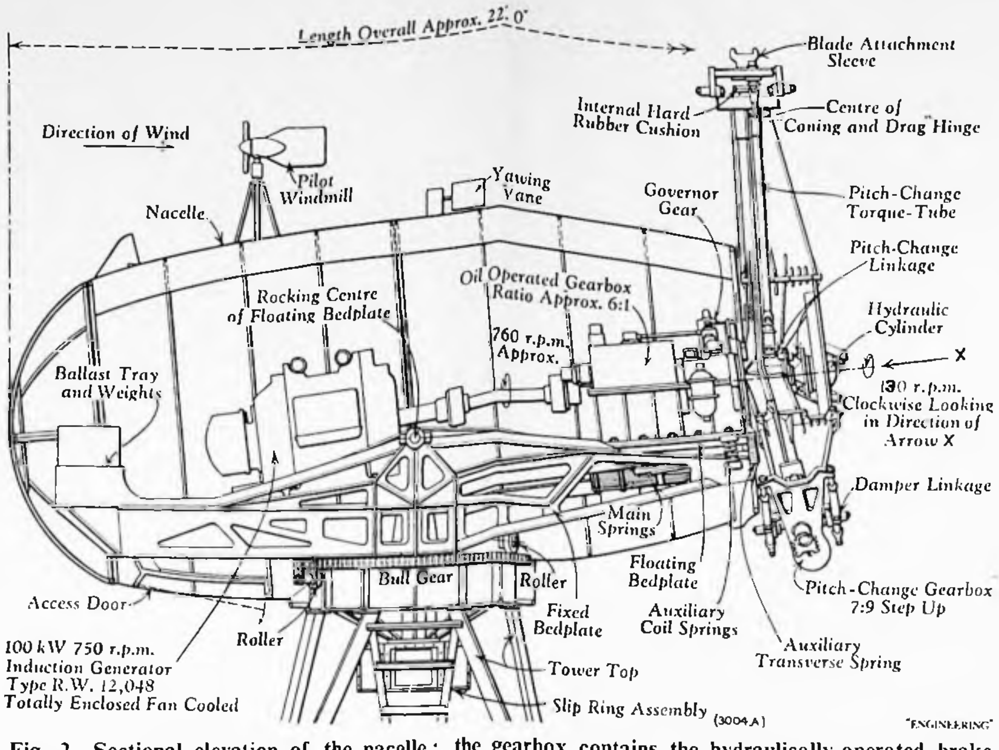

Fig. 2 Sectional elevation of the nacelle; the gearbox contains the hydraulically-operated brake and clutch. Power from the generator is fed through slip-rings, which allow the nacelle freedom to yaw, and down cables to the transformer at the foot of the tower.

output speed of 750 r.p.m. The gearbox also contains a brake and a clutch, both hydraulically operated. The output shaft of the gearbox drives the induction generator. The generator was made by Metropolitan-Vickers Electrical Company, Limited, Trafford Park, Manchester, 17, who also made the electrical control gear. The generator is of the slip-ring type, is totally enclosed and fan cooled, and its output is 100 kW at 415 volts, 3 phase, 50 cycles; it weighs about 2 tons.

CONTROL OF ROTOR SPEED

The control mechanism of the Costa Head generator holds the rotor speed nearly constant while the machine is generating. In addition, the control mechanism starts the machine when the wind speed becomes sufficiently high, stops the machine when the wind speed becomes too low, and also stops it in emergencies. The sequence of starting is first described in general terms, and is followed by a more detailed account of the control mechanism.

With the clutch disengaged the generator is run up to speed as an induction motor; this also starts the oil pumps for main lubrication and the various hydraulically-controlled systems. A brake on the rotor is released and the pitch-change mechanism gradually alters the pitch of the blades from full feather to fine pitch, thus enabling the wind to start up the rotor. The rotor gathers speed at a pre-determined rate under the control of the governor, and when the speeds of the rotor and generator are correctly matched the clutch is engaged to connect them mechanically. The electrical control gear then measures the electrical output and cuts out resistance in the generator rotor circuit and adjusts the governor so that the machine is made to carry full load.

Under working conditions this operation is automatic, controlled by the electrical gear in the building shown at the foot of the tower in Fig. 1. If necessary, however, the operation can be done manually through a series of press-buttons associated with coloured signal lights which indicate how far the starting procedure has progressed. The shut-down sequence is normally automatic. Safety devices ensure that in the event of an electrical failure or any other mishap the windmill is brought to rest and prevented from re-starting until the fault has been rectified.

When the plant is operating automatically indication of the wind-speed is given to the control gear from the pilot windmill shown on top of the nacelle in Fig. 2. The pilot windmill drives a tacho-generator the output voltage of which is proportional to the wind-speed over the appropriate range. When the wind speed rises above 23 m.p.h. the tacho-generator voltage becomes sufficient to close an instantaneous relay. Since the wind may reach 23 m.p.h. in a gust and then die away again the instantaneous relay is connected to an integrating relay, which can integrate the wind speed over varying periods up to a maximum of 10 minutes. If the wind remains strong enough for the required period supply to the generator is switched on, and it runs up to full speed as an induction motor. At this stage all the resistance in the generator rotor circuit is in, and the clutch in the gearbox is disconnected.

ELECTRIC AND HYDRAULIC CONTROL GEAR

As soon as the generator is running the pumps, which are mechanically connected to the generator, begin to deliver oil. The low-pressure pump (which is not shown in Fig. 4) supplies oil at 60 lb. per square inch, which releases the brake in the gearbox, setting the blades free to rotate. The high pressure pump supplies oil to the 2½-gallon capacity accumulator (shown in Fig. 4), gradually increasing the pressure to 500 lb. per square inch. When the accumulator pressure reaches a pre-set value (about 400 lb. per square inch) a pressure-switch closes and allows the starting sequence to continue.

During this time the governor speed-setting lever, which bears on the speeder spring, has been brought to its lower position by the actuator. The actuator is basically a small electric motor, and the impulses that operate it are entirely electrical. When it is at its lower position it operates a switch which causes the solenoid connected to the governor emergency valve (both shown in Fig. 4) to be energised, and this gives control of the blades to the governor working through the main governor valve, shown just above the emergency valve in Fig. 4.

The lowest speed setting of the governor is about 40 r.p.m. and the blades now move towards fine pitch under the control of the governor, speeding up under the influence of the wind until they reach this set speed. When they do so a switch on the governor is closed and the actuator starts to move the speed-setting lever slowly upwards; once the switch is closed the actuator moves independently of anything else. The speed of the blades now increases under the control of the governor until it reaches the highest speed permitted by the governor, about 10 per cent. above normal running speed.

RUNNING UP AND CONTROLLING GENERATOR OUTPUT

When the blades are running at the highest permitted speed a switch on the governor closes, causing the clutch in the gearbox to be engaged. The set now starts to generate, but the output will not be large since all the resistance is still in the rotor circuit. A power relay now operates the actuator to reduce the generator speed and so reduce the generated power. When the power lies between 0 and 5 kW one resistance bank is removed from the rotor circuit. The generated power therefore increases, and the power relay again reduces the speed until the power lies between 0 and 5 kW and then cuts out a further stage of rotor resistance. This process continues until the rotor resistance is reduced to the required value.

Control of the actuator now passes from the power relay to a current relay which endeavours to increase the speed until the power output is 100 kW. This will only be possible if the wind is over 35 m.p.h.; if it is not, the blades will go to the fully-fine position and the windmill output will depend upon the wind speed.

If the wind is over 35 m.p.h. normal governing will take place. Suppose that the speed of the blades rises above the set speed of the governor. The governor fly-weights will move outwards compressing the speeder-spring, and lifting the governor pilot-valve. The governor servo-piston will follow the movement of the pilot valve and will open the main governor valve, the connecting link pivoting about the end of the feed-back dashpot. The blades will now tend to seek coarse pitch and as they do so the pitch-change cylinder (the Rotol cylinder in Fig. 4) will operate the rack and pinion gearing of the feed-back motion (shown as "return-motion linkage" in Fig. 4), compressing the centring spring and re-closing the governor valve. The blades now slow down so approaching the set speed and the governor pilot-valve will tend to reset followed up by the governor servo-piston. At the same time the feed-back dashpot will reset under the pressure of the centring spring. Ideally the dashpot rate will correspond to the re-setting rate of the governor pilot-valve so that the lever pivots about the governor valve fulcrum. A given movement of the governor pilot-valve thus causes a proportional movement of the

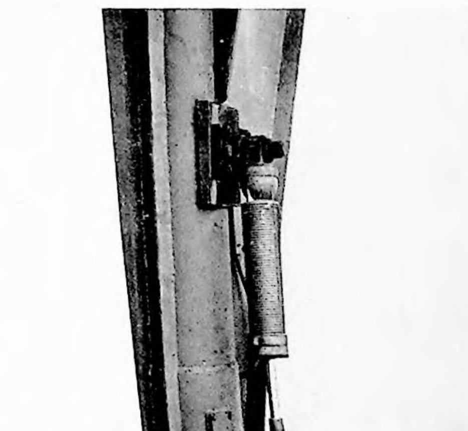

Fig. 3 The damper gear which is mounted on each of the three arms of the hub controls blade movement in the drag plane; the blades themselves act as dampers in the coning plane.

blades, tending to prevent departures from the set speed. The dashpot in the return-motion ensures that the set speed is always in the centre of the range of the pilot-valve travel.

While the governor maintains the windmill speed at its set value the current relay continually causes the actuator to make small adjustments to this set speed in order to maintain the output at 100 kW despite changes of line frequency. The total effect is that normal control of speed is by the governor fly-weights: the actuator, operating through the speeder-spring and subsequent linkage, acts as an over-riding control to make the necessary adjustments for changes of line frequency. A view of the governor and the inboard part of the hub is shown in Fig. 5. One of the torque-tubes which change the blade pitch can be seen extending upwards and to the left at the far end of the control gear.

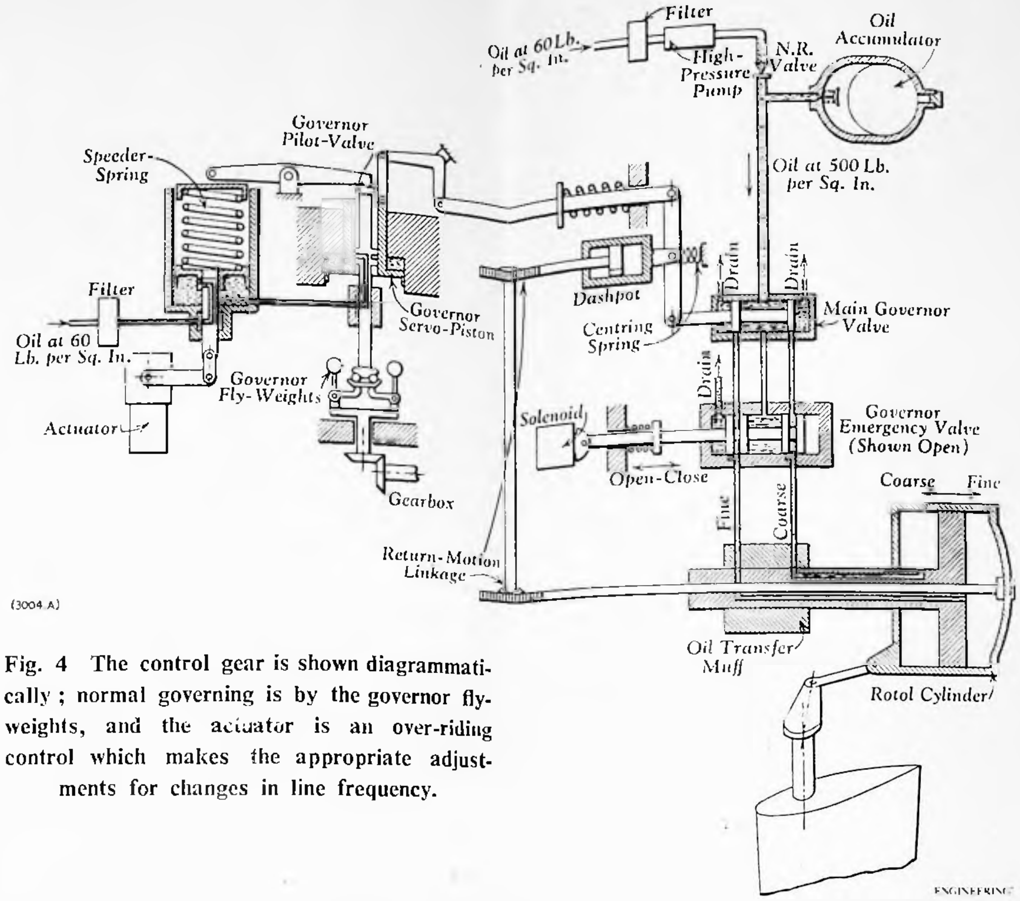

Fig. 4 The control gear is shown diagrammatically; normal governing is by the governor fly-weights, and the actuator is an over-riding control which makes the appropriate adjustments for changes in line frequency.

SHUTTING THE WINDMILL DOWN

If the speed of the wind rises above a pre-set value (about 60 m.p.h.) and remains above that value, the pilot windmill operates a relay which de-energises the master contactor taking the generator off the line. The speed setting is now reduced to 30 per cent. full speed and the windmill will slow down. At its bottom limit the actuator operates a switch which de-energises the solenoid holding open the emergency valve. The same procedure is followed if the wind falls permanently below the lowest setting (about 23 m.p.h.). The clutch in the gearbox remains engaged.

When the solenoid of the emergency valve is de-energised the valve is closed by a spring. The governor then has no control over the blades, which move gradually to their fully-coarse position, thus stopping the windmill. Oil pressure is meanwhile maintained by the oil accumulator, backed up by the pumps, since the generator continues to be driven by the blades. When the blades come to rest oil pressure is lost and the brake in the gearbox engages, holding the blades against rotation.

In an emergency shut-down the solenoid holding open the emergency valve will be immediately de-energised by operation of an emergency relay or by line failure, and will thus allow the set to be shut down fairly rapidly. If the shut-down was due to an emergency condition the machine cannot be started again until the emergency relay has been re-set by hand. Otherwise the machine will start again as soon as conditions are suitable.

Yawing of the nacelle is controlled by a vane on top of the nacelle. This was originally a separate vane but is now combined with the pilot windmill. As the wind blows the vane away from the centre-line of the nacelle an electric contact is made which drives the yawing motor in the appropriate direction. The motor is a 1-h.p. electric motor which drives a pinion which engages with the bull-gear. The drive is transmitted from the motor to the pinion through a 400 : 1 speed reducing gearbox. Between the gearbox and the pinion there is a slipping coupling which allows the nacelle to rotate if struck by a sudden exceptionally strong gust of wind from an unexpected quarter.

Some of the problems of using wind-power have been discussed in ENGINEERING previously, particularly in an article on Enfield Cables' experimental machine near St. Albans (March 25, 1955, vol. 179, page 374), and in the report on Mr. E. W. Golding's paper before the Institution of Electrical Engineers on March 31, 1955 (ENGINEERING, April 8, 1955, vol. 179, page 433). The main problem is essentially that the wind is a reliable source of energy but an unreliable source of power, and if wind machines are to be used to the best advantage they must incorporate some method of storage.

Wind machines must first be a sound practical installation, and it is not until they have worked on an operational site that they may be said to have proved themselves fully. John Brown and Company have learnt much from their machine on Costa Head, and while this machine will continue to supply useful amounts of energy to the network on the Orkney mainland, they are developing a new and larger wind-driven machine on slightly different lines.

The new machine will be of 250-kW capacity, and its design has been guided by experience gained in construction of the Orkney windmill. Many of the components found redundant at Costa Head will be eliminated in the projected model, thus simplifying construction. The most important change is that it will have only two blades rigidly mounted on a rocking yoke to allow them relief when struck by a gust of wind. Development of this model is proceeding, and it is hoped that operational sites will be found both in this country and overseas.

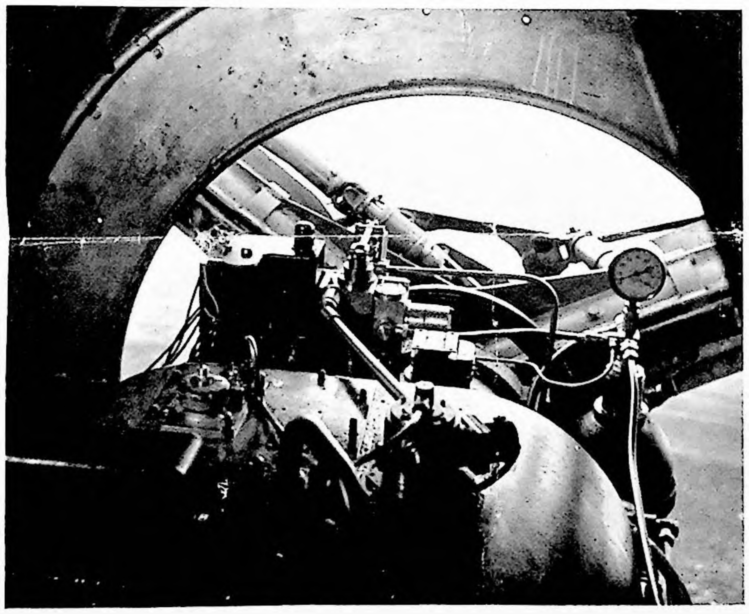

Fig. 5 The governor and inboard parts of the hub shown from inside the nacelle; one of the torque tubes which adjust blade pitch can be seen at the far end of the governor mechanism going off upwards and to the left.

Fig. 6 A stage during construction, showing the hub and gearbox being lifted into position in the nacelle. The top half of the nacelle can be seen lying on the ground at the foot of the tower.

5 P 4

Y. H.

C.M.O's report on wind speed measurements submitted fi. at 43 - 58. It is highly technical and I am afraid that I do not understand much of it except that it is an initial experiment to help in deciding in due course whether the generation of electricity from wind power would be successful and economical.

2. Further research is necessary. To implement the proposal at 43 that additional equipment be purchased would require a supplementary grant of about £30 to Head VIII (b) 3, payment for which is a legitimate charge against the vote.

3. Y.H. may wish to see the C.M.O. for an oral report in layman's language.

4. The C.M.O. appears to have gone carefully into the questions of wind generation and I recommend further experimentation as requested at 43. Subject to Y.H's approval, I'll approach S.F.C. for a supplementary vote of £30 at the next meeting.

[signature] 4/9

C.S.

I should like to discuss with you and C.M.O. - who has obviously done a very thorough job.

But before making any further move I should like to know whether Walker's report has yet been received. Govt. had a hand in financing his investigation and will presumably get a copy of his report. annexed

I should also like to know whether Walker is likely to see this report. I see a copy has gone to Golding and I believe that there is some tie up between the two. If not would you and C.M.O. consider whether or not a copy should go to Walker for information and comments.

Then pl. discuss. Gutteridge should be brought in on it. But Walker might have a word first with Mr. Ian Clark - who gave me some interesting information on his calculations [illegible] on cost of oil-firing for heating the West Stores. 8/9. [illegible]

H.C.S.
Graphs 54-58 returned for C.M.O.

[illegible]
19-9-55.

'201

56

No. 100/55/44

It is requested that, in any reference to this memorandum the above number and date should be quoted.

COLONIAL SECRETARY'S OFFICE
11 OCT 1955
* FALKLAND ISLANDS *

MEMORANDUM.

7th October 1955

From: C.M.O.

To: H.C.S.

Stanley, Falkland Islands.

SUBJECT :— Report on Sapper Hill Wind Speed Measurement

Mr. Gutteridge, the Superintendent of the Power and Electrical Department, has supplied up to date figures for fuel consumption in the Power House and these appreciably affect the third section of the Report on Wind Power which was sent to you recently.

Inserted. The report has been redrafted to take cognisance of these new data and the following new pages should be substituted for those in the initial report.

C.A. Howlin

File early pl.

[illegible]

58

CIVIL ENGINEERING DEPARTMENT,

STANLEY, FALKLAND ISLANDS.

10th October 1955

Possibilities of Hydro-Electric and Aero-generation

Y.H.

Reference your minute of 28.9.55

The Chief Meteorological Officer and I visited the Murrel River on 7th October, 1955 and opportunity was taken to gauge the flow. It amounted to 4.3 cubic feet per second only.

It will be noted that the weather had been particularly dry in the preceeding weeks.

2. This low flow may not materially alter the "characteristic flow" of the river which in my memorandum I assumed to be 33 cusecs but it does mean that there can be no hope whatever of a hydro-electric scheme on the Murrel meeting the total power demand of Stanley without an impounding reservoir of magnitude

In these circumstances I suggest that ~~xxxxxxxxx~~ (iii) on page 5 of your draft memo be amended by deletion from the ninth line onwards to end of paragraph.

3. In view of the difficulty of transport I estimate that the cost of constructing a measuring weir on the Murrel River Item A (i) page 10 would be £100, and the cost of taking periodic gaugings for one year, i.e. three times weekly during dry season of six months and once weekly during wet season of 6 months @ £1 per visit would be £100... Item A (ii)... £100 per annum.

4. The items of expenditure in the summary on page 11 would be :-

Capital

(i) Measuring Weir - Murrel River £100.

(ii)

Recurrent

(i) Periodic readings at the Murrel River measuring weir ..... £100.

Civil Engineer.

c.c. Hon C.S.
C.M.O.

No.

It is requested that, in any reference to this memorandum the above number and date should be quoted.

MEMORANDUM.

59

1st. October 1955

To:- His Honour The Officer Administering The Government.

From:- Supt. P.E.D.

Stanley, Falkland Islands.

SUBJECT :- Hydro Electric and Wind Generated.

10-20 un 0428 D

I have the honour to refer to your draft Memorandum addressed to the Executive Council & Standing Finance Committee.

Page one of Your Memo.

1·9d per K.W.hr. was the price calculated on Montevideo drummed fuel including losses. Recent measurements show a cost of 0·94d. per K.W. hr. and tallies with Makers specifications, therefor it will not be improved upon. 1·0d should be allowed, the0·06d be ing allowed for wastage, in pumping and ullage.

Page 4

I have shown an estimated saving of £2,700 on fuel, this figure is calculated on the total output of the generator being used, in actual fact it wouldnt be at the present time, but if , and by the time the plant was commissioned it is almost certain all of its output would be used. Estimated saving on depreciation is a difficult figure to assess and I have included a tentative figure of £500. It would be well to note that the estimated cost of 1d per unit for Hydro Generation covers the whole cost of civil, mechanical, and electrical engineering works, the civil engineering costs forming the major fraction will be the most enduring and lasts,if maintained,for centuries. Likewise the transmission line but not of course to the same extent. After the first thirty years the price of 1d. will therefor drop considerably and if after the survey as recommended by the C.E. is Carried out it is found that the potential output is much higher, say 3-400K.W.s. then it would appear a most attractive project indeed.

No.

It is requested that, in any reference to this memorandum the above number and date should be quoted.

MEMORANDUM.

60

19

Stanley, Falkland Islands.

SUBJECT :-

Page 6

Wages2·Od. I believe a reduction in Power Station Staff Likely. Replacement, would consist of the amortisation figure. Lubrication and spares would decrease. Distribution might increase owing to longer lines and expected increase in demands.

Page 7

I regret I misinformed you on the relative outputs of similar Hydro & Wind sets being the same. In the case of the wind 315,000units only would be available and the saving is calculated at £1,300. Estimated saving on depreciation is again difficult and £300 is what I estimate might be allowed. The basic cost per unit would be 0·64d. and not o·33d. Here again I regret the error, the cost of transmission lines had been omitted. I dont think there would be any reduction in the3·74d. unless, we had a very heavy increase in consumption.

Page 8

Basic costs of 0·94d. & 0·33d. for Oil and Aero generated electricity should now read 1·0d. and 0·64d. respectively and the total costs ad adjusted to 4·74d. & 4·38d.

Page 10

I think fifteen to sixteen years hence for replacement of existing machinery.

[signature]

Copies filed in relevant files 61

No. 1201
Circ. No. 4.

November, 1955.

To: All Members of Ex. Co.
S.F.C. (Bur. No. 1).

From: The Colonial Secretary,

Subject: Power Resources in the Falkland Islands.

1. As Honourable Members are aware Mr. J.H. Walker, the London Manager of Gilbert Gilkes and Gordon Ltd., recently carried out a survey of hydro-electric and other power resources in the Falkland Islands. This Memorandum summarises, for the information of Members, certain recommendations and conclusions made and formed by Mr. Walker in his report. It also summarises the conclusions reached by Government after consideration of the Walker Report.

2. In general terms Mr. Walker concluded that there are a number of sites in the Falkland Islands where small water power schemes would be possible but that few of these are deserving of further consideration on account of various factors. He has recommended that measuring weirs should be constructed in certain streams which might be harnessed and flow readings should be taken for twelve months and then analysed in conjunction with rainfall figures, in order to determine whether hydro-electric plants should be installed on the farm stations concerned. The report contains advice to farm managers as to how records should be obtained. Finally, the Walker Report indicates the possibility, subject to more data, of the development of wind power.

3. Specifically the Walker Report examines the cost of production of electricity in Stanley (at the time Mr. Walker collated his information the basic cost of the fuel component was 1.9 pence per Kw. Hr. as compared to .99 pence per Kw. Hr. now that oil is purchased in bulk) and suggests that it would be well worth while investigating the possibility of some power being obtained by other means i.e. hydro or aero generation.

4. After a visit to the Murrel River, Mr. Walker concluded that it would be worth while installing a measuring weir in the river and arranging for readings to be taken. He had in mind that subject to satisfactory data being obtained over a year or so, it might prove an economic proposition, as an adjunct to the present Stanley supply, to install a small diversion dam that would lead water into a contour channel, in turn feeding a pressure penstock to convey water down to a turbine. A hydro-electric installation such as this would be automatic in the sense that its output would be automatically adjusted according to the available water supply. It could be so designed that a visit would only be necessary every few days and continuous attendance would not be required. But, before the full costs and economics of such a scheme could be established, a detailed survey of the area would be necessary.

5. The Walker Report and the question of utilising the power resources of the Falklands have been referred to and considered by the Civil Engineer, the Superintendent of the Power and Electrical Department and the Chief Meteorological Officer. The situation as it exists today

/and

and the conclusions reached by the technical officers concerned are summarised in the paragraphs that follow:-

I. STANLEY.

6. Electricity is at present generated from diesel engines at a cost of 4.73d. per unit, made up as follows:-

		Annual Cost	Cost per Unit.
1.	Wages	£4600	2.00
2.	Replacement	1500	0.65
3.	Maintenance	1000	0.44
4.	Distribution	1500	0.65
5.	Fuel	2250	0.99
	Total	£10850	4.73

The above fuel component, (previously 1.9d. per unit) is based on the latest bulk price of oil and it is very probable that it is as low a figure as can be achieved with diesel plant in the Falklands. Demand is rising at about 16% per annum (80,000 units) and several heavy loads may be expected in the near future (the hospital electrode boiler, the water pumping station, the Falkland Islands Company peat bricketting plant and possibly the ancillary equipment for a Falkland Islands Company slipway, which, it is understood, is under consideration by the Company). Present indications are that the demand may reach a maximum of 10^6 units per annum several years hence, although it may be expected to increase beyond this figure if any substantial reduction in the cost per unit could be achieved. It will be appreciated from the above data, that costs of production are closely related to consumption. Thus, if the consumption doubled, components 1-4 would be spread over more units and a reduction in the cost per unit could be achieved.

7. There are four possible methods of generation:

1. Diesel
2. Steam, fired by peat.
3. Water Power.
4. Wind Power.

In any event wind power cannot provide a continuous supply and must be linked with one of the other three forms of generation. It is, in effect, a fuel saver.

8. Peat has been used effectively in a number of countries (including Ireland and Russia) and about 4,000 yards would be required to produce the present demand of 550,000 units per annum, assuming the same order of efficiency as in the case of the existing diesel plant (i.e. 30%). However, this type of plant is not likely to be as flexible as the diesel engine and it may be necessary to generate at full output for most of the day to meet peak demand. If this is necessary then up to twice the fuel would be required but as the demand increases the load distribution should become smoother and the consumption of fuel should become closer to 8,000 yards per million units. At present Government contract rates, peat costs about £230 per 1,000 yards and the fuel component cost of meeting the present demand for $.55 \times 10^6$

/units

units per annum should lie between £900 and £1,840 per annum (approximately .4 to .8d. per unit), which compares favourably with the £2,250 spent on gas oil (.99d. per unit). Replacement and maintenance costs might also be rather less than with diesel plant, but it is not possible to estimate these components accurately. Wages and distribution would be as for diesel plant. The problem with peat would be to ensure a regular supply (especially for a large plant) and this would become increasingly more difficult as peat in the proximity of the town is worked out. However, the potentially low fuel component might justify further enquiries from the Department of Scientific and Industrial Research, Fuel Research section, to see whether conversion to peat might be worthwhile when the question of replacing the existing diesel plant arises in fourteen or fifteen years time.

Hydro Plant.

9. This type of generation has of course important advantages over both diesel and steam in that it can be semi-automatic in operation (cost of wages might be reduced), the maintenance costs are low and there is no fuel component. Mr. Walker estimated a flow of 50 cusecs during his visit and, from a study of the contours, thought that a fall of 50ft. might be obtained in a distance of about 500 yards. A flow measurement made later by the Civil Engineer gave 33 cusecs and a more recent one in October yielded only 4.3 cusecs. Assuming a fall of 50ft. this minimum flow would yield only about 15 kw. in the absence of a large storage dam. Mr. Walker warns against the use of large storage dams because of the nature of the foundation material and, in view of this and the very small flow obtained recently, it is considered that there can be no possibility of the Murrel providing a regular source of power for the whole of Stanley unless a dam of considerable size were to be constructed. However, if the average flow is of the order of 20 - 30 cusecs, the Murrel stream could provide a useful booster supply for Stanley, amounting in effect to a fuel saver and could in all probability meet the requirements of Stanley over a long period.

10. It is impossible to provide reliable estimates until a careful survey of both flow and fall have been carried out and related to the demand, but the following figures will indicate the probable order of cost and the financial implications of a hydro-electric "booster" scheme that would generate 75 kw.

Hydro Plant to generate 75 kw.

Transmission line from Murrel to Moody Brook +	£11,500
Civil Engineering Works	19,500
Hydraulic Machinery	4,000
Total	£35,000

Present indications are that, assuming a 50ft. fall is available, this plant would operate at full output for at least nine months each year and when the new water works are in operation the Stanley load is never likely to fall below 70-75 Kw, so that the entire output from the hydro plant could be used. The plant should therefore

/replace

+Line Moody Brook/Stanley will be provided in any event for the new water works.

replace about .5 x 10^6 units per annum, which would otherwise be provided by diesel. It is possible that a C.D. & W. grant might be obtained for this project but, assuming the necessary capital was obtained by loan, the immediate financial implications would be :-

Estimated Annual Saving		Estimated Annual Expenditure	
Saving of diesel fuel p.a.	£2,080	Amortisation payments (for 30 years)	£2,150
Saving in depreciation and replacement of existing diesel plant	£500	Replacement Dam	195
		Replacement generators	200
		Maintenance of Plant & extra lines	300
Total	£2,580	Total	£2,845

The installation would be automatic in operation and need only be visited once every few days. No extra staff would be required.

11. From the above, and assuming that it would be necessary to service a loan, the scheme would not appear to be an economic proposition. However, once the loan has been paid the estimated annual savings and expenditure would be £2,580 and £695, i.e. a net saving of £1,385 p.a. The latter represents a fuel component cost of .3d. per Kw. The following factors should also be borne in mind:-

(i) Hydro-electric generation, in the circumstances of the Falklands (and assuming of course that survey and other data indicate a satisfactory source of power) is an assured source of supply and it is not dependent on the importation of fuel from overseas which, in time of emergency, might be difficult and might in certain circumstances cease for some time. On the other hand, with the installation of the new storage tanks a two year supply is assured unless there is a substantial increase in consumption or heavily increased demands from other sources. Consequently this factor is important but need not be overstated.

(ii) The basic cost per Kw. Hr. in the case of oil fuel generated power is calculated on the present price of imported fuel - £14. 15. 0. per ton in bulk. It is unlikely that this price will decrease in future. It may, in fact, increase and in that case hydro-electric generated power would present a more attractive proposition.

(iii) If the Murrel River yields a flow of the order of 30 cusecs for nine or ten months during the year then it would be possible, by storage of water overnight for use on the following day (and this would not require a very large dam), to provide hydro power for the whole of Stanley for the greater part of the year. It would still be necessary to retain the diesel plant for use in the dry spring months but there would be an appreciable drop in maintenance and replacement costs and a reduction in the cost of electricity to the consumer might perhaps materialise. However, the possibilities could only be assessed after relating the flow in the Murrel to the actual demand and a good deal of further thought would have to be given to the matter.

Electricity from Wind Power.

12. The tests so far carried out at Sapper Hill indicate that this site compares with the best so far investigated in the British Isles, and it would be capable of yielding 4,500 units of electricity per annum for each kilowatt of rating. Therefore a plant rated at 70 Kw. would produce 315,000 units per annum, all of which would be absorbed after the water pump is installed and as the general consumption rises. The cost of the plant would be about £7-9,000 plus £3,000 for power lines to Stanley. The wind plants are expected to give thirty years' service with virtually no maintenance. Therefore, assuming that the sum of £12,000 is borrowed for thirty years at 4½%, the estimated costs would be:-

Annual Saving on Diesel Plant.		Annual Expenditure	
Saving on gas oil (315,000 units)	£1,310	Amortisation on £1200	£740
Saving on depreciation and replacement of existing diesel plant	300	Maintenance of plant and extra power lines	£100
Total	£1,600	Total	£840

The annual saving would therefore be of the order of £800. No allowance is made for replacement of plant, which is regarded as consumable over a period of 30 years and the annual cost of £840 may be regarded as the "fuel component" in the production of 315,000 units i.e. $\frac{£840}{315,000} = .64d.$ per unit. Figures as low as .3d. per unit have been suggested by the British Electricity Authority in their preliminary reports. From paragraph 10 it will be seen that these compare with $£\frac{2845}{.5 \times 10^6} = 1.36d.$ per unit for hydro power, dropping to .3d. after the initial loan is cleared.

13. A further possibility is that with the utilisation of wind power as a fuel component it may be possible to utilise surplus electricity for the heating of buildings. It will be seen from paragraph 12 that it may be possible to produce electricity from wind power at a fuel component cost of around .3d. - .6d. per unit, in which case surplus production from a generator larger than 70 kw. could be used economically for heating furnaces. This would ensure that there was no loss as a result of the greater capital expenditure on a larger plant and much of the output from a larger plant could be absorbed by the town when demand exceeded the minimum of 70 Kw. A preliminary investigation suggests that a plant of the order of 200 Kw. might be obtained for a maximum capital outlay of £30,000 (£1,850 p.a. for 30 years) and a net saving on gas oil of nearly £1,000 per annum might be expected at the Power House and in heating furnaces, plus about £350 p.a. on depreciation of diesel engines. The 70 Kw. and 200 Kw. plants would therefore compare as follows:-

	Annual Expenditure	Net Saving
70 Kw.	£840	£770
200 Kw.	£1,850	£1,350

It should be borne in mind, however, that it will be some years before aero generators of suitable rating for use

/at

at Sapper Hill are in production, and then it would be advisable to wait a short period after the first production models are available for the design to be perfected.

Summary and Comparison of the different methods.

14. (i) Peat and gas oil are the only two certain sources of power because it appears that neither hydro power nor wind power can be obtained in sufficient amounts at all times.

(ii) Peat would appear to be capable of yielding a fuel component between .4 and .8d. per Kw., which is appreciably less than can be achieved with gas oil (.99d. per unit) but there may be over-riding difficulties in winning the quantity required and preparing it in a form suitable for automatic stoking.

(iii) Hydro power is capable of yielding a fuel component of about .3d. per Kw. after the initial loan is cleared but the cost would be 1.36d. per Kw. if a loan had to be serviced.

(iv) Wind power should yield a fuel component of between .3 and .64d. per Kw. and the capital outlay is much less than for a hydro plant. However, the output from a wind generator will be liable to short period variations and the diesel plant must be available at all times to take over the load; whereas the hydrogenerator output will change comparatively slowly and there may be long periods in the winter when the diesel plant could be dispensed with (see paragraph 10).

II. The Camp.

Hydro Power.

15. The Walker Report indicates a number of places where hydro power might be developed economically and gives details of how to measure potential output. Hydro power is only likely to be available at a few stations and the alternative for the remainder is wind power.

Wind Power.

16. The results at Sapper Hill suggest that exposed sites in the Falklands will yield 4,500 units per kilowatt of rating and it seems reasonable to suppose that the majority of farms could find sites within a short distance of their settlements, capable of producing 2,500 units per annum. It is not intended that wind power should be used as the only source of supply, as this would require very large battery storage to provide against long periods of calm, but aero-generators might be used effectively with existing diesel and battery plant, to save fuel. Also it is understood that new designs of wind plant are being tested and it is possible that these may prove more reliable than the small plants used in the Colony for many years. The cost is likely to be of the order of £150 - £200 per kilowatt of rating and assuming that the plant gives only ten years of service the fuel component cost per unit could be $\frac{£200}{2,000 \times 10}$ = 2.4d. per unit.

66

This is less than can be achieved by small diesel plant and a figure of less than 1d. per Kw. might be attainable on good sites, if the plant has a life of 20 - 30 years. Many farms would find the output of 2,000 units per annum from a plant of 1 Kw. rating sufficient for the whole of their requirements and the diesel plant would only be required for periods of calm and periods of heavier load, beyond both the wind generator and the storage batteries.

17. In these circumstances, the C.M.O. has recommended that:-

(a) Cheap cup counter wind instruments should be installed at Stanley, Darwin, Fox Bay and Pebble Island to bring out any important variations in wind speeds over the area as a whole.

(b) The measurements taking place on Sapper Hill should be continued for a further twelve months so that comparisons can be made with the simultaneous records from the Camp stations.

(c) Long term averages should be extracted from existing Stanley records to derive more representative power curves for Stanley and, by comparison with the camp stations, for the area as a whole.

18. In addition consideration has been given (and further advice is being obtained from the Colonial Research Laboratory) on the possibilities and implications of linking diesel plant, such as that installed in a number of farm settlements, which is capable of carrying a maximum load with a smaller wind plant and storage batteries capable of dealing with the average load. Preliminary calculations and estimates suggest that some such system, if practicable, would result in a substantial saving in fuel oil. The principle would be that the batteries would "float" between both the wind driven and diesel generators and the switching of both generators would be automatic.

General Summary and Conclusions.

19. The following summary and conclusions are suggested for the consideration of Honourable Members:-

i. On the information available there would appear to be some possibilities and potentialities with regard to both hydro-electric power and aero-generated power so far as the supply of electricity to Stanley is concerned and it would be worth while carrying out further investigations.

ii. There might be possibilities with regard to small hydro electric schemes on individual farms. The potentialities should be left to the farms to explore and take whatever action is necessary and required.

iii. There appear to be possibilities in linking aero-generation with diesel plant and these should be given further examination. It might be worth giving consideration when further information has been obtained to the installation of a small pilot wind plant of about 2 Kw. at Fox Bay where full records of output and fuel consumption can be maintained. This would provide a practical test

/of

of the type of plant now available and might assist farmers in deciding whether it would be to their advantage to install similar equipment.

If Honourable Members are in agreement with these conclusions, expenditure of the following order would be required:-

A). Hydro-Electric.

1. A measuring weir should be constructed on the Murrel River. Estimated cost £100

2. Readings should be taken for a minimum of 12 months. Estimated cost £100

Total £200

Note:

(a) A survey of the Murrel River area between a point above the 150 ft. contour to a point below the 100 ft. contour. This survey can be undertaken at no cost by a F.I.D.S. surveyor passing through Stanley and it is proposed that the necessary arrangements for this should be made. This survey was recommended in the Walker Report.

(b) The installation of measuring weirs (where necessary) measuring notches and the collation of data at points on individual farms (as recommended by the Walker Report) as preliminaries to the possible installation of small hydro-electric projects on individual farms should be left to the farms concerned should they desire to take further action.

B). Aero-Electric.

1. The installation of cup counter anemometers at Darwin, Fox Bay and Pebble Island. Estimated cost £100

2. Replace anemometer at Sapper Hill Estimated Cost £20

Note: Further enquiries to be made with regard to the desirability of installing a 2 Kw. wind generator at Fox Bay

Total £120

[signature]
COLONIAL SECRETARY.

ADT.

Extract from the Minutes of a Meeting of Executive Council held 15th November, 1955.

1201. 6. Power Resources in the Falkland Islands.

After discussion Council adopted Executive Council Circular No. 4 of 9th November, 1955, and advised that the proposals set out in paragraph 19 be put into effect.

Clerk of the Executive Council.

Being referred to S.F.C.

Bell. for minute

22/11

DM

Original filed in 1040/II - S.F.C.
Minutes of Meetings.

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MINUTES OF A MEETING OF STANDING FINANCE COMMITTEE
HELD IN THE OFFICE OF THE COLONIAL SECRETARY ON
FRIDAY THE 25th NOVEMBER, 1955.

Present:- The Honourable the Colonial Secretary (Chairman)
The Honourable Mr. S.C. Luxton
The Honourable Mr. A.L. Hardy, B.E.M., J.P.
The Honourable Rev. W.F. McWhan, M.B.E.
The Honourable Mr. K.W. Luxton, J.P.

Minutes

The Minutes of the Meetings held on 14th September, 26th September and 7th October were confirmed.

Arising out of Minutes

The Chairman informed the Meeting that it was Government's intention to amend the Old Age Pensions Ordinance to enable pensioners to draw pension in the United Kingdom and other countries. The Secretary of State had raised the question of extending to the Falkland Islands the reciprocal agreements at present in force between the United Kingdom and a number of other Colonies with regard to Old Age and Sickness Benefits. The Chairman informed members that this matter was being taken up with the Colonial Office with a view to examining the full implications.

A.I.S.E's.

The Committee approved Additional provision as shewn on the attached schedule.

Purchase of Houses at Ajax Bay

The Chairman informed members that Government considered it desirable to tender for the Manager's house and bungalows at Ajax Bay with a view to easing the housing shortage in Stanley. If obtained they would be used for housing Government Staff. The Committee agreed to the purchase but considered the estimated figures shown in the Memorandum were too low, with regard to both the proposed tender figures and the estimated amount required for dismantling and re-erection. The Committee recommended the following :-

(1) That Government tender for 4 bungalows @ £900 each plus furniture £225 making a total per bungalow of £1,125.
(2) That Government tender for one unfurnished bungalow at £900.
(3) That Government tender for the Manager's house for £2,800 plus £500 for furniture. (£3,300 complete).
(4) If Government acquired the houses, Government should endeavour to arrange for dismantling and re-erection by contract on the understanding that the same contractor would be required to both dismantle and re-erect. The advice of the Committee should be sought as to which tender should be accepted. The Hon. Mr. S.C. Luxton and the Hon. Mr. A.L. Hardy agreed to make enquiries with regard to persons able and willing to tender.
(5) Government should tender for the remaining two bungalows when the Receiver puts them up for sale.
(6) In the event of Government being unable to arrange for dismantling and re-erection by contract, Government should proceed on the basis of the recommendation made in Memorandum No. 5.

Sighting of Vessels from Cape Pembroke Lighthouse

The Committee agreed to the payment to Keepers at Cape Pembroke Lighthouse of a fee of 7/6d for reporting the presence of ships other than H.M. Ships, "Fitzroy" and locally registered craft. Additional provision amounting to £10 was approved for the remainder of the year.

David Alazia

The Committee agreed to expenditure from Public Funds amounting to £390 per annum together with £78 per annum in respect of holidays for a training course in the School for

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the Blind, Liverpool, for David Alazia with the proviso that no further committments would be involved.

Government House Car

The Committee were asked to consider the purchase of a car for H.E. the Governor to replace the present one which is in a bad state of repair. The cost of a new car landed at Stanley was estimated at £707 and additional expenditure was approved by the Committee. With regard to the present vehicle it was agreed that the question of it being converted for the purpose of a hearse be left in the handsof the Colonial Secretary who would approach the Falkland Islands Co. Ltd. regarding conversion. In the event of the cost of this work being much in excess of £100 the matter would be referred back to Committee. Approval of a moderate amount over and above the £100 was left to the Colonial Secretary's discretion.

Salary Adjustments

Committee were asked to consider the following increases in salaries :-

(a)	R/T Operator	from £270 - £290
(b)	District Nurse	from £240 - £275
(c)	Clerk Treasury	accelerated promotion from £300 to £345 and then £360, £375, £390, £400.

The Committee recommendations were as follows :-

(a)	R/T Operator	from £270 - £320	w.e.f.	1st	October,	1955.
(b)	District Nurse	from £240 - £300	"	"	"	"
(c)	Clerk Treasury	from £300 - £345 and then £360, £375, £390, £400.	"	"	"	"

Power Resources in the F. Is.

The Committee considered a Memorandum dealing with a survey carried out by Mr. J.H. Walker in connection with hydro-electric and other power resources in the Falkland Islands. It was recommended that further investigations with regard to both Hydro-Electric and Aero-Electric power should be followed up on a moderate scale for a period of two years. The recommendations made in Memoradnum No. 2 were approved.

Copies in 1398 0428/D.

Roads and Water Filtration Projects

The Committee considered a Memorandum regarding Stanley Roads and Water Filtration Projects. The unanimous opinion was that a qualified engineer should be appointed to complete the road programme after the expiry of the contract of the present Engineer.

Port Howard School

The Chairman informed the Meeting that it was likely that the cost of the West Falkland school at Port Howard would exceed the estimate by some £500 - it was possible, however, that the amount might be reduced by the purchase of a second hand generator from Port Howard and a stove from Albemarle.

Peat Survey

The Chairman produced a letter in which the Falkland Islands Co. Ltd. asked if Government would be prepared to meet half the cost of a survey on peat carried out by Mr. Ohrstram, a peat expert, and amounting to £693. 5s. 0d. Committee were unable to recommend any payment by Government.

Messengers

The Committee agreed that the salary scale for messengers should be converted to a fat £70 per annum. Salaries would be adjusted accordingly.

Materials ex Ajax Bay

The Chairman informed the meeting that Government wished to purchase certain stores from Ajax Bay and asked Committee's approval to spend up to £1,000. The Committee agreed and intimated that further funds would be made available for this purpose if required.

Chairman

Secretary

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A

APPLICATIONS TO INCUR SUPPLEMENTARY EXPENDITURE

	Head	Subhead	Amount
			£
II	AGRICULTURE	8. Tools and Implements	100
V	EDUCATION	1. Assistant Masters	640
		9. School Cleaning	582
		N.I. Matron	105
		" Provisions	500
		" Fuel and Oil	223
VI	HARBOUR & AVIATION	6. Upkeep of Lights etc.	400
VII	MEDICAL	6. Bandages etc.	1000
		7. Instruments etc.	500
		12. Transport of Patients	250
X	MISCELLANEOUS	5. Local Transport	700
		15. Caretaker & Fuel, Town Hall	427
		N.I. Camp Hydro-Electric Survey	100
XIII	POSTS & TELEGRAPHS	19. Broadcasting etc.	175
XIV	PUBLIC WORKS	B. Electrical- N.I. Typewriter	46
XVI	SECRETARIAT & TREASURY	5. Income Tax Refunds	820
		7. Postage	150
			£ 6,718

BVC 20/1/56

B

H.C.S.

70. with 67 pl. Who will do this work pl. & when should they commence? WH 9/1/56

C

C.S.

Clme she be in on this - pl. pass to him to see & for any comments he may wish to offer.

[illegible] 10/1

72

A

C.M.O

C on 71 pl.

[initials] 10/1

B

H.C.S.

I imagine Mr. W[illegible] would do the hydro electric work and the Met Office the aero-generator. As to the latter I can see no prospect of any work of this kind and suggest you B.U [illegible] for my relief when he arrives in May (if appointed) and assuming that he has a full complement in Stanley.

G H
11. 1.

C.

C.S.

B supra. C[illegible] is, without [illegible], hard pressed & I can see no alternative?

[initials]
16/1

No. BU [illegible] pl.

[initials]
17

BU 30/1?

[initials] 17/1

BM 18/7/56

BM 30/7/56

BM 10/8/56

A

C.S.

72. This is a bill for the new C.M.O.

[illegible]
10.7/8/56

B

H.C.S./

Yes - but we should give him two or three months to settle in. B.U. early Feb.

[initials]
13.8.56.

B.U. 5/10/56
B.U. 27/10/56

C

C.M.O./

I should be glad if you would study these papers and f.61 (Memorandum 4) in particular. Exco. decision at f.58 should be noted. Will you then discuss with Supt. P. & E. and either arrange to discuss with me or put down on paper your recommendation as to how we should proceed.

[initials]
23/10/56.

D.

H.C.S.

Staff situation as at Hawkins minute of 11/1. I have, however, analysed Sapper Hill for period 1955-56 & on accompanying graph have compared two years' readings. There seems little significant difference & on basis of comment in 53A, this may be sufficient for Stanley scheme. As far as I know nothing has been done, regarding the installations mentioned at 64. Will discuss with Supt. P.& E. before proceeding further.

P.A.C.

B.U. ~~15/2/57~~ ~~20/1/57~~ 22/2

E.

C.M.O.

How does this matter stand

[initials] 23/2

F.

A.C.S. Please B.U. mid April & I can probably present a complete report by late April or early May. P.A.C. 26/2/57

14.

Bu. 15th April – pass file to C.no. PR.

[initials] 27/3.

A.C.S.

(1) Ref wind power for camps. Supt. P. & E. has taken home available wind data for Fox Bay, Darwin, Pebble as he thinks this may be sufficient. If it isn't then we shall have about 6 mths more delay before proceeding with arranged programme (see 64 B. 1.). In my opinion relating camp winds to long term averages at Stanley will present a tremendous task & will have to await a decent staff complement here (e.g. the 1955 Stanley winds have not yet been analysed).

(2) G. Hawkins & Supt P. & E have gone very thoroughly into the economics, (costs of fuel, peat, distribution of load, etc) but I think one point could be stressed more. Once aero generation and/or water generation has been established costs will be known. In the case of oil or peat, variations of cost (almost certain rises) will invalidate many of the calculations (48 et seq) & there is always the possibility of oil rationing in the case of emergency.

(3) Sapper Hill – I have completed 3 years analysis & the results are, to my non-expert mind highly promising. I suggest that the attached report, Tables & graphs be forwarded to Mr. E.W. Golding, British ~~Electrical~~ Electrical & Allied ~~Electrical~~ Industries Research ~~Authority~~ Association, Thorncroft Manor, Dorking Road, Leatherhead, Surrey (see f 10 para 9). He can pronounce judgement on the suitability of the Sapper Hill site, & will probably know about the latest developments in the manufacture of wind generators. If he requires any further data, we will do our best to supply it, but I think in the first instance, it will be best to keep the report as brief & clear as possible.

P.A.C.
8/4/57.

F.H.

Para 1) on reverse – PR. see above.

[initials]
10/4.

75

C.M.O./

I am afraid this is very much above me - but so far as I can judge your report appears to be admirably concise and clear. I am very much obliged for all the trouble and care you have taken over this matter.

I agree the report should go to Mr. Golding - and perhaps you would forward it.

I assume that the tables and copies pinned to the envelope at back cover are for retention on the file - though the tables ~~do~~ appear to differ from those inside the envelope? Have you kept copies?

[initials]
14.4.51.

SAPPERS HILL, 3rd APRIL, 1955 TO 1st APRIL, 1956, INCLUSIVE

Frequency Distributions of Wind Speeds

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KNOTS	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT	NOV.	DEC	JAN	FEB	MAR	TOTAL	CORRECTED TOTAL	
	383	600	717	743	615	680	735	720	662	421	696	766	7738	8760	
0	12	7	10	30	17	14	6	3	2	16	18	7	142	161	8760
1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	8599
2	0	0	0	0	0	0	3	2	0	2	0	0	7	8	8598
3	0	0	0	0	0	0	9	2	3	5	5	0	24	27	8590
4	1	0	0	0	0	0	8	7	8	7	9	2	42	48	8563
5	11	5	14	6	12	18	10	6	11	16	12	7	128	145	8515
6	3	3	16	11	16	12	10	14	16	12	18	24	155	175	8370
7	5	3	20	10	20	18	20	26	28	18	29	28	225	255	8195
8	6	9	14	13	21	16	13	12	18	12	17	16	167	189	7940
9	1	9	18	14	15	18	11	14	9	9	13	14	145	164	7751
10	3	24	12	12	9	16	23	15	13	14	19	22	182	206	7587
11	2	20	25	21	15	23	24	18	31	18	16	36	249	282	7381
12	5	21	20	24	26	25	28	23	22	15	18	15	242	274	7099
13	6	25	19	24	44	27	36	33	36	12	25	28	315	357	6825
14	8	40	32	23	44	31	25	19	23	13	24	28	310	351	6468
15	11	31	31	22	41	29	19	18	29	18	35	32	316	358	6117
16	13	15	27	22	23	24	18	25	24	21	29	27	268	303	5759
17	16	25	19	26	33	29	37	25	34	18	48	31	341	386	5456
18	15	36	25	29	28	25	16	26	22	10	19	35	286	324	5070
19	17	25	22	21	35	25	25	28	21	18	25	32	294	333	4746
20	23	22	24	33	32	35	30	30	33	19	26	42	349	395	4413
21	15	16	18	32	21	32	21	22	12	20	28	24	261	295	4018
22	17	26	30	19	12	30	24	30	14	12	30	26	270	306	3723
23	20	16	24	27	16	27	22	24	19	10	15	21	241	273	3417
24	16	20	38	18	23	16	22	24	18	16	26	21	258	292	3144
25	27	6	34	23	10	32	26	28	29	14	22	33	284	321	2852
26	11	16	36	25	13	24	31	32	35	19	18	21	281	318	2531
27	16	14	28	20	16	24	17	29	14	12	26	16	232	263	2213
28	9	14	29	14	13	18	23	22	11	9	14	12	188	213	1950
29	10	8	24	18	13	11	17	10	8	8	11	7	145	164	1737
30	7	13	15	19	3	7	18	20	17	8	14	11	152	172	1573
31	16	16	14	22	8	15	18	12	11	5	16	16	169	191	1401
32	3	14	14	21	7	4	15	13	9	3	7	7	117	132	1210
33	6	14	7	23	5	11	12	16	12	1	10	13	130	147	1078
34	12	9	4	16	3	7	22	15	19	2	9	12	130	147	931
35	5	6	3	18	4	6	13	15	7	3	6	16	102	115	784
36	5	14	6	22	2	5	10	12	13	1	10	13	113	128	669
37	6	6	2	19	3	6	8	8	3	1	4	8	74	84	541
38	4	5	2	10	4	4	6	6	3	0	2	9	55	62	457
39	4	8	4	11	1	6	6	5	8	1	7	4	65	74	395
40	3	5	7	9	1	4	10	5	13	2	3	11	73	83	321
41	3	5	3	5	2	2	2	2	3	0	2	5	34	38	238
42	1	6	2	1	1	1	0	1	0	0	0	6	19	22	200
43	4	6	2	3	1	2	1	5	1	0	4	11	40	45	178
44	1	1	3	1	0	0	4	2		0	1	2	15	17	133
45	1	3	1	1	0	0	4	2		1	3	4	20	23	116
46	3	1	1	4	1	0	6	1			0	3	20	23	93
47		3	3	1	0	0	1	1			1	2	12	14	70
48		4	2		0	1	1	1			0	0	9	10	56
49		3	1		1		3	1			0	0	9	10	46
50		0	5				0	2			2	4	13	15	36
51		1	1				1	1				1	5	6	21
52		0	3					0				1	4	5	15
53		0	1					0					1	1	10
54		0	0					0					0	0	9
55		1	0					2					3	3	9
56			1					1					2	2	6
57			1					1					2	2	4
58								1					1	1	2
[illegible]								1					1	1	1

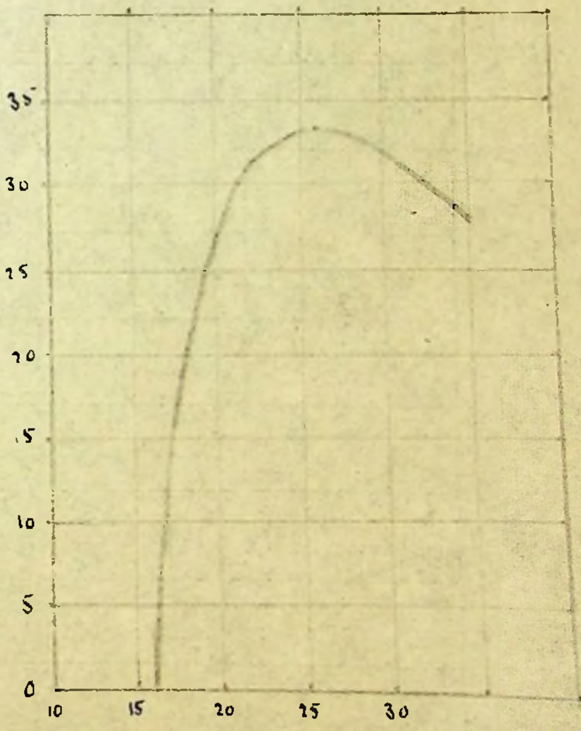
SAPPERS HILL, 2nd APRIL, 1956 to 1st APRIL, 1957, INCLUSIVE

Frequency Distributions of Wind Speeds

77

KNOTS	APRIL ✓	MAY ✓	JUNE ✓	JULY ✓	AUGUST ✓	SEPT ✓	OCT. ✓	NOV. ✓	DEC. ✓	JAN. ✓	FEB. ✓	MAR.	TOTAL	CORRECTED TOTAL	RUNNING TOTAL
	696	608	602	744	585	624	744	720	744	674	672	768	8181	8760	
0	18	13	2	20	3	2	1	3	2	2	2	2	70	75	8760
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8685
2	6	0	0	0	3	0	0	0	0	0	0	0	9	10	8685
3	12	0	0	2	6	3	0	0	1	1	1	0	26	28	8675
4	13	3	1	13	9	7	3	3	2	3	5	6	68	73	8647
5	12	2	6	23	13	7	4	8	8	1	7	5	96	103	8574
6	32	4	9	21	19	7	16	18	14	17	15	6	178	191	8471
7	35	9	15	18	19	10	21	22	6	11	16	9	191	204	8280
8	23	8	4	14	9	11	13	11	12	15	17	6	143	153	8076
9	20	15	4	14	2	7	10	9	9	6	16	6	118	126	7923
10	32	14	9	18	24	16	20	19	24	16	28	13	233	249	7797
11	36	19	19	21	21	25	23	11	10	18	24	14	241	258	7548
12	15	18	15	17	28	18	17	13	25	17	22	11	216	231	7290
13	34	20	28	24	27	49	26	22	37	28	26	20	341	365	7059
14	32	17	15	14	15	20	19	21	30	21	39	21	264	283	6694
15	32	16	17	17	17	24	14	26	45	20	18	22	268	287	6411
16	33	36	26	19	20	29	26	27	28	17	21	23	305	324	6124
17	35	29	26	16	22	27	30	21	54	38	35	35	368	394	5799
18	24	37	26	16	17	29	34	32	26	20	17	36	314	336	5403
19	23	26	12	22	25	39	35	21	36	18	23	41	321	344	5067
20	31	29	21	51	27	27	40	31	27	50	30	41	405	434	4723
21	24	28	20	30	25	20	31	25	23	29	24	42	321	344	4289
22	20	23	21	32	24	23	38	28	20	31	22	40	322	345	3945
23	21	25	20	39	31	29	36	28	20	26	19	36	330	353	3600
24	21	29	22	28	24	23	32	34	39	27	28	37	344	368	3247
25	11	15	19	37	17	18	32	21	24	24	26	27	271	290	2879
26	18	28	18	31	16	11	22	28	23	20	23	34	272	291	2589
27	14	11	23	17	9	10	23	25	19	16	20	19	206	221	2298
28	4	15	24	16	15	11	14	18	17	23	12	16	185	198	2077
29	8	21	26	21	14	7	17	15	13	14	7	15	178	190	1879
30	18	19	18	17	9	9	16	23	27	30	15	13	214	229	1689
31	9	16	18	20	11	6	18	15	13	16	7	16	165	177	1460
32	2	9	21	10	5	4	15	9	10	17	12	16	130	139	1283
33	7	13	11	15	8	9	18	14	7	16	5	19	142	152	1144
34	1	9	13	10	5	3	17	12	9	14	10	20	123	132	992
35	8	3	5	9	7	2	7	13	5	5	8	12	84	90	860
36	4	4	7	8	8	5	8	12	12	6	6	8	88	94	770
37	5	5	12	8	5	6	16	10	22	4	6	7	106	114	676
38	2	5	5	4	1	4	7	8	13	6	8	11	74	79	562
39		1	10	4	4	5	4	8	5	5	6	2	54	58	483
40	1	5	12	2	2	5	5	15	13	8	5	9	82	88	425
41		3	6	6	3	5	2	11	4	7	3	7	57	61	337
42		2	3	3	3	4	3	5	2	1	8	4	38	41	276
43			1	4	3	2	3	2	1	2	2	5	25	27	235
44				1	3	5	2	4		2	6	7	30	32	208
45			1	2	1	2	3	4		5	1	7	26	28	176
46		1	3	4	2	5	1	2	1		2	6	27	29	148
47			3	1	3	6	1		1		2	7	24	26	119
48			1			1	1	1			2	5	11	12	93
49			1	2		5		1			1	1	11	12	81
50			2	2	1	5		4			4		18	19	69
51				1		3		2	3		4	1	14	15	50
52		1							2		1	1	5	5	35
53			1			1		1		1	4	1	9	10	30
54		1				2		2			1		6	6	20
55		1				1		1					3	3	14
56						4							4	4	11
57								1					1	1	7
58						4							4	4	6
59						1(63) 1(44)							2	2	3

mph	kn	%
16	13.9	0 ✓
17	14.8	10 ✓
17½	15.2	15 ✓
18	15.6	20 ✓
19¼	16.7	25 ✓
21¼	18.5	30 ✓
25	21.7	33 ✓
26	22.6	33 ✓
28	24.3	32½ ✓
30	26.0	32 ✓
~~32½~~	~~28.2~~	~~30~~ ✓
~~35~~	~~30.4~~	~~28~~



79

REPORT ON WINDS AT SAPPER HILL, STANLEY, FALKLAND ISLANDS

Sapper Hill (453 feet) lies two miles south-west of the town of Stanley, the capital and only town in the Falklands, and about 2000 yards from the Electricity Power House. The hill is generally rounded with smooth contours, apart from rocky outcrops near the summit on the south and south-west slopes. There is an almost flat area about 100 yards square at the crest of the hill. Mount William (796 feet), 4000 yards to the west, the closest high ground, is a narrow ridge of rock sub-tending a very small angle at Sapper Hill, and almost certainly has little influence on wind speeds experienced at the latter.

2. The hill, therefore, has all the characteristics which are looked for in potential sites for wind driven generators, and early in 1954, a 30 foot lattice steel tower was installed at the summit to carry a standard figure 3-cup Mk. 1B anemometer driving a recording voltmeter made by Everett-Edgecumbe. This instrument had been purchased for use at a Meteorological Station where records of gusts were required in addition to mean speeds, and was employed for economy, instead of the integrating recorder recommended in E.R.A. Report C/T.108. Extraction of mean hourly winds, although more laborious than with the integrating recorder, is relatively simple if a measuring scale is used.

3. Observations were commenced on 3rd April 1954, and this report deals with the three-yearly periods 3rd April 1954 to 2nd April 1955, 3rd April 1955 to 1st April 1956, and 2nd April 1956 to 1st April 1957, all dates being inclusive.

4. The attached tables give the wind frequencies for the various mean hourly wind speeds. A number of breaks occurred in records (the instrument was visited once a week), so the frequency distribution has been calculated in each case on the assumption that the distribution for the missing hours followed the same pattern as that for the hours recorded. This distribution is shown in the column headed "Corrected Total".

5. Figure I shows the frequency curve for each of the years mentioned.

6. (i) Figures II, III and IV each deal with a separate year. Firstly the frequency curve is drawn, secondly a power curve ($speed^3$) is shown. Now using a cut-in speed of 16 m.p.h. (13.9 knots), and a rated wind speed of 30 m.p.h. (26.0 knots), the specific out-put is calculated according to the instructions of E.R.A. Technical Report C/T.101, and the figures 4640, 4440 and 4630 obtained. These figures compare with the best sites shown in Table 6 of E.R.A. Technical Report C/T 108.

(ii) Using the over-all power co-efficients of Figure 18 of E.R.A. Report C/T 108, an actual power out-put curve has been drawn for each year, and the "actual" out-put per annum per kilowatt of rated out-put calculated. The figures obtained in this manner are 4560, 4360 and 4550.

P.A. Canning
8/4/57

80

8th April 57

E. W. Golding, Esq.,
British Electrical & Allied Industries Research Assocn.,
Thorncroft Manor,
Dorking Road,
LEATHERHEAD, Surrey.

Dear Mr. Golding,

Attached are the results of 3 years wind records at Sapper Hill, Stanley, Falkland Islands. Using E.R.A. Technical Reports C/T 101 and C/T 108, I have performed several calculations.

2. The results seem to me to be very encouraging, but your expert comment and advice would be much appreciated.

Yours sincerely,

P.G.C.

Y.H.

Youth comments at 75. Thank you.

Copies of tables, etc in this file (76 et seq) would be sufficient to repeat report. I have omitted copies of graphs because of bulk.

Will forward report to Mr. Golding.

P.A.B.
17/4/57

82

Y.H.
76 · 81 submitted [illegible]

[illegible] 24/4

83

Noted. Thank you.

B.A.
1.10.57.

24/4
25.4.57.

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R. A. McMAHON
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~~LONDON W.C.~~
~~TELEPHONE: TEMPLE BAR~~
WINDMILL RESEARCH STATION
HIGH STREET
CRANFIELD
BLETCHLEY, BUCKS.
TELEPHONE: CRANFIELD 391

(84)

YOUR REFERENCE

OUR REFERENCE AHS/MP

17th May, 1957.

Dear Mr. Canning,

I have been asked by Mr. Golding to acknowledge receipt of your recent letter to him and to thank you for the extremely interesting information contained in the attached papers.

This information will be studied and we will let you have our comments as soon as possible.

I see from your notes that a generator-type cup anemometer was used and that you will, therefore, have a fairly full record of gust speeds. It would be of considerable interest, from a design point of view, to know something of the extreme values of wind speed at the site.

A catalogue of the number of days in each year of record during which the maximum wind speed exceeded 60, 70, 80, 90, 100, (110?) knots would be most valuable. Is it possible for such information to be extracted from the records?

I doubt whether three years constitutes a large enough population to enable a statistical evaluation of the highest probable wind speed in any given number of years to be made, but certainly the order of magnitude of such speeds can be assessed. Similar figures are being extracted from wind speed records at Costa Hill, Orkney; a comparison would be very interesting.

Yours sincerely,

A.H. Stodhart

A. H. Stodhart.

P. A. Canning Esq.
Chief Met. Officer,
Meteorological Service,
Stanley, Falkland Islands.

(85)

H.C.S.

With reference to the suggestion of §4, this work can, & will, be done but I suggest we await Mr. Golding's report first. If he requires any further information, the whole job can then be done. Any analysis of the wind records is a very tedious business, which will fully occupy 2 people for the better part of a week, & I think it would be a waste of time to plod all through now, & possibly do it all over again in another month or two.

P.A.G.
C.M.O.
16/8/57.

C.M.O. 86

I must leave this entirely to you. I assume taking no action on para 4 will not discourage them?

[signature]
19.8.57.

87

H.C.S.

I don't think any harm will be done by waiting. If nothing heard by the October [illegible], will forward the information required & send a gentle reminder at the same time.

P.A.G.
C.M.O.
21.8.57

88

C.M.O.

Action accordingly then. Thank you.

[signature]
24.8.57

89

Seen thank you
P.A.G.
2/9/57

THE BR

(90)

AHS/MP of 17th May 1957

11th November 57

A. H. Stodhart, Esq.,
The Electrical Research Assocn.,
Windmill Research Station,
High Street,
Cranfield,
BLETCHLEY, Bucks.

Dear Mr. Stodhart,

As you requested in your letter of the above reference, I have analysed the Sapper Hill winds for the three years' records and the results are shown in the attached table.

There are, of course, gaps in the records as noted in my previous report. No gusts of 90 kt are recorded. The highest gust yet shown was of 85 kt on the 2nd April 1957 (the day after these records officially ceased).

I hope these figures will be of some help.

Yours sincerely,

P. A. Canning

(P. A. Canning)

	3rd April 1954 to 2nd April 1955 (inc.)			3rd April 1955 to 1st April 1956			2nd April 1956 to 1st April 1957 (inc.)		
Days with gusts greater than or equal to	60kt.	70kt.	80kt.	60kt.	70kt.	80kt.	60kt.	70kt.	80kt.
APRIL	2			1					
MAY	2			5	1		1		
JUNE	2	1		3	3	1	3	1	
JULY	2	1		1	1		2	1	
AUGUST	3	1		1			2		
SEPTEMBER	5			1			4	2	
OCTOBER				4			4		
NOVEMBER	4			3	1		2	2	1
DECEMBER							2		
JANUARY							2	1	
FEBRUARY	1	1		1	1		3		
MARCH	2	1		4	1		4	3	1
TOTAL:	23	5	0	24	8	1	29	10	2

(92) H.C.S.,

I have heard nothing more since the letter of 17th May (f 84). I am, therefore, sending the data asked for in that letter. It will, perhaps, serve as a gentle reminder.

P.A.C. 11/11/57

93.

Note. Thank you. B.u. 4 months.

[illegible] 16/11/57

B.u. 16/3/58 [illegible]

101

AHS/MP

PAC/DMD 19th June 58

A. H. Stodhart, Esq.,
The Electrical Research Association,
Windmill Research Station,
High Street,
Cranfield, Bletchley, Bucks.

Dear Mr. Stodhart,

With reference to my report on the winds at Sapper Hill, Stanley, Falkland Islands, of April 1957, and further correspondence of November 1957, I have been requested by the authorities here to enquire if you have arrived at any conclusions.

Could you please let me know of any comments or suggestions?

Yours sincerely,

P. A. Canning

BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION

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H. G. TAYLOR, D.Sc. (ENG), M.I.E.E., F.Inst.P.
DIRECTOR
R. A. McMAHON M.I.E.E.
SECRETARY

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~~SHINFIELD ROAD~~
~~SHINFIELD GREEN~~
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~~TELEPHONE: READING 81269~~

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CRANFIELD
BLETCHLEY, BUCKS.
TELEPHONE: CRANFIELD 391

106

YOUR REFERENCE PAG/DMD
OUR REFERENCE JRT/MP

15th August, 1958.

P. A. Canning, Esq.
Meteorological Service,
Stanley,
Falkland Islands.

Dear Mr. Canning,

I have just received your letter of 19th June, 1958, addressed to Mr. Stodhart. He left this Association earlier in the year, and has gone to live in Uganda. No doubt, in the preparations for his departure, he overlooked his promise to send you some comments on the wind records from the Falkland Islands. I have taken over his interest in this work and will write to you in a week or so when I have had a chance to look over the previous correspondence.

Yours sincerely,

J R Tagg

J. R. Tagg.

U.D.C. 621.311.24

THE ELECTRICAL RESEARCH ASSOCIATION

Wind Data Related to the Generation of Electricity by Wind Power

by J. R. TAGG, B.Sc.(Eng.), A.M.I.E.E.

TECHNICAL REPORT C/T115
1957

Price 30/-

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23.1.57—400

WIND DATA RELATED TO THE GENERATION OF ELECTRICITY BY WIND POWER

CONTENTS

WIND DATA RELATED TO THE GENERATION OF ELECTRICITY BY WIND POWER

PREFACE

This report describes the results obtained up to the end of 1954 from a wind survey covering the whole of the British Isles.

The information obtained during the previous six years is presented in graphic and tabulated form. Similar information is given for other parts of the world to enable comparisons to be made.

WIND DATA RELATED TO THE GENERATION OF ELECTRICITY BY WIND POWER

SUMMARY

The report describes the results obtained from a wind survey of Great Britain and Ireland. Its purpose was to assess the potentialities of the wind as a source of electrical energy. Initially, the survey covered the western and south-western coastlines but later, to complete the study of winds over the whole country, several sites on the east coast were included.

The results of these measurements are analysed and presented in both tabular and graphical form.

A section dealing with the results of wind measurements in other countries is included to help in assessing the potentialities of wind power overseas, and to compare different wind régimes.

(1) INTRODUCTION

In the summer of 1948 the Electrical Research Association began to make measurements of wind speeds on several hills in the Orkney Islands. The first results helped to show that suitable sites existed in this country for the generation of electricity by wind power. In the following five years a wind survey was established to include sites in most of the coastal districts of the British Isles, as well as a few isolated sites inland.

At the outset, data on wind conditions were readily available only from Air Ministry Meteorological Office records.* These gave the results of measurements of wind speed† and direction made at regular intervals at a large number of stations widely dispersed over the British Isles. For convenience, these installations are, naturally, sited mainly on airfields and in, or near, towns. They are often situated on low ground and are sometimes screened by buildings, so that the results can give only a general indication of the much stronger winds to be expected over any nearby hills.

Some of the results were in the form of hourly mean‡ wind speeds obtained from continuously recording apparatus. Robinson and Beckley's rotational anemograph (see Refs. 3 and 26) was an early recorder of this type, which was later superseded by the Dines Pressure Tube Anemograph (see Refs. 10 and 13). From the records produced by these instruments, the hourly mean wind speeds were estimated by eye with the aid of a simple scale. Occasionally they were totalled over the months and years to provide integrated run-of-wind§ figures.

More usually, the hourly mean values of wind speed were grouped under the Beaufort numbers of wind force. These were then combined to cover wider ranges of mean wind speed, usually <4, 4–12, 13–24, 25–38 and >38 m.p.h. (see Section 5.3.5). The total number of hours of each range of wind speed were then used to plot curves representing the number of hours during which the wind exceeded specified values. By measuring the areas under the resultant curves it was possible to obtain the monthly and annual values of average wind speed.

At other stations, cup generator anemometers were used (Refs. 21 and 36). With these instruments, mean wind speeds were estimated from observations over short periods at fixed hours during the day. All results clearly showed that in any year at any site there are long periods during which wind speeds are below the normal cut-in value for a windmill. Nor can the wind be relied upon to blow at any particular time. Some parts of the world, on the other hand, are fortunate in being able to rely upon winds blowing during certain hours of the day for many weeks at a time. However, annual average wind speeds at a given site in the British Isles vary over only a limited range from year to year and, for this reason, a wind-driven generator erected on a reasonably windy site may be relied upon to produce a certain quantity of energy every year. The object of the first study carried out by the Electrical Research Association was to determine this quantity.

The first E.R.A. report on this subject (Ref. 14), describes how use was made of wind data from twenty Meteorological Office stations. These stations were widely dispersed; they were chosen as having wind régimes representative of the range to be found in Great Britain. A detailed analysis was made for eight of these stations and the results were used to estimate the possible outputs from wind-driven generators installed in various parts of the country. It was shown that the best results were to be expected from the more westerly and northerly regions of the British Isles. Isovent charts, derived from Meteorological Office records, indicated that low-level sites in these areas had annual average wind speeds in excess of 15·0 m.p.h. and it was to be expected that values of annual average wind speeds over suitable hill-top sites might be much greater than this figure.

The main characteristics of winds over these islands are well known. It is usual for the strongest gales to occur between October and April. These seven months are invariably more windy than the remaining five. The British Isles lie within the influence of the persistent " anti-trade " winds or " westerlies," which blow between the latitudes 40° and 60° North. The prevailing wind is south-westerly, but its prevalence is obscured by the frequent passage of cyclonic depressions which generally move in an easterly direction with their centres passing over, or to the north of, the British Isles. As a result the strongest winds tend to blow from the quadrant south-west to north-west.

To a windmill designer, extreme conditions will be of interest. In particular, rates of change of wind speed and direction in both the horizontal and vertical planes, and the duration, magnitude and frequency of occurrence of the more severe gusts need to be known. But, for the successful operation of an aerogenerator, a knowledge of the prevailing wind régimes is also required. It was not, therefore, the aim of the investigators on the wind survey to consider extreme conditions, but rather, in the first instance, to confirm that average wind speeds at selected sites were high enough to ensure that wind power would be an economic proposition.

The economic aspect has been fully discussed in previous reports (Refs. 15, 19, 20) and need not be reconsidered in detail here. It is sufficient to emphasize that the cost of the electrical energy produced will be dependent upon only two factors. First are the annual capital charges, which are proportional to

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* Any figures quoted in subsequent sections are based on information supplied by the Meteorological Office and reproduced by permission of the Director.

The following conventions are observed throughout:—

† *Wind speed* is used as a general expression of speed where direction is neither constant nor intended to be specified. *Wind velocity* is used as a vector when both speed and direction are known.

‡ *Mean* and *average:* Although these two words are usually interchangeable, in this report the word *mean* is used exclusively to indicate the mean of a whole series of readings obtained from instrument records, or as the mean of a trace produced by a pen and ink recorder. *Average* is used to describe the average value of a number of mean values.

§ *Run-of-wind* is taken to be the integrated total of wind passing any position in a given time, and is usually expressed in miles.

the initial cost of the machine, its associated equipment and connecting power line and which include also the annual maintenance charges. The second, with which this report is concerned, is the annual electrical output which is directly related to the *specific output* of a machine installed at any given site. The specific output may be conveniently expressed in "kilowatt-hours per annum per kilowatt of installed capacity" (see Section 5.4.4). From the work of P. C. Putnam and his colleagues on the 1250-kW Smith-Putnam wind turbine project at Grandpa's Knob in the U.S.A. (described in Ref. 25) and the Danish experience with wind-driven generators (Ref. 17, 30), it appeared probable that specific outputs of 4,000 kilowatt-hours per annum per kilowatt and upwards might be attained and that the capital costs might amount to about £50 per kilowatt. Two lines of investigation thus presented themselves. One was the study of general factors affecting the design of the most promising types of windmill; the other was an investigation of the wind régimes and wind structure influencing the output of any windmill when built. Unless it could first be proved that there were an ample number of reasonably favourable sites, it would be unprofitable to build large wind-driven electric generators. The E.R.A. wind survey was undertaken to provide this proof.

(1.1) Objects of the Wind Survey

The first aim, then, was to investigate the wind régimes at a number of sites widely distributed over the whole country. It was hoped, and later confirmed, that favourable wind conditions existed at a very large number of sites in Great Britain. Thus, if these sites were developed, power contributions could be made to the national electric grid network at many different points.

A second aim was to determine the magnitude of these contributions. There was little information on the optimum economic size for a large wind-driven machine but it was thought to be of the order of 2,000 kilowatts (Ref. 25). If, therefore, measurements were made on several potential wind power sites within a group of hills, the results would indicate the probable contribution to the grid at any one point. Any such grouping of plant would reduce the proportion of the overall constructional costs of access roads and transmission lines to be charged against each machine. Maintenance charges would also be reduced by the use of a central depot or workshop and maintenance staff might be housed nearby.

It was intended that the wind survey should be extended gradually until there were measuring sites throughout the country. At a later date, studies would be made of the optimum size and spacing of windmills. From the results of both of these investigations, it would be possible to make a reasonably accurate estimate of the total wind power capacity which might be installed. Its value within the national economy might then be assessed.

Finally, it was necessary to develop a technique for selecting good sites. For instance, it was thought that a ridge lying across the prevailing wind might prove to be more favourable than a conical hill of similar exposure, although later evidence did not support this view. The experiences of other investigators were studied, in particular those of the Smith-Putnam team who had been obliged to develop their own principles for selecting and testing sites. Three methods were tried, only one of which was used at Grandpa's Knob, the site finally chosen for the windmill. When measurements were made later at this site it was found that wind speeds at a height above the hill amounted to only some 70 per cent. of the values which had been predicted by calculation.

The first of the three American methods was a simple mathematical study of the " speed up " of the wind across the summit of a smooth ridge assumed to be continuous and to lie across the prevailing wind. The only example of a calculation of this type given by Putnam (Ref. 25) involved the use of an idealized hill with an aerofoil section.

Next, wind tunnel tests were carried out, on models of suitable hills, in wind speeds of up to 85 m.p.h. and for six different wind directions. Measurements were made at about a hundred points for each set of conditions. From these small scale measurements, it was hoped to predict the behaviour of the wind over a full-sized hill. Unfortunately, the experimental results did not agree with those from full scale measurements and the method had to be abandoned. Impossibly high speeds would be needed in wind-tunnel tests to achieve a similarity of Reynolds numbers between the model and the actual hill.

The final method was ecological. It had been found possible, by members of the American group, to correlate the average wind speed and the distorted growth effect which it produced in trees and shrubs. This method would be of little use in the British Isles where it could give information only in a negative way, as it is most unusual to find trees growing on any favourable wind-power site.

The fundamental requirements of good wind-power sites have already been stated in Ref. 16, where the authors have described the methods whereby a simple technique of selecting sites was developed in this country, but the outline given in the following section may be of assistance in understanding the progress made during the period June 1948 to the end of 1954.

Section (3) is devoted exclusively to a description of the wind-measuring sites in Great Britain, Northern Ireland and Eire. Most of the measuring equipment was installed by E.R.A. staff but some installations in Eire were carried out by the Electricity Supply Board. As well as giving details of each installation, this section includes two cross-sectional views of each hill, and photographs are shown where these are available.

The results obtained are presented in Section (4), which includes the run-of-wind, monthly and annual average wind speeds, and some information on wind direction.

Analyses of these results are given in Section (5), where the variation of specific output for different annual average wind speeds is shown. Sections are also included on the variation of wind speed with height, direction and time.

Wind data from overseas have been included in Section (6), to give some idea of the different wind régimes which may be encountered and to help in assessing the contribution which may be made by wind power to world energy resources.

(2) PROGRESS OF THE WIND SURVEY

An account of the work may be divided naturally into three parts. First a technique of measurement had to be established. Then the survey was extended to cover the whole of the British Isles. Finally more detailed measurements were made at a few selected sites.

The three types of anemometers used were of the same pattern as those employed by the Air Ministry Meteorological Office. Short descriptions of them, together with an account of a modification to the gearing of one type, are given in Appendix 1 which also describes the different types of supporting masts and poles used.

The recording instruments, which have included some novel features, were made in the E.R.A. laboratories and, as experience was gained in their use, various modifications in their design were made. The two latest patterns are described in Appendix 2.

Table 1.

General Details of Wind Survey Sites

List of Sites			Classification of Site	Location of Sites		Height of Hill (feet)	Height of Pole or Mast (feet)	Duration of Records	
No. (1)	Name (2)	District (3)	(4)	Lat. and Long. (5)	Nat. Grid Ref. (6)	(7)	(8)	First (9)	Last (10)
1	Costa Hill R	Orkney	A	59°09'N 3°13'W	N30/311297	500	10/66/118	25–11–48	31–1–52*
2	Vestra Fiold R	Orkney	A	59°05'N 3°20'W	N30/241222	430	10/66	16–12–48	13–7–49
3	Bignold Park	Orkney	D	58°58'N 2°58'W	N30/454102	130	30	9–7–48	20–2–50
4	Greenay	Orkney	A	59°06'N 3°14'W	N30/296236	490	10	24–6–48	7–8–48
5	Shurton Hill	Shetland	A	60°09'N 1°13'W	N41/442403	576	10	7–6–52	o
6	Ward of Scousburgh R	Shetland	A	59°57'N 1°18'W	N41/388187	863	30	7–6–52	21–9–53
7	Sandness Hill	Shetland	A	60°17'N 1°39'W	N41/192557	817	10	9–6–52	o
8	Ben Dorrery	Caithness	B	58°28'N 3°37'W	39/063550	810	10	12–10–53	o
9	Dunan Mor	Sutherland	B	58°37'N 5°00'W	29/262744	510	10	26–6–51	o
10	Meall an Fheadain	Ross-shire	A	58°02'N 5°24'W	19/999109	663	10	25–6–51	15–1–54
11	Ben Geary	Skye	A	57°34'N 6°36'W	18/253614	929	10	22–6–51	o
12	Chaipaval	Harris	A	57°49'N 7°06'W	08/972923	1,203	10	19–6–51	o*
13	Easaval	South Uist	A	57°07'N 7°20'W	08/774157	800	10	16–6–51	31–12–51
14	Ben Tangaval	Barra	A	56°57'N 7°32'W	07/639991	1,092	10	14–6–51	17–1–54
15	Crauchan Treshnish	Mull	A	56°33'N 6°19'W	17/347474	704	10	12–6–51	31–8–53*
16	Maol Buidhe	Islay	B	55°38'N 6°18'W	16/298459	542	10	9–10–52	17–1–54
17	Ben Cladville R	Islay	A	55°42'N 6°29'W	16/183545	410	30	11–10–52	o
18	Sgarbhe Breac	Islay	A	55°55'N 6°09'W	16/406766	1,192	10	13–10–52	o
19	Macrihanish	Kintyre	D	55°27'N 5°40'W	16/663222	100	a	7–5–50	o
20	Cnoc Moy R	Kintyre	A	55°22'N 5°47'W	16/613152	1,462	15	2–5–50	16–10–51
21	Torr Mor	Kintyre	A	55°18'N 5°48'W	16/600078	1,358	10	1–5–50	o
22	Crockan Donn	Arran	B	55°28'N 5°20'W	16/911248	716	10	7–10–53	o
23	Torr Righ Mor	Arran	B	55°31'N 5°22'W	16/888311	447	10	7–10–53	31–10–54
24	An Tunna	Arran	C	55°34'N 5°04'W	16/967362	1,184	10	8–10–53	28–2–54
25	Pinbain Hill R	Ayrshire	A	55°01'N 4°54'W	25/149921	734	15	30–5–50	31–12–53*
26	Downan Hill	Ayrshire	B	55°05'N 5°01'W	25/071803	348	10	25–4–50	25–10–51
27	Newlaw Hill	Kirkcudbright	B	54°49'N 3°58'W	25/732486	600	10	31–12–51	26–9–53*
28	Eweside Hill	Berwickshire	B	55°55'N 2°22'W	36/777688	820	10	18–9–53	o
29	Carnane	Isle of Man	B	54°08'N 4°30'W	24/848970	491	10	14–7–52	30–6–53
30	South Barrule	Isle of Man	A	54°09'N 4°40'W	24/734985	1,585	10	15–7–52	19–1–54
31	Snaefell R	Isle of Man	A	54°16'N 4°28'W	25/875106	2,034	30	17–7–52	30–4–53*
32	Holyhead Mountain	Anglesey	B	53°19'N 4°42'W	23/207824	431	b	31–4–49	30–10–50
33	Dolgarrog R	Caernarvonshire	C	53°11'N 3°11'W	23/749675	1,390	30	22–4–49	4–4–50
34	Mynytho Common	Caernarvonshire	B	52°51'N 4°31'W	23/298318	600	10	26–4–49	31–12–49
35	Mynydd Rhiw	Caernarvonshire	A	52°50'N 4°37'W	23/231295	990	30	16–4–51	13–3–52*
36	Mynydd Anelog R	Caernarvonshire	A	52°49'N 4°44'W	23/153274	628	10/66	16–11–49	o
37	Mynydd Mawr R	Caernarvonshire	A	52°48'N 4°45'W	23/140258	524	30	4–4–49	30–9–53c
38	Foel Eryr A R	Pembrokeshire	A	51°53'N 4°49'W	12/067322	1,535	15	25–8–49	31–8–53*
39	Foel Eryr B	Pembrokeshire	A	51°58'N 4°49'W	12/067322	1,535	10	26–11–51	25–6–54
40	Mynydd Castlebythe	Pembrokeshire	B	51°56'N 4°52'W	12/028296	1,137	10	24–8–49	30–9–50
41	Mynydd Kilkiffeth	Pembrokeshire	B	51°58'N 4°54'W	12/009325	1,096	10	26–8–49	11–11–49
42	Rhossilli Down R	Glamorgan	A	51°34'N 4°17'W	21/419888	633	15	30–8–49	15–12–52*
43	Garth Mountain	Glamorgan	C	51°32'N 3°18'W	31/313836	1,009	10/30	2–4–52	21–5–53
44	St. Agnes Beacon R	Cornwall	A	50°19'N 5°13'W	10/710503	629	15/30	17–5–49	31–12–50
45	Watch Croft	Cornwall	B	50°10'N 5°37'W	10/422358	827	10	19–5–49	15–11–49
46	Carn Bean	Cornwall	B	50°08'N 5°41'W	10/384332	665	10	19–5–49	12–5–50
47	Carn Brea R	Cornwall	A	50°05'N 5°39'W	10/386282	657	30	24–5–49	31–10–50
48	Tregonning Hill R	Cornwall	A	50°07'N 5°22'W	10/600297	615	30	18–5–49	31–12–49
49	Lizard	Cornwall	D	49°58'N 5°12'W	10/171117	100	10	14–5–49	30–9–50
50	Portland Bill	Dorset	C	50°31'N 2°27'W	30/678692	141	10	27–2–52	31–12–52
51	Les Landes	Channel Isles	B	49°15'N 2°15'W	—	250	10	10–1–50	31–10–50
52	Brecqhou	Channel Isles	B	49°26'N 2°24'W	—	360	10	23–9–50	31–5–52
53	Alderney	Channel Isles	B	49°43'N 2°12'W	—	284	10	1–1–54	31–10–54
54	Firle Beacon	Sussex	C	50°05'N 0°07'E	51/471059	600	10	26–4–51	31–12–51
55	Telegraph Hill	Norfolk	B	52°56'N 1°08'E	63/103426	257	10	7–8–52	11–9–53
56	Winthorpe	Lincolnshire	B	53°09'N 0°19'E	53/560662	30	10	10–4–52	2–8–52
57	Spurn Head	Yorkshire	B	53°34'N 0°07'E	54/402110	30	10	9–4–52	24–7–52
58	Robin Hood's Bay	Yorkshire	B	54°24'N 0°30'W	45/969012	890	10	15–9–53	26–12–54
59	Holy Island	Northumberland	B	55°41'N 1°48'W	46/127434	60	10	17–9–53	o
60	Moor House	Westmorland	C	54°41'N 2°21'W	35/761327	1,906	10	18–10–53	31–10–54
61	Dore Moor R	Yorkshire	C	53°20'N 1°34'W	43/301820	800	38	14–10–49	25–1–51
62	Bull Point	Devon	C	51°12'N 4°12'W	21/464466	220	10	19–7–53	o
63	Cranfield R	Bedfordshire	C	52°04'N 0°37'W	42/949417	370	45	20–1–53	o
64	Slieve Gullion	Co. Armagh	A	54°07'N 6°26'W	—	1,894	10	7–9–50	8–2–54
65	Chimney Rock A	Co. Down	A	54°09'N 5°55'W	—	2,152	10	1–2–51	16–1–54*
66	Chimney Rock B	Co. Down	A	54°09'N 5°55'W	—	2,152	10	12–6–52	21–12–52

Table 1—*continued*

List of Sites			Classification of Site	Location of Sites		Height of Hill (feet)	Height of Pole or Mast (feet)	Duration of Records	
No. (1)	Name (2)	District (3)	(4)	Lat. and Long. (5)	Nat. Grid Ref. (6)	(7)	(8)	First (9)	Last (10)
67	Slieve Donard	Co. Down	A	54°10′N 5°55′W	—	2,804	10	23- 8-52	7-11-52
68	Divis Mountain R	Co. Antrim	A	54°37′N 6°01′W	—	1,574	30	5- 9-50	31-12-51
69	Big Collin	Co. Antrim	B	54°48′N 6°05′W	—	1,163	10	12- 9-50	10- 5-51
70	Evish Hill	Co. Antrim	C	54°59′N 6°09′W	—	1,100	10	11- 9-50	15- 6-51
71	Carnanmore R	Co. Antrim	A	55°11′N 6°06′W	—	1,253	10/66	12- 9-50	31- 8-54*
72	Knocklayd R	Co. Antrim	A	55°09′N 6°15′W	—	1,695	30	14- 9-50	30- 8-51
73	Binevenagh	Co. Derry	A	55°07′N 6°55′W	—	1,260	30	16- 9-50	30- 6-51
74	Mullaclogha	Co. Tyrone	A	54°48′N 7°68′W	—	2,088	10	1- 5-51	30- 9-52*
75	Dooish R	Co. Fermanagh	B	54°34′N 7°31′W	—	1,100	30	21- 9-50	6- 9-51
76	Ard Malin	Co. Donegal	B	55°22′N 7°22′W	—	362	10	28- 9-50	30- 8-51
77	Bloody Foreland R	Co. Donegal	A	55°08′N 8°16′W	—	1,038	10/30	27- 9-50	15-12-53*
78	Crocknafarragh	Co. Donegal	A	55°00′N 8°12′W	—	1,707	10	27- 9-50	16- 1-52
79	Slieve Tooey	Co. Donegal	A	54°45′N 8°38′W	—	1,515	10/30	25- 9-50	o
80	Leahan R	Co. Donegal	A	54°40′N 8°45′W	—	1,418	30	23- 9-50	21- 8-51
81	Blue Stack Mts.	Co. Donegal	C	54°45′N 8°05′W	—	2,219	10	1- 3-51	22- 9-51
82	Glencastle Hill	Co. Mayo	B	54°12′N 9°52′W	—	760	10	26-10-51	12- 9-52
83	Gortbrack South	Co. Mayo	A	54°02′N 9°49′W	—	791	10	16-11-51	13-12-52
84	Knockmore	Co. Mayo	A	53°56′N 10°00′W	—	1,119	10	26-10-51	31-10-54
85	Tully Mountain	Co. Galway	A	53°35′N 10°00′W	—	1,172	10	9- 1-53	30- 4-54
86	Errisbeg	Co. Galway	A	53°23′N 9°57′W	—	987	10	22-10-51	4- 1-53
87	Inishmore	Aran Islands	A	53°08′N 9°43′W	—	406	10	24-10-51	21- 5-52
88	Knockanore	Co. Kerry	B	52°32′N 9°37′W	—	880	10	20-10-51	20- 3-54
89	Mount Eagle	Co. Kerry	A	52°07′N 10°26′W	—	1,696	10	19-10-51	24-11-52
90	Killelan	Co. Kerry	A	51°57′N 10°19′W	—	921	10	1- 3-52	19- 7-52
91	Cahernageeha	Co. Kerry	A	51°47′N 10°07′W	—	1,040	10	1- 1-54	o
92	Knockgour A	Co. Cork	A	51°38′N 10°00′W	—	1,589	10	16-10-51	11- 5-53
93	Knockgour B	Co. Cork	A	51°38′N 10°00′W	—	1,589	10	24-11-52	30- 9-53
94	Mount Gabriel	Co. Cork	B	51°33′N 9°33′W	—	1,339	10	15-10-51	26-11-52
95	Castle Mountain	Co. Louth	A	54°02′N 6°17′W	—	1,265	10	1- 1-54	30- 9-54
96	Howth	Co. Dublin	C	53°23′N 6°04′W	—	500	10	8- 6-53	31- 8-53
97	Verschoyle's Hill A	Co. Dublin	C	53°16′N 6°27′W	—	1,097	10	14- 5-52	o
98	Tievealehid	Co. Donegal	A	55°05′N 8°12′W	—	1,413	10	17- 6-54	30- 9-54
99	Three Rock Mountain	Co. Dublin	C	53°15′N 6°14′W	—	1,479	10	6- 8-52	1- 7-53
100	Two Rock Mountain	Co. Dublin	C	53°13′N 6°14′W	—	1,699	10	24- 2-53	5-10-53
101	Croghan Kinshela	Co. Wicklow	A	52°48′N 6°19′W	—	1,990	10	13- 9-54	14-12-54

Column (2) " R " Indicates a recorder installation.

Column (4) " A " A good potential wind power site where the estimated annual average wind speed exceeds 20 m.p.h. and wind power might compete with either steam or diesel generation.

" B " A measuring site other than classification A, C, or D, installed to complete the wind survey of the British Isles. Estimated annual average wind speed less than 20 m.p.h.

" C " A site not normally considered as a potential wind power site, but where some special physical features or other reasons warranted wind measurements. (Excluding " D " below).

" D " A site where measurements were made specifically for correlation with long term records obtained from a Meteorological Office station.

Column (8) Wind measurements occasionally made at more than one height above the ground.

" a " Approximately 6 ft. above aerodrome control tower.

" b " 10-ft. pole on old radar installation—total height approx. 30 ft.

Column (10) " o " Site still in operation on 31st Dec 1954.

" * " Records not continuous.

" c " Measurements re-started after 31st Dec. 1954.

(2.1) The Early Work

The mainland of Orkney was chosen for the start of the wind survey. It lies in a windy district and maps showed that it had many smooth hills likely to induce a considerable local increase in wind speed. Also, the North of Scotland Hydro-Electric Board had expressed its willingness to operate a wind-driven electric generator connected to its distribution network on the island.

Initial measurements made on Costa Hill and Vestra Fiold in the north-west corner of Orkney mainland have been described in Ref. 15. Between 12th July and 9th August, 1948, the average wind speeds at 10 ft. above the summits of the two hills were 19·5 m.p.h., and 15·1 m.p.h., respectively. A short period of measurement at a hill nearby showed it to be slightly more windy than Vestra Fiold.

During this time results had also been obtained from an anemometer set up on the disused Meteorological Office site at Bignold Park, Kirkwall. Long-period wind records for this site showed that the annual average speed was 14·8 m.p.h. The figure obtained from Kirkwall for this summer period was 12·3 m.p.h. which, when compared with the long term records, proved to be a normal value for the time of year.

The evidence of a fairly large increase in wind speed obtained on Costa Hill was sufficiently encouraging to justify consideration by the North of Scotland Hydro-Electric Board, of the installation of a wind-driven electric generator in Orkney, and the construction of a 100-kW machine was planned. Meanwhile preparations were made to obtain measurements of wind speed at greater heights above both Costa Hill and Vestra Fiold. Two tubular steel masts, each 66-ft. high, were used as supports for the anemometers and two recorders (Ref. 27) were built and installed.

The first records were obtained from both sites by the end of the year and during the following months their windiness was confirmed. Whilst the average wind speed at Kirkwall for the seven months December 1948 to June 1949 was 15·9 m.p.h., the average wind speeds at 35 ft. over Costa Hill and Vestra Fiold were 26·8 m.p.h. and 24·8 m.p.h. respectively.

(2.2) Extension of the Wind Survey

After the completion of the measuring installations in Orkney, efforts were directed towards extending the wind survey to include the rest of the British Isles. The following table gives the dates of installation of wind survey equipment in different areas:—

North Wales	March/April	1949
Cornwall	May	1949
South Wales	August	1949
Channel Islands	January	1950
South-West Scotland	April/May	1950
Northern Ireland and Donegal	September	1950
North-West Scotland	June	1951
West and South-West Eire	September/October	1951
East England	April	1952
Shetland	June	1952
Isle of Man	July	1952
Islay	October	1952
North-East England	September	1953
Arran Island	October	1953

A few other sites were also equipped. In addition, the Electricity Supply Board installed several anemometers on hills along the eastern coastline of Eire. The full list of sites, as at 31st December, 1954, is given in Section (3.1) (Table 1).

Much the same procedure was followed in all cases. For each new district 1 in. Ordnance Survey maps were obtained and, from these, hills which might prove suitable were selected. To determine the local wind régime in detail, recording instruments were installed on one or two convenient hills. On the remaining hills cup counter anemometers were used to help in assessing the relative windiness of the different hills within the group. This assessment could be made in a few months, but for record purposes the instruments were usually left for a year. By the end of that time the run-of-wind, in miles, over each of the hills had been compared and relationships established. It was then possible to remove most of the anemometers, leaving only one or two to obtain continuous records for the area. By the end of 1954 all the regions in Great Britain and Ireland considered worth investigating had been adequately surveyed.

(2.2.1) Local Arrangements

Usually, permission to install measuring equipment on hills was freely given and, indeed, great interest was often shown in the work. Only occasionally, when land was held in common ownership, was there any delay in obtaining permission.

Since, after the installations had been completed, it was quite out of the question for E.R.A. staff to visit them except for maintenance purposes, local observers were recruited. Occasionally a member of the staff of the local electricity undertaking did the work but at most sites it was done by farmers or members of their family, by shepherds, postmen, coastguards and others who lived or worked nearby. Little instruction was needed for the reading of a cup anemometer; for Series 1 impulse recorders, needing regular weekly attention, an hour's tuition was usually sufficient. An instruction sheet was left with each instrument for reference.

The work of the local observers was essential to the success of the survey and the investigators gratefully acknowledge their help.

(2.3) Second Stage of the Wind Survey

Normally, this part of the work is begun only when the selection of a site for a wind-driven generator has been made, and when more information is needed, at greater heights above the hill, than is provided by an anemometer on a 30-ft. pole. In the early stages of wind power development it is probable that only medium-sized windmills will be constructed, with hub heights of less than 100 ft. Most of the information required can be provided by mounting anemometers at or near to the actual height of the wind wheel hub.

Four installations of this type have been made. Tubular masts 66 ft. high were erected on Costa Hill in Orkney, Mynydd Anelog in Caernarvonshire and Carnanmore in Co. Antrim. Also, a 120-ft. lattice mast was erected on Costa Hill near the site of the first 100-kW windmill. The purpose of this installation was to obtain more detailed information on the gustiness and general behaviour of winds flowing over hills. The mast itself takes the form of a large cross, with the crossarm at a height of 80 ft., corresponding to the hub height of the Orkney windmill. Anemometers are located at the extremities of this platform and also on the upright section at heights of 30 ft. above and below the centre of the cross. These four positions correspond to four points on the circle swept by the windmill rotor. This mast has facilitated investigations on the structure of the wind and the results obtained form the subject of a separate report (see Ref. 34).

The 66-ft. masts are arranged with duplicated anemometer positions both at the top and at the 35-ft. level. A remote-indicating wind vane is usually mounted on the top of the mast. The indications of this instrument together with those of four cup contact anemometers are then recorded photographically. When wind directions are not required, a four-channel impulse recorder is used instead. At all these sites, a cup counter anemometer is maintained on a 10-ft. pole to preserve continuity in the results should any fault occur in the recording installation.

(3) WIND SURVEY MEASURING SITES

(3.1) List of Sites

The full list of the sites is given in Table 1 together with such information as seems to be relevant. For convenience the district of each site is included in this table but to save space it is omitted from all subsequent tables. Each site has been given a number for ease of reference between this and subsequent tables.

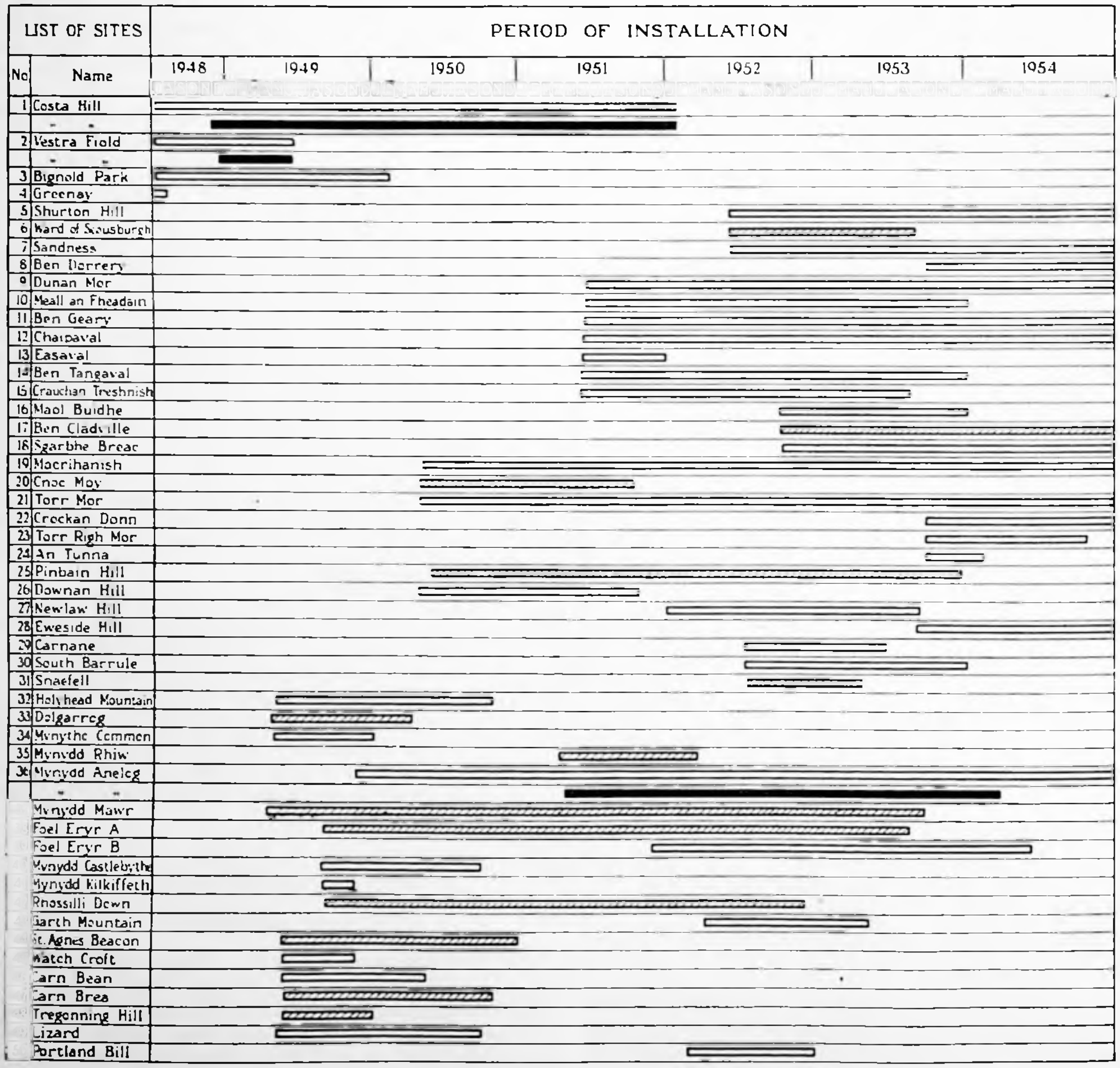
(3.2) Duration of Records

The period of operation and the type of instrument used at each site is shown in Table 2. The diagram covers the six-year period ending 31st December, 1954.

Although all records are shown to be continuous this was not always the case. Information was lost through the occasional failure of an instrument, but for some analyses it was possible to minimize the importance of this loss by reference to the readings from a nearby instrument. During the operation of any group of anemometers, various relationships were established between the run-of-wind at different sites within the group, and when a gap occurred in the readings of a counter type of anemometer, it was usually possible to estimate fairly accurately the probable run-of-wind during that period. Similar gaps

Table 2

DURATION OF WIND MEASUREMENTS.



KEY:—

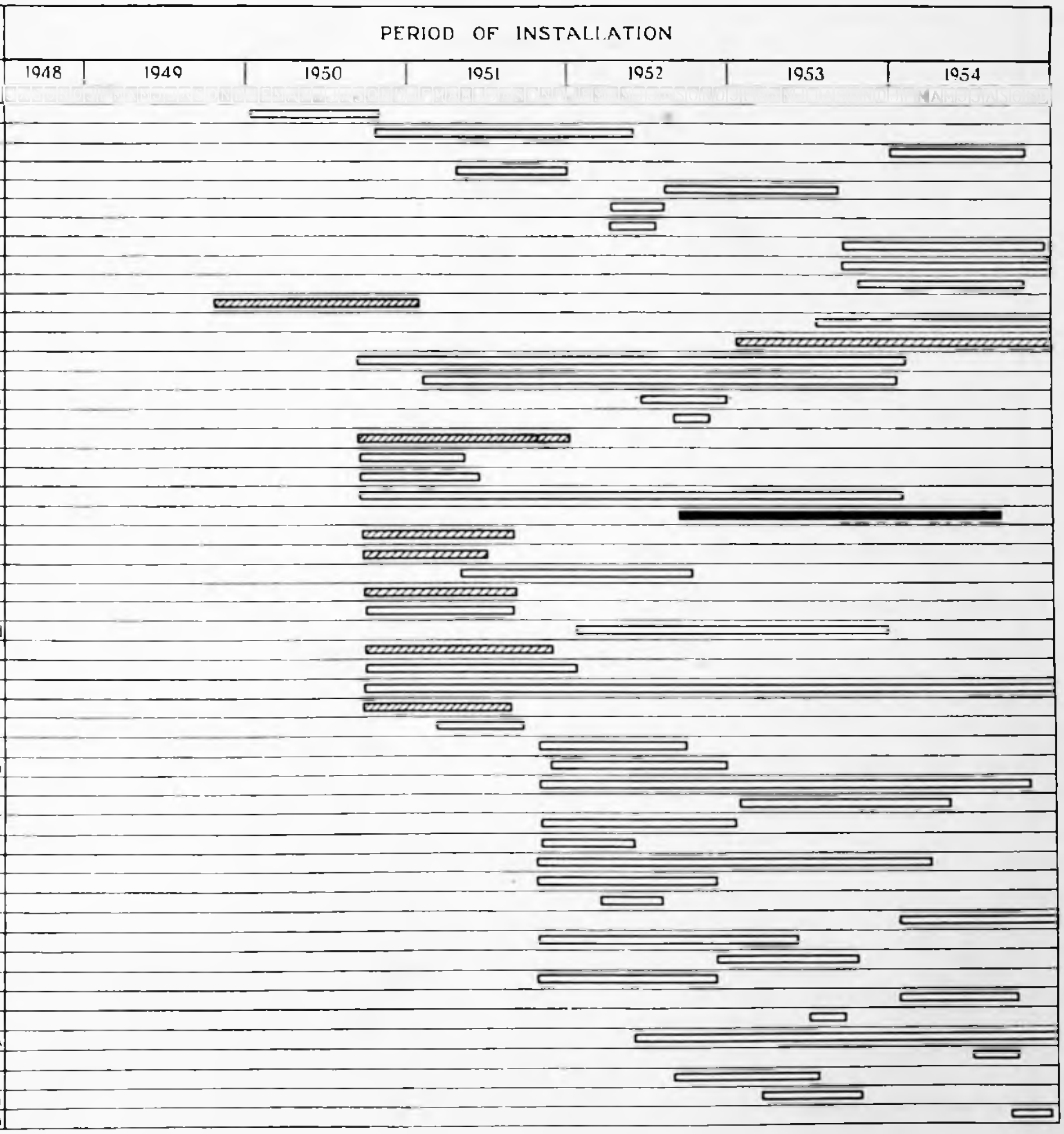
☐ Counter anemometer, or contact anemometer with electrical contact (usually 10 ft. pole).

▨ Contact anemometer and recorder (usually 30 ft. pole).

■ Multi-channel recorder (usually 66ft. mast).

Table 2—*continued*

LIST OF SITES	
No	Name
51	Les Landes
52	Brecqhou
53	Alderney
54	Firle Beacon
55	Telegraph Hill
56	Winthorpe
57	Spurn Head
58	Robin Hoods Bay
59	Holy Island
60	Moor House
61	Dore Moor
62	Bull Point
63	Cranfield
64	Slieve Gullion
65	Chimney Rock A
66	Chimney Rock B
67	Slieve Donard
68	Divis Mountain
69	Big Collin
70	Evish Hill
71	Carnanmore
	″
72	Knocklayd
73	Binevenagh
74	Mullaclogha
75	Dooish
76	Ard Malin
77	Bloody Foreland
	″ ″
78	Crocknafarragh
79	Slieve Tooey
80	Leahan
81	Blue Stack Mts.
82	Glencastle Hill
83	Gortbrack South
84	Knockmore
85	Tully Mountain
86	Errisbeg
87	Inishmore
88	Knockanore
89	Mount Eagle
90	Killelan
91	Cahernageeha
92	Knockgour A
93	Knockgour B
94	Mount Gabriel
95	Castle Mountain
96	Howth
97	Verschoyle's Hill A
98	Tievealehid
99	3 Rock Mountain
100	2 Rock Mountain
101	Croghan Kinshela



could be filled in the records of cup-contact anemometers when these were used for the sole purpose of obtaining the run-of-wind curve. When they were used for more detailed analyses, as described in Sections (4) and (5), even slight gaps assumed a greater significance. The gaps which were particularly troublesome were those which occurred towards the end of one monthly period and carried on slightly into the next. This automatically prevented complete analysis of the whole of both periods. Occasionally, there was sufficient independent information for an estimate to be made of the windflow during such a break, and

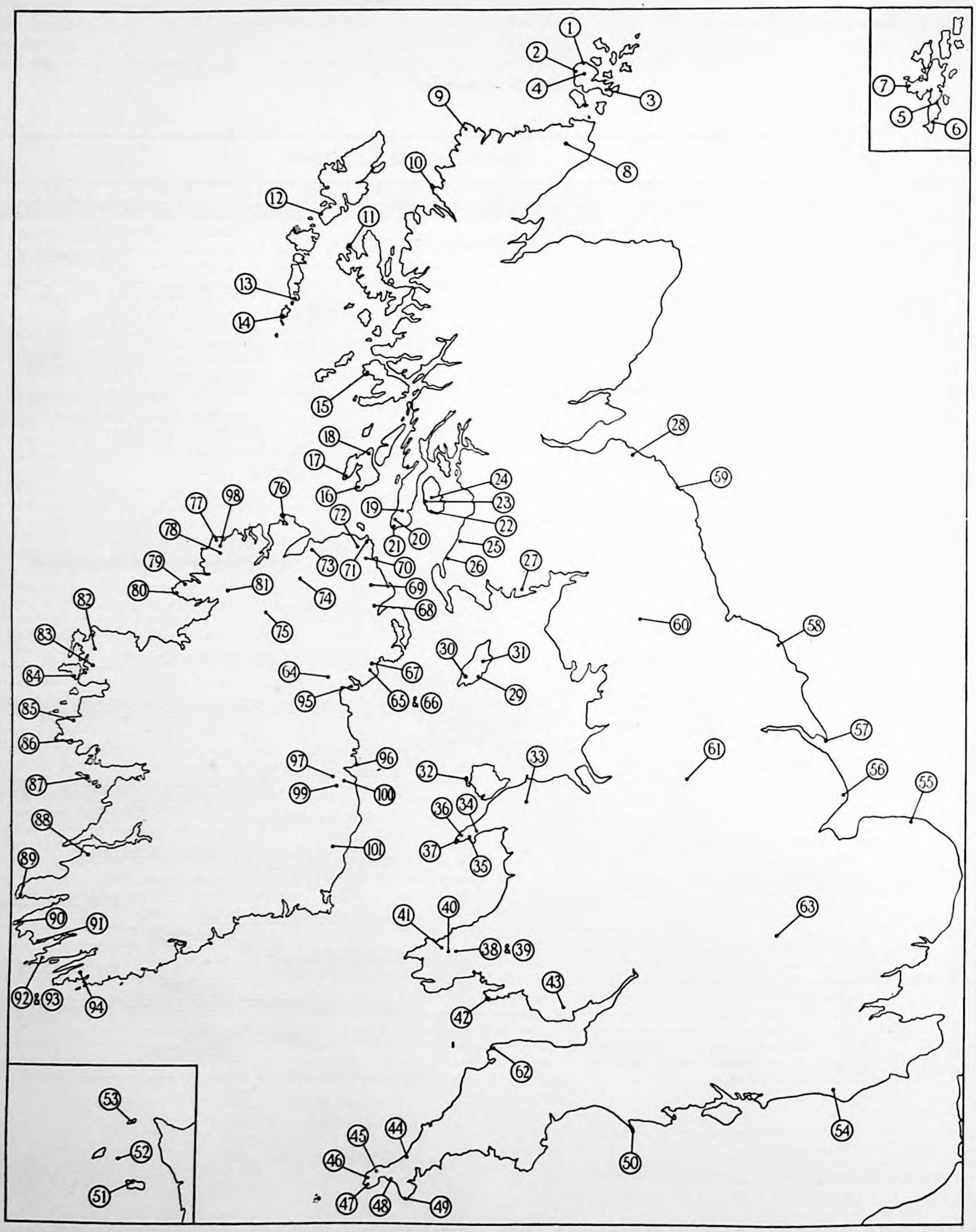


Fig. 1.—E.R.A. wind survey sites.

The numbers against each site correspond to the characteristic numbers given in Tables 1 and 2, etc.

the corresponding results are indicated thus (†) in Table 3. Estimates were made only when the filling of a few short gaps in the figures of the mean hourly wind speeds greatly increased the amount of information to be obtained from the records and, in all cases, the length of the gap was insignificant when compared with that of the whole period.

(3.3) Map of Sites

In Figure 1 the measuring sites are represented by the characteristic site number.

(3.4) Hill Profiles

To obtain a reasonably clear picture of the shape of a site, a large scale Ordnance Survey Map, together with photographs, is desirable. Since the former, at any rate, cannot be reproduced here, a series of cross-sectional views of the hills are given in Fig. 2 to indicate the types of site which were chosen. Photographs of some of them are shown in Fig. 3.

In Figure 2, vertical sections have been drawn at right angles through the anemometer site on each hill. In the horizontal scale, one inch represents approximately one mile; the vertical scale has been exaggerated by a factor slightly greater than two. The direction of view of each section is clearly marked. When a contour map of the hill shows an elongated shape, the two sections are drawn through the major and minor axes. In each case the direction of view of the second section is ninety degrees clockwise from the direction of view of the first. Where there are no definite major and minor axes, the first section is usually drawn looking due north. The position of the anemometer on each hill is marked by a vertical line.

(3.5) Some Comments on Particular Hills

(1) *Costa Hill* is a ridge lying roughly S.E./N.W. The summit is almost level over a distance of 300 yds. The two long sides have an average slope of about 1 in 4. It was chosen because of its good exposure to winds from all directions, but the effect of a cliff 400 ft. high at the north-western end was uncertain. A period of wind measurements made at a height of 10 ft. failed to reveal any noticeable disturbance due to the cliff. A road passes the foot of the hill, and an 11-kV line runs along the lower slopes. These circumstances combine to produce an excellent site for a wind-driven generator on Orkney, whilst frequent gales with salt-laden air have provided a severe test for the 100 kW machine which was installed there in 1950.

(2) *Vestra Fiold* was chosen at the same time as Costa Hill. It was well exposed to winds from all directions. A short period of wind measurement revealed that the average slope of the hill—about 1 in 12—was not sufficient to produce a speed-up of the wind as great as that at Costa Hill.

(3) *Bignold Park*. The Meteorological Office had taken wind speed measurements at this site on the outskirts of Kirkwall for many years. More recently their instruments had been moved to another position about a mile away. An anemometer was therefore installed on the 30-ft. mast which was still in existence so that simultaneous measurements made elsewhere in Orkney could be compared with long term records.

(8) *Ben Dorrery*, rising to 810 ft., lies in the centre of a huge peat moor in Caithness. The quantity of peat is such that some consideration is being given to its exploitation by a peat-fired power station. This hill was chosen as it was well-exposed and might be expected to have a high average wind speed. It would, therefore, be a convenient site on which to install a windmill to operate in conjunction with the projected power station.

(12) *Chaipaval* on Harris in the Outer Hebrides, is situated on a narrow neck of land projecting out into the Atlantic and is an obvious choice for a windmill site. The huge mass of rock rises smoothly on all sides from almost sea level to over 1,200 ft. The exposure to winds from all directions is excellent. Since an anemometer was installed on the summit, the results obtained have fully satisfied all expectations.

(20) *Cnoc Moy* and (21) *Torr Mor* are two nearby hills among several others situated at the end of the Mull of Kintyre. They were chosen as being representative of a large number of hills in this peninsula. Their exposure is generally good to winds from the east as well as the more common westerly winds. Excellent average wind speeds have since been measured, which, when considered with the number of potential windmill sites indicates that very large quantities of electrical energy could be generated by wind power in this area.

(25) *Pinbain Hill*, on the western coast of Ayrshire, is a smooth rounded hill with two small subsidiary summits which could readily be used for two different machines. The hill sides which are fairly steep, provide a good speed-up of all winds except those from the north-east quadrant. Accessibility is good; a main road passes the foot of the hill. This fact, together with the high average wind speeds which have been recorded here, combine to make this one of the more attractive sites in the country for the development of wind power.

(31) *Snaefell* (2,034 ft.) is the highest hill on the Isle of Man. Records suggest that it is the windiest of any of the sites at which measurements have been taken. The installation suffered, however, from severe icing conditions during the late winter months.

(32) *Holyhead Mountain*. The anemometer was mounted on a pole above a disused tower some 400 yds. to the west of the summit. It was therefore screened from the full force of winds in the eastern quadrant by the main bulk of the mountain. In spite of this, high average wind speeds were recorded and the wind speed on the actual summit is likely to be even higher.

(36) *Mynydd Anelog* is situated near the end of the Lleyn peninsula in Caernarvonshire and has excellent exposure to winds of all directions. Its slopes are moderately steep and high average wind speeds have been recorded. Indeed, it may be considered as one of the best potential windmill sites in Wales.

(42) *Rhossili Down* is a long ridge lying across the western end of the Gower peninsula. Although situated in a well-exposed position, the main mountain mass of South Wales tends to screen the hill from the full force of northern and eastern winds. Nevertheless, the ridge would accommodate a number of machines within quite a small area.

(44) *St. Agnes Beacon* and (47) *Carn Brea*. These two hills in Cornwall are very similar in height, shape and also in average wind speed. When simultaneous wind measurements were made on both hills, the run-of-wind curves were indistinguishable, although the average wind speed was rather low compared with other parts of the west coast: the relatively shallow slopes which are generally associated with Cornish hills, may account for this.

(52) *Brecqhou*, a small island off Sark in the Channel Islands, is a fair example of an isolated community. Wind measurements were originally made at the request of the owner. The results obtained were not exceptional, but could be considered to be promising in view of the absence of other sources of energy.

(63) *Cranfield* in Bedfordshire is the site of the Windmill Research Station of the E.R.A. It is on the western edge of a low plateau, about 400 ft. above sea level. Other factors,

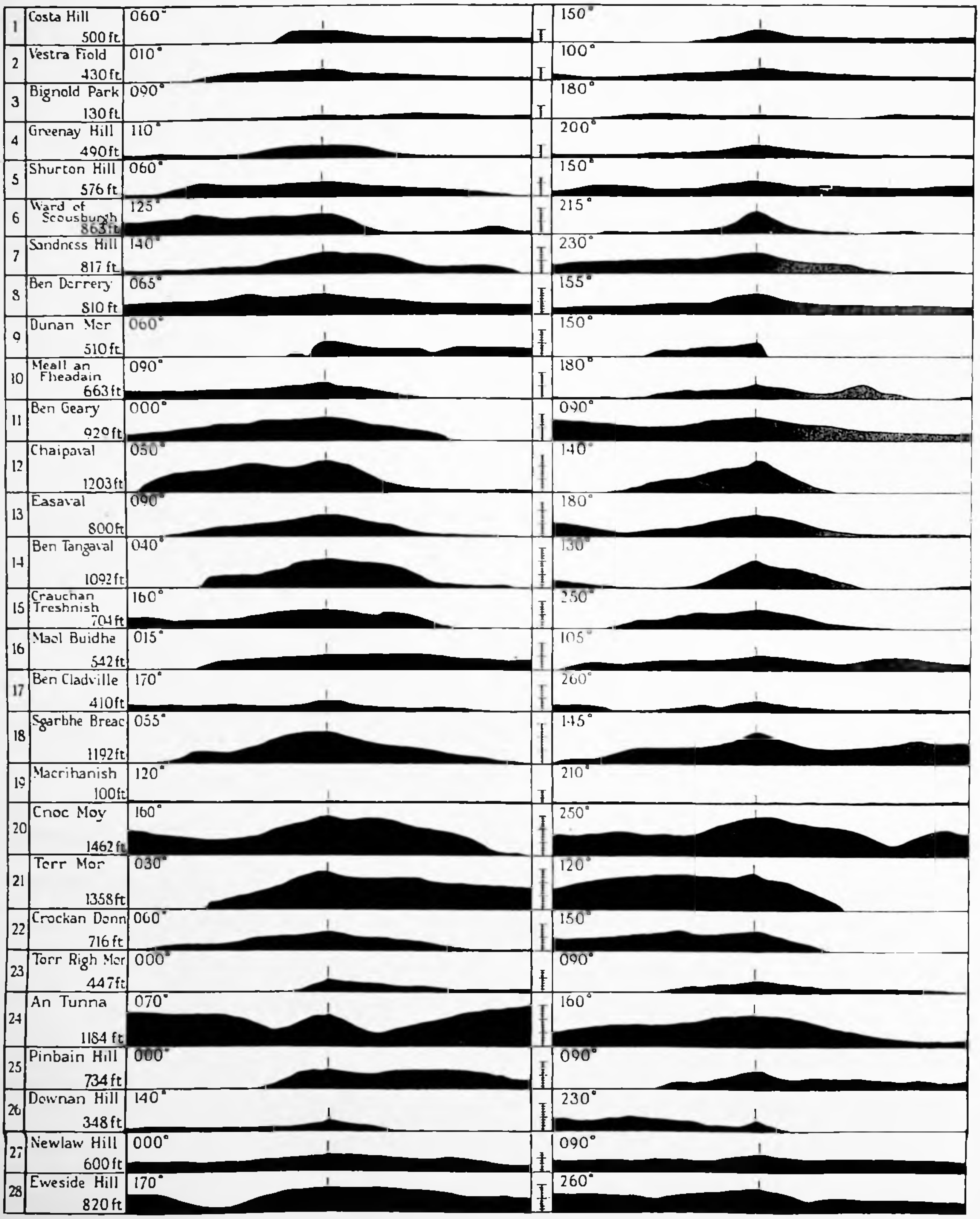


Fig. 2 (*a*)

Fig. 2.—Sectional elevation of E.R.A. wind survey sites.

Two cross-sectional views at right-angles are shown for each site. The first view of each hill is of the cross section having the largest area. The second one is drawn looking in a direction 90° clock-wise from the first. When the hill profile is similar from all directions, the first profile is drawn looking due north. The figures in degrees on each diagram refer to direction in which the observer is facing. The altitude of each site is given in feet. The position of the anemometer on each diagram is indicated by a short vertical line. The width of each cross-sectional view is 3 miles.

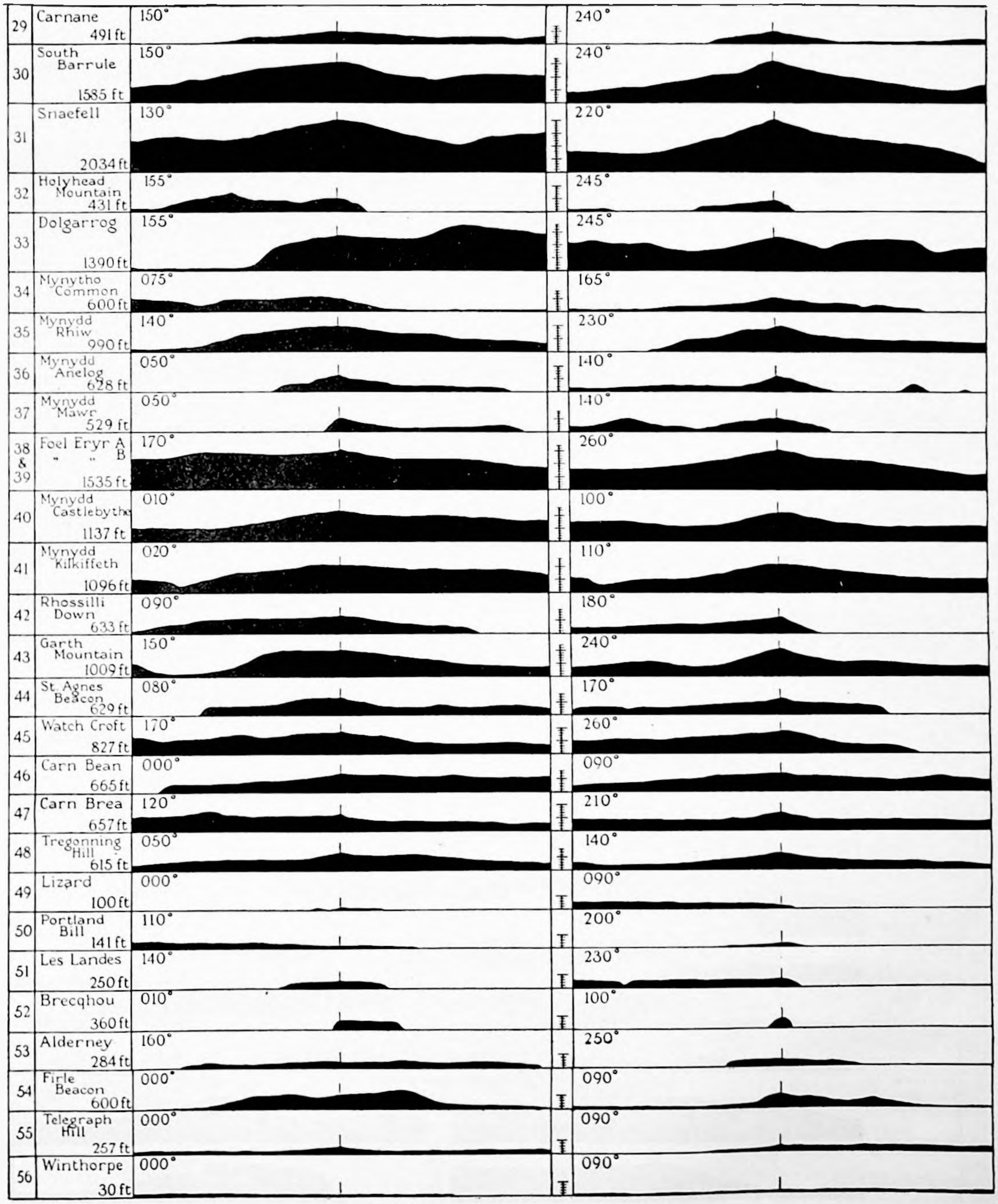
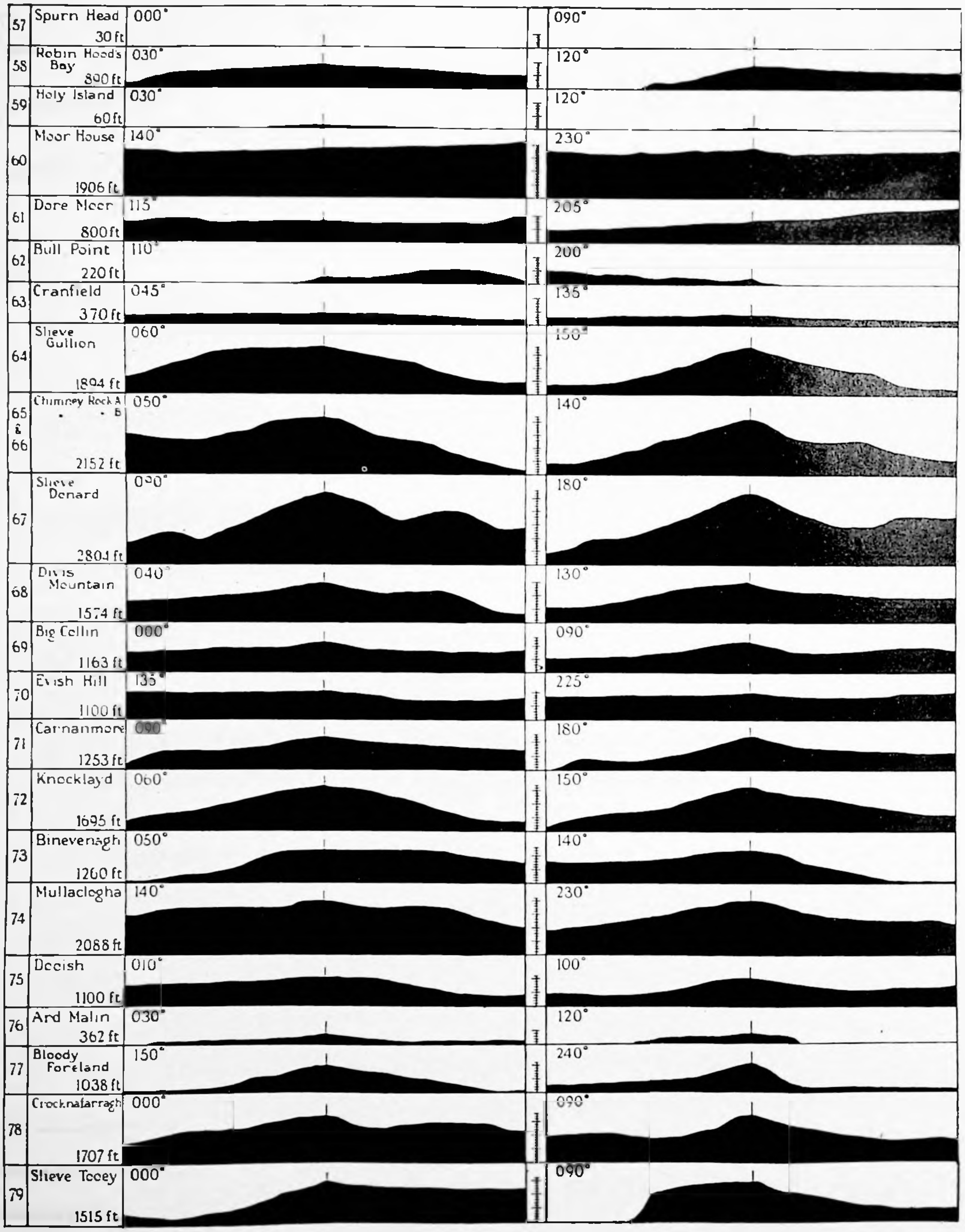

29 Carnane 491 ft 150° 240°
30 South Barrule 1585 ft 150° 240°
31 Snaefell 2034 ft 130° 220°
32 Holyhead Mountain 431 ft 155° 245°
33 Dolgarrog 1390 ft 155° 245°
34 Mynytho Common 600 ft 075° 165°
35 Mynydd Rhiw 990 ft 140° 230°
36 Mynydd Anelog 628 ft 050° 140°
37 Mynydd Mawr 529 ft 050° 140°
38 & 39 Foel Eryr A " " B 1535 ft 170° 260°
40 Mynydd Castlebythe 1137 ft 010° 100°
41 Mynydd Kilkiffeth 1096 ft 020° 110°
42 Rhossilli Down 633 ft 090° 180°
43 Garth Mountain 1009 ft 150° 240°
44 St. Agnes Beacon 629 ft 080° 170°
45 Watch Croft 827 ft 170° 260°
46 Carn Bean 665 ft 000° 090°
47 Carn Brea 657 ft 120° 210°
48 Tregonning Hill 615 ft 050° 140°
49 Lizard 100 ft 000° 090°
50 Portland Bill 141 ft 110° 200°
51 Les Landes 250 ft 140° 230°
52 Brecqhou 360 ft 010° 100°
53 Alderney 284 ft 160° 250°
54 Firle Beacon 600 ft 000° 090°
55 Telegraph Hill 257 ft 000° 090°
56 Winthorpe 30 ft 000° 090°

Fig. 2 (*b*)



57 Spurn Head 30 ft 000° 090°
58 Robin Hood's Bay 890 ft 030° 120°
59 Holy Island 60 ft 030° 120°
60 Moor House 1906 ft 140° 230°
61 Dore Moor 800 ft 115° 205°
62 Bull Point 220 ft 110° 200°
63 Cranfield 370 ft 045° 135°
64 Slieve Gullion 1894 ft 060° 150°
65 & 66 Chimney Rock A B 2152 ft 050° 140°
67 Slieve Donard 2804 ft 180°
68 Divis Mountain 1574 ft 040° 130°
69 Big Collin 1163 ft 000° 090°
70 Evish Hill 1100 ft 135° 225°
71 Carnanmore 1253 ft 090° 180°
72 Knocklayd 1695 ft 060° 150°
73 Binevenagh 1260 ft 050° 140°
74 Mullaclogha 2088 ft 140° 230°
75 Dooish 1100 ft 010° 100°
76 Ard Malin 362 ft 030° 120°
77 Bloody Foreland 1038 ft 150° 240°
78 Crocknafarragh 1707 ft 000° 090°
79 Slieve Tooey 1515 ft 000° 090°

Fig. 2 (*c*)

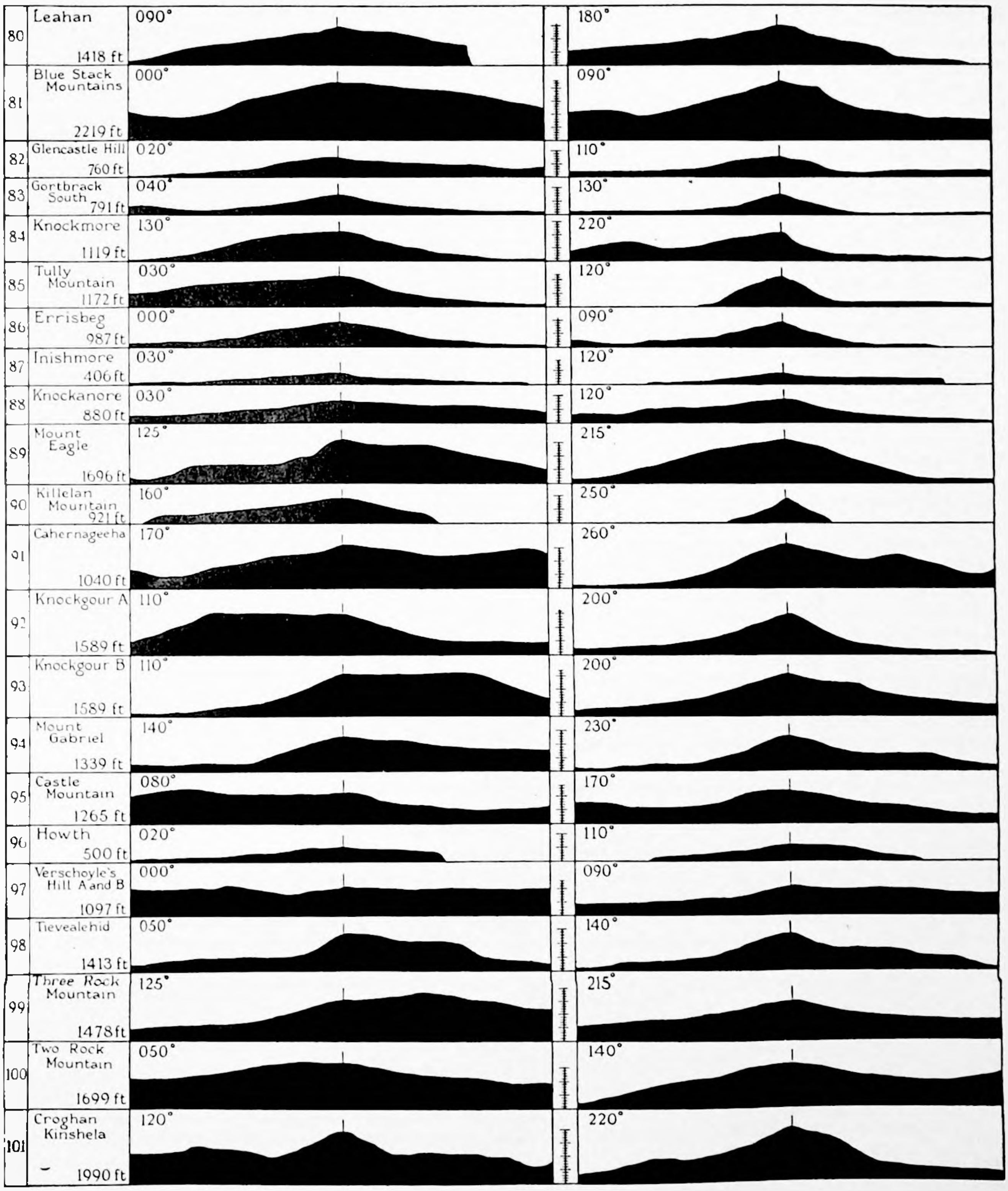

80 Leahan 1418 ft 090° 180°
81 Blue Stack Mountains 2219 ft 000° 090°
82 Glencastle Hill 760 ft 020° 110°
83 Gortbrack South 791 ft 040° 130°
84 Knockmore 1119 ft 130° 220°
85 Tully Mountain 1172 ft 030° 120°
86 Errisbeg 987 ft 000° 090°
87 Inishmore 406 ft 030° 120°
88 Knockanore 880 ft 030° 120°
89 Mount Eagle 1696 ft 125° 215°
90 Killelan Mountain 921 ft 160° 250°
91 Cahernageeha 1040 ft 170° 260°
92 Knockgour A 1589 ft 110° 200°
93 Knockgour B 1589 ft 110° 200°
94 Mount Gabriel 1339 ft 140° 230°
95 Castle Mountain 1265 ft 080° 170°
96 Howth 500 ft 020° 110°
97 Verschoyle's Hill A and B 1097 ft 000° 090°
98 Tievealehid 1413 ft 050° 140°
99 Three Rock Mountain 1478 ft 125° 215°
100 Two Rock Mountain 1699 ft 050° 140°
101 Croghan Kinshela 1990 ft 120° 220°

Fig. 2 (*d*)

besides that of windiness, governed the apparent paradox of choosing an inland site: these included the provision of suitable land, buildings and power lines, the availability of nearby laboratory facilities, including wind tunnels, and also the general accessibility from London.

(71) *Carnanmore*. This site is at the centre of a long rounded hill on the north Antrim coast It is representative of many such hills which surround the Antrim plateau Initial wind measurements by a counter anemometer on a 10-ft. pole gave such good results that further measurements were made up to a height of 66 ft. It is considered that this hill is one of the most suitable in Northern Ireland for the development of wind power.

(77) *Bloody Foreland* lies within a mile of the sea in the extreme north-western corner of Donegal. The surrounding country is poor agriculturally but thickly populated. The contours of the hill are almost circular whilst the upper slopes are smooth and well-rounded. The summit is bare of any form of vegetation. The high average wind speeds already measured place this site among the best in the British Isles.

(84) *Knockmore* is one of several suitable wind power sites on Achill Island in Co. Mayo. Although technically an island, there is only a narrow sea channel between it and the mainland, and this is spanned by a bridge. Crofting is the main-stay of the district, although recently, a local shark fishing industry has grown up for the pupose of producing a high quality animal oil from the shark livers. The people are dependent upon peat for fuel, but recent increases in the number of tourists have increased the demands for electricity supplies. Undoubtedly wind power could be used widely in this part of Eire.

(87) *Inishmore* is the largest island of the Aran group lying at the entrance to Galway Bay. The measuring site was on a rather flat hill about 400 ft. above sea level. Although only about 15 miles from the mainland, frequent gales on this inhospitable coastline make the regular importation of supplies impossible. There is little peat; all fuel has to be brought in by boat. The way of life is hard in the extreme. It was hoped that wind power might make a significant contribution towards easing the lot of the islanders. Unfortunately, average wind speeds measured at 10 ft. were disappointingly low and could not be considered for early exploitation. At a later stage, however, wind power could well save a considerable amount of imported fuel on the island.

(92) and (93) *Knockgour* is a ridge about 1,500 ft. high in the extreme western end of Co. Cork. It is one of the best of many such potential wind power sites in this part of the country. The steeply sloping hill sides produce a great speed-up of winds blowing across the narrow ridge. High average winds were measured even at 10 ft., and a considerable increase might be expected at the hub height of an aerogenerator.

(4) RESULTS

(4.1) Run of the Wind

For the direct comparison of the wind conditions at different sites, the method of plotting shown in Fig. 4 is probably the most convenient. It may be used for measuring installations having either a cup-contact anemometer and a recorder, or a cup-counter anemometer integrating the total run-of-wind past it. For recorder sites, the hourly mean wind speeds are totalled for each day on analysis sheets (see Ref. 16, page 21) and the totals can then be plotted.

With a cup-counter anemometer, the run-of-wind, as given by the difference between readings during a given period, can be plotted directly on the graph. For convenience in calculating monthly average wind speeds, readings may be taken once a fortnight, but weekly readings are preferable. Monthly readings are tolerated only from particularly inaccessible sites or when values of monthly average wind speed are not required with great accuracy. In these cases it is preferable that the monthly readings should be taken within a day or two of the first of the month. There should also be at least one other near and comparable site where the appropriate curve may be drawn from more frequent readings.

When a gap occurs during weekly or fortnightly readings of the counter type of instrument, there is only a slight straightening of the final line and a correspondingly slight loss of accuracy in the results subsequently obtained by calculation. A gap in readings which are normally obtained monthly is much more serious, particularly during the windy months. Unless the anemometer counter train has a capacity of 100,000 miles, or readings are available from a site nearby, there is a possibility that the results will be 10,000 miles out in the total for the year of, say, 180,000 miles. Such an error makes a difference of 1 m.p.h. in the calculated value of the annual mean wind speed.

With a gap in the run-of-wind total from a recorder site, it is fairly easy to estimate the loss in miles during the period, provided that there are other sites nearby where sufficient readings are available. If the appropriate run-of-wind curves are drawn, a visual relationship is established between the curves representing the different sites, and the missing line may be sketched in. If the period is fairly short (e.g., a week) there is not likely to be an error of more than 500 miles.

(4.2) Monthly Average Wind Speeds

Monthly average wind speeds are given in Table 3. The symbol (†) has been used to indicate any reading which may have involved an estimation of the type described in the preceding paragraphs.

(4.3) Comparison of the Years 1949–1954

(4.3.1) Variation in Run-of-Wind

Figure 4 shows, for Mynydd Anelog, the different curves representing the run-of-wind in successive years. It will be seen that the run-of-wind in 1950, the windiest year, is 40,000 miles greater than that in 1953 (the least windy). This figure amounts to some 20 per cent. of the annual total. It is difficult to see from the record when this actually occurs. The fact that the five lines are nearly parallel over the summer months—May to August—shows that the average wind speed remained fairly constant in the summer. The main variations in wind flow occur during the remaining months, as will be seen more easily from the following section.

(4.3.2) Variation in Monthly Average Wind Speeds

In Figure 5 the change in monthly average wind speed over the months and years is more clearly shown.

Two interesting, if not altogether unexpected, facts emerge. The shapes of the graphs are substantially similar for sites over quite a wide area. Indeed, when sufficient experience had been built up, any dis-similarity was regarded with suspicion. On further examination the discrepancy was always found to be due to some fault; such as the failure of an instrument, or a misinterpretation of the anemometer readings. The latter fault was usually caused by there being too great an interval of time between readings.

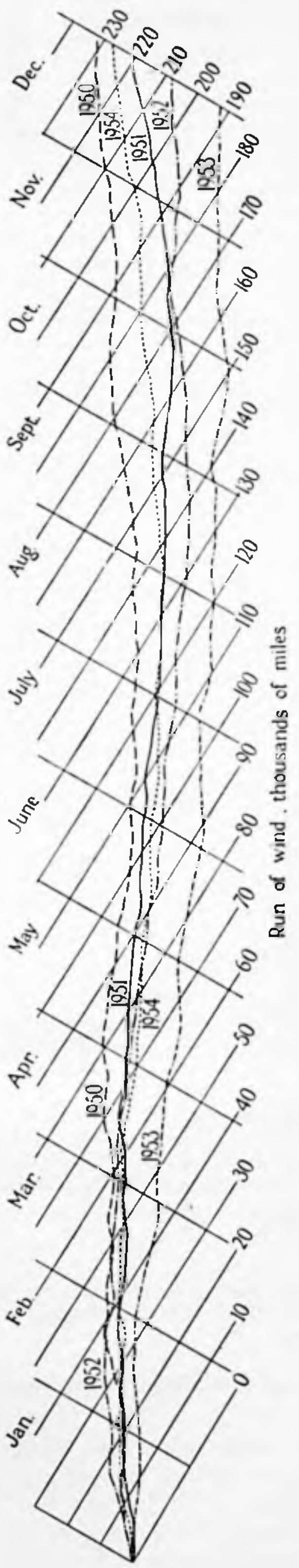


Fig. 4.—Run of wind curves for (36) Mynydd Anelog. (Years 1950–4 inclusive).

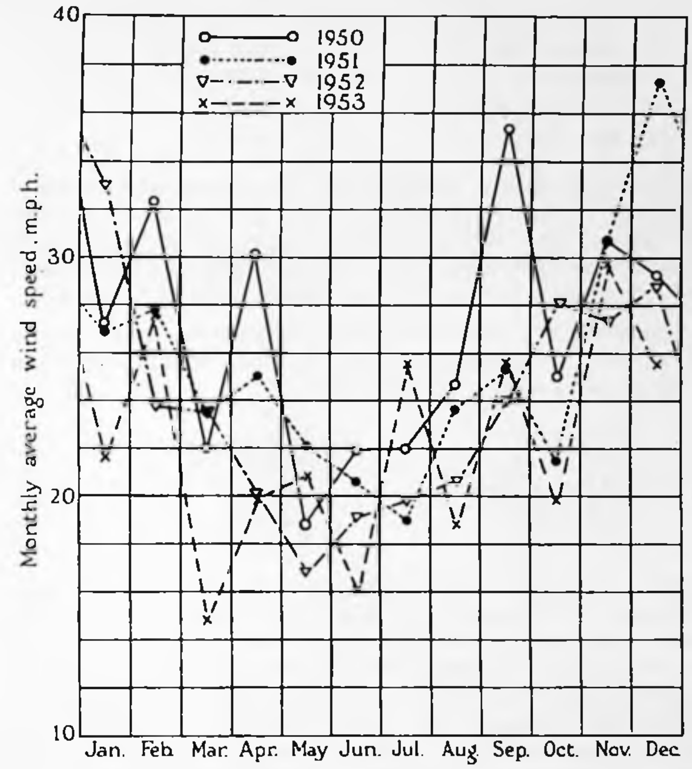


Fig. 5.—Monthly average wind speeds at (36) Mynydd Anelog.

The second point concerns the monthly average wind speeds for May, June, July and, to a lesser extent, August. Over the period for which the site records are available, it was rare for the values of these monthly average wind speeds to vary by more than 6 m.p.h. This was true both for the four summer months of any one year and for the same month in each succeeding year.

For the remaining months of the year—September to April—the values of monthly average wind speed were generally larger and more widely scattered. It was confirmed that all individual monthly average wind speeds lay within the range of 60 per cent. to 150 per cent. of the average annual wind speed.

Complete monthly average wind speeds for the six years 1949–1954 were obtainable from only four Meteorological Office Stations: Lerwick, Oxford, Southport and Kew (see Table 4). When these values were plotted, the shapes of the graphs obtained were, except in the case of Lerwick, much smoother and more uniform than those of the majority of E.R.A. sites. This, of course, reflects their geographical position in areas not generally subjected to the worst of the winter gales. A similar effect was noticed with E.R.A. sites in the less windy areas of the British Isles. The most outstanding instances of this uniformity were all south-east of a line joining the Wash to South Wales and included (43) Garth Mountain; (50) Portland Bill; (54) Firle Beacon; (55) Telegraph Hill and (63) Cranfield.

(4.3.3) **Variation in Annual Average Wind Speeds**

The complete list of E.R.A. sites numbers approximately one hundred, rather less than half of which were left in operation at the end of 1953; by the end of 1954 twenty were still in commission. About a dozen of the installations had been running for longer than three years. Fairly continuous results for three years had been obtained from the nine sites listed overleaf:—

1. Costa Hill.
9. Dunan Mor.
11. Ben Geary.
19. Macrihanish.
21. Torr Mor.
36. Mynydd Anelog.
37. Mynydd Mawr.
79. Slieve Tooey.
89. Knockmore.

It was thus difficult to make any assessment of the relative windiness of the six years covered by the survey up to 31st December, 1954. When the few annual average wind speeds for two or more of these years were compared, the results were conflicting and failed to show the relative order of windiness.

Annual average wind speeds for the same period, were obtained for ten Meteorological Office sites, including the four mentioned in the previous section.* They are:—

Lerwick.	Tiree.
Bell Rock.	Aldergrove.
Point of Ayre.	Southport.
Aberporth.	Scilly (St. Mary).
Oxford.	Kew.

When the figures from these sites were plotted (see Fig. 6) and compared with the results from the E.R.A. sites, it was apparent that it would be impossible to describe the windiness of one year in terms of another without also specifying the site. It is probable that the variation in exposure to different wind directions at each site influences the results obtained. For instance, a particular site might lie to the north-west of a large range of hills. During a year when south-easterly winds were unusually prevalent, such a site would have an annual mean wind speed rather less than the average.

The weather and, of course, the winds which blow over the British Isles are primarily influenced by a succession of cyclonic depressions passing from west to east. Their tracks usually cross, or pass to the north of, Scotland. These low pressure systems usually result in the strongest winds blowing from the south-west and west. Examination of page 4 of the Monthly Supplements to the daily weather report (see Ref. 37) show that in 1950, an unusually large number of low pressure systems affected the more southerly parts of the British Isles; and in this year also, annual mean wind speeds over much of the country were rather higher than usual.

The year 1953 was characterized by relatively few depressions directly affecting England; and in that year, the measured average wind speeds of sites showed a fairly general drop over most of the British Isles. The exceptions were four sites on the north-west coast of Scotland, Lerwick and Kew. The results at the last-named site are probably not significant. Lerwick, the most northerly site, would still come within the influence of the more northerly depressions as, to a lesser extent, would the other four Scottish sites. Yet a fifth site in this area, Chaipaval, showed a large drop in annual mean wind speed from 1952 to 1953. In general, however, it may be said that the more northerly sites show less percentage variation in the annual average wind speed from year to year than do sites in the south of the British Isles. It is most probable that there is a close connection between the mean path followed by the succeeding cyclonic depressions and the annual average wind speeds at English sites. This subject can be discussed in detail only when more extensive records of wind speeds are available together with more information on the frequency and strength of winds from the different directions.

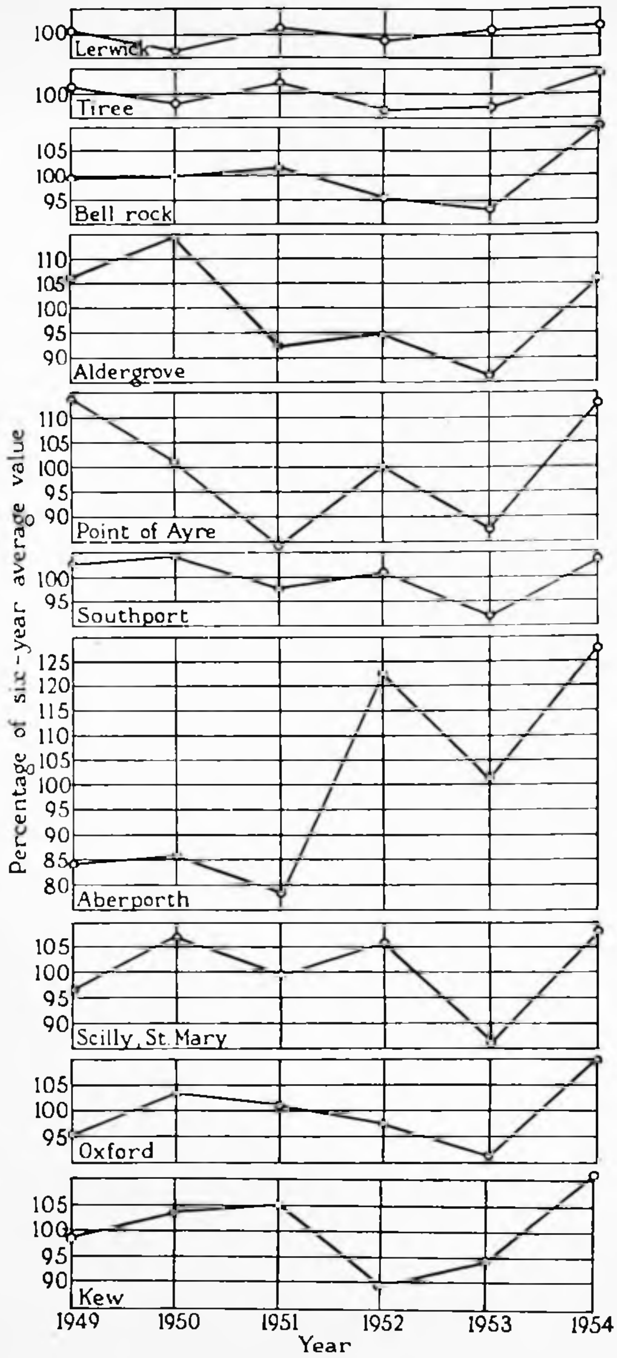


Fig. 6.—Annual average wind speeds for 10 Meteorological Office stations plotted as percentages of the six-year average values.

Considering the results as a whole, it may be said that 1949 was slightly above the average in windiness and that 1950 was even more windy than 1949. The year 1951 showed a drop to about the average value. 1952 was less than the average, and 1953 was well below the average over almost the whole country. 1954 was again very windy and comparable with the year 1950.

There is little information available on the range of annual average wind speeds to be expected at sites in the British Isles.

* In most cases, these figures were not available directly, but only in the form of modified velocity/frequency tables. These were plotted to give velocity/duration curves as described in Section (5.3) and the annual average wind speeds were then obtained from the areas underneath the curves.

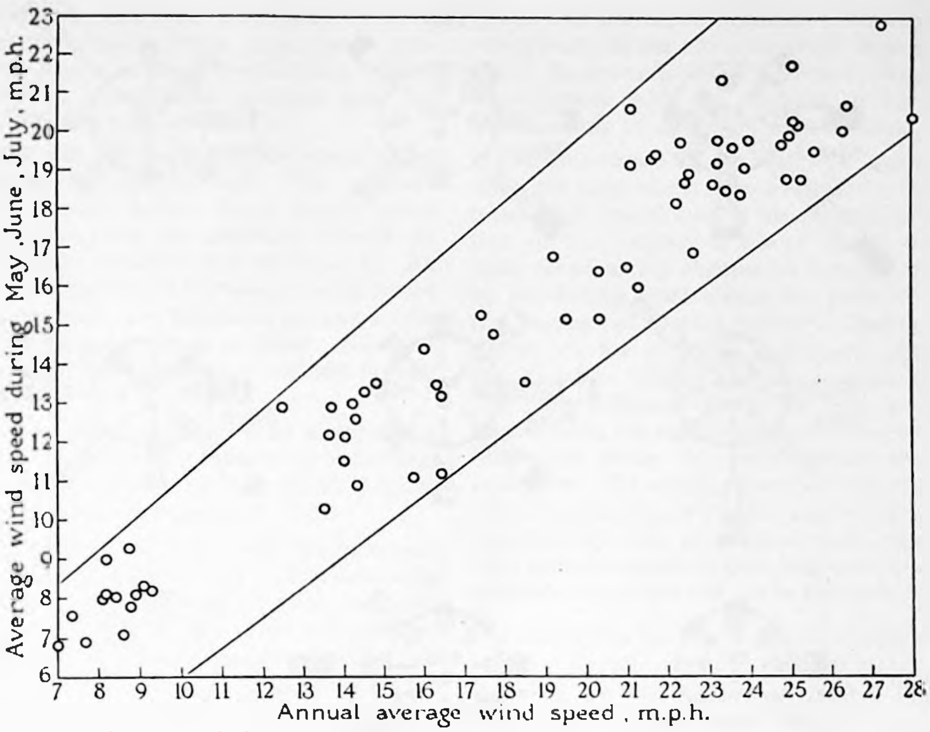


Fig. 7.—Relationship between the average wind speed during the summer to the annual average wind speed.

The Meteorological Office does not normally evaluate the annual average wind speed except for a very small number of stations. Of these, Southport may be taken as an example. In 1942, calculation showed that there had been a standard deviation of 7·6 per cent. in the annual average wind speed over the previous 42 years. The range covered was from 84 per cent. to 118 per cent. of the average value. For 37 years the variation was within the range of 90 per cent. to 110 per cent.

The period of measurement at E.R.A. sites is relatively quite short. The results from them tend, however, to confirm that the range of variation of annual average wind speed is quite small. At Mynydd Anelog, for example, the maximum deviation from the average value for the five years 1950–1954 was only 10·5 per cent.

(4.3.4) **Estimation of Annual Average Wind Speeds**

Quite frequently, through accident or design, results from only a relatively short period of measurement were available from some of the E.R.A. sites. It is possible to use two methods to estimate the probable annual wind speeds of such sites.

The first method involves the use of the three summer monthly average wind speeds for May, June and July. In Section (4.3.2), it was shown that these monthly average wind speeds were much more consistent than those for the remaining nine months. Figure 7 shows relationships between the average wind speed for the three months May, June and July and the annual average wind speed. Naturally, the relationship does not follow a single smooth curve, but is characterized by a fairly wide area of possibility. If wind measurements are made at any site for these three months to obtain the average wind speed, then reference to Fig. 7 will indicate the probable range of the corresponding annual average wind speed. It will be seen that if the three-monthly value is, say, 20 m.p.h., then the yearly value will lie within the range of 22·0 m.p.h. and 25·0 m.p.h. Although this range is rather large the results may well prove sufficiently accurate to make a first assessment of the value of any potential wind power site.

The second method involves comparison with any other sites nearby for which much longer periods of records are available. It is necessary first to consider, in turn, the relative exposure of each site to winds of different directions. In some cases it may be necessary to disregard much apparently useful information on monthly wind speeds on the grounds that the site or sites concerned have a poor exposure to certain directions of wind. Gradually, however, with practice and experience, it is possible to build up relationships between the run-of-wind at a number of stations and finally to make a reasonable estimate of the run-of-wind at a particular survey site for which the measured value is not available. In the same way it is possible to make an estimate of the run-of-wind in a particular area during any year and to compare it with a long-term average of, say, ten years or more at a Meteorological Office station. In this way, estimated long term average wind speeds have been evaluated for most sites and are included in Table 3.

(4.4) **Wind Direction**

The only sites at which wind direction has been measured continuously are (1) Costa Hill; (2) Vestra Fiold; and (36) Mynydd Anelog. The photographic recorders used gave the direction of the wind every hour or half hour. The results have been used in drawing the diagrams in Fig. 8. These are wind roses for the different months and for the year at (1) Costa Hill, during the period April 1949 to March 1950 inclusive. The particular form adopted is one used by the Meteorological Office and is a modification of the Baillie wind rose. The arrows fly with the wind. The thickness of an arrow indicates the Beaufort forces 1–3, 4, 5–6, 7 and >8. The distance from the head of the arrow to the centre of the circle is five per cent. The upper figures in each circle indicate the number of hourly observations of wind direction. The lower figure in each case represents the period of calms (i.e., wind speeds of less than one m.p.h.) expressed as a percentage of the upper figure.

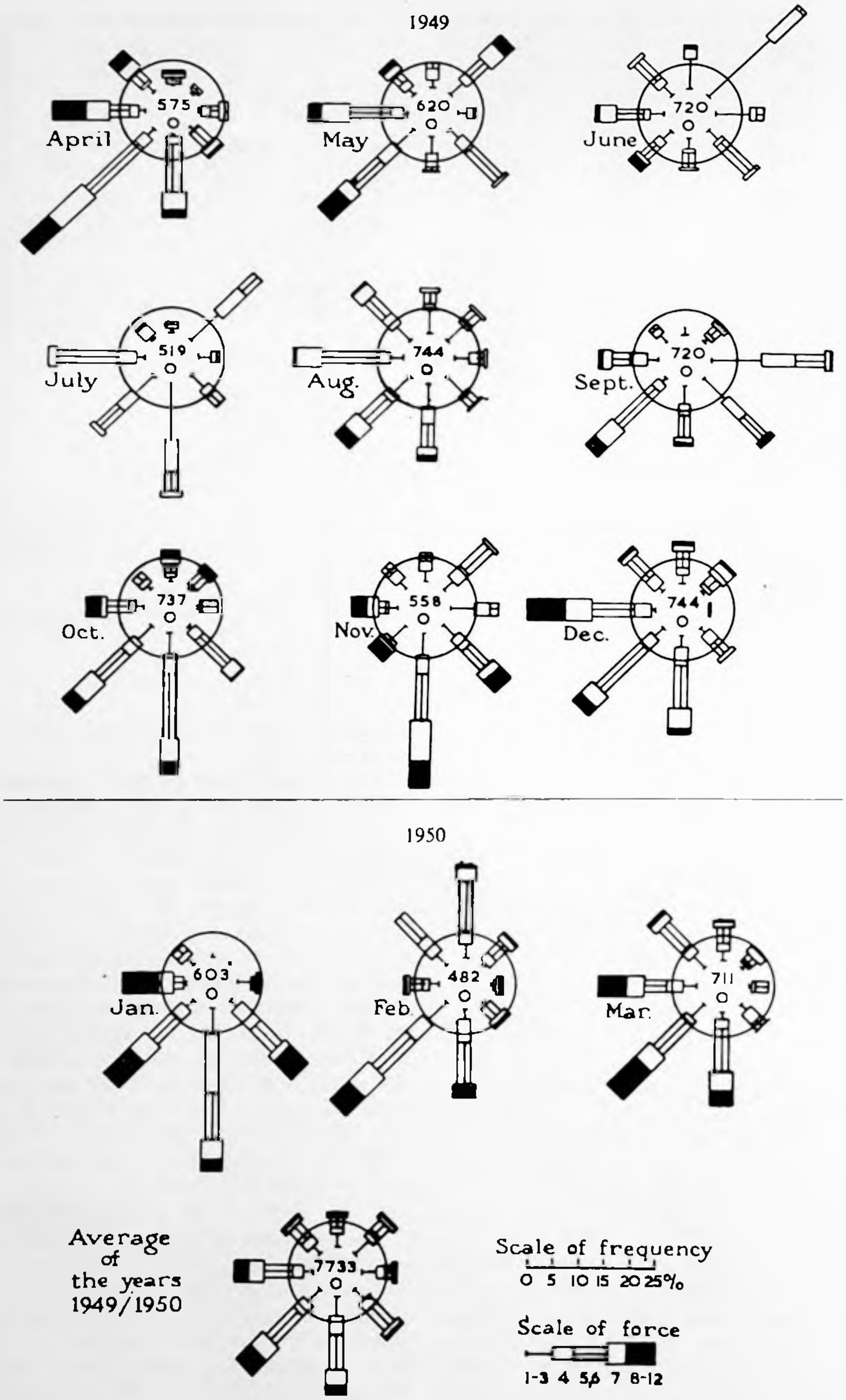


Fig. 8.—Monthly wind roses for (1) Costa Hill.

(5) ANALYSIS OF THE WIND SURVEY RESULTS

The information obtained from the wind survey has been presented in its simplest form in the preceding sections. Here it is intended to continue the analysis of the results and to present the most useful part of the information so obtained in the most convenient form.

(5.1) Characteristics of the Instrument Records

It will be helpful in understanding the following sections if the characteristics of the cup-contact anemometers and recorders described in Appendices 1 and 2 are briefly restated here. It is also necessary to define the conventions and methods employed in obtaining the tabulated figures from the different types of recorder chart.

Three types of recorder have been used in conjunction with the standard type of Meteorological Office cup-contact anemometer. This instrument has a mercury switch which makes a brief short-circuit across the anemometer terminals after the passage of each one-twentieth of a mile of wind.

In the photographic recorder, message registers count these impulses and so integrate the run-of-wind. The message registers are photographed every hour. Mean hourly wind speeds in m.p.h. are obtained from the resulting records by subtracting consecutive hourly readings and dividing by 20. During the tabulation of these figures, all fractions are eliminated and the mean hourly wind speeds are tabulated correct to the nearest whole number of miles per hour *up or down*. All cases of fractions of ½ m.p.h. exactly, are expressed as the next highest whole number.

Two recorders of this type were originally used at (1) Costa Hill and (2) Vestra Fiold. After a few months of recording, the second instrument was installed at (36) Mynydd Anelog, where it was in constant use until the autumn of 1954.

The Series 1 impulse recorder is the type which has been used most frequently at the E.R.A. recorder sites. (The following remarks also apply to the Series 3 type, first used in 1954.) A standard recording clock is used to drive a chart at a speed of three inches per hour. The impulses from the anemometer are passed through a 40 : 1 divider unit and a mark is made on the chart for every two miles of wind passing the anemometer. Thus the spaces between consecutive dots indicate the time taken for the passage of each successive two miles of wind. The number of spaces occurring during each hour, or three inches of chart, is then directly proportional to the mean wind speed during each hour. In interpreting these records, the accuracy is dependent upon the steadiness of the wind flow. During periods of changing wind speed it is necessary to decide how to apportion each two-mile period which lies across the hourly time marks on the chart. In analysing the records, it is easy to exaggerate the number of hours of even values at the expense of the odd values. Taken as a whole, however, the tabulated values of mean hourly wind speed are correct to the nearest mile per hour.

The recorder of the type designated Series 2, has been used at only a few sites since the latter part of 1953. In this instrument a paper tape, half an inch wide, is moved at a rate of one inch for every sixteen miles of wind passing the anemometer. Marks are made on the tape at hourly intervals. The distance between consecutive marks when measured to the nearest sixteenth of an inch represents the mean hourly wind speed correct to the nearest mile per hour.

It is thus seen that with all three types of recorder used on the wind survey, the final tabulated figures of mean hourly wind speed are obtained correct to the nearest mile per hour *up or down*. For certain analyses, as will be seen later, it would have been preferable to have expressed all mean hourly wind speed values as the next *lowest* integer number.

(5.2) Velocity*/Frequency Curves

In studying the wide range of observed wind speeds obtained from the recorder sites, the velocity/frequency histograms were used extensively in the early stages of the study: the wind speed in miles per hour is plotted horizontally, and the total number of hours of each integer value of wind speed is plotted vertically. In practice, a smooth curve is drawn through the points and the figure becomes a *velocity/frequency curve*. The smoothness of the curve obtained depends upon the number of hourly figures considered, i.e., on the length of the period. This improvement with the increase in the size of the sample is characteristic of all sets of natural data.

The smoothness of the velocity/frequency curves also depends upon the care taken in extracting the figures from the Series 1 recorder as mentioned in the preceding section. The exaggeration of the number of hours' duration of the even values of wind speed at the expense of the odd values is best eliminated by combining each successive pair of values and so halving the number of plotted points*. Examples are shown in Figs. 9 and 10, for monthly and yearly periods. It may be seen that the two sets of curves are essentially similar in outline. The main difference lies in the smoothness of the lines. Those representing the monthly velocity/frequency curves are irregular in outline whilst the yearly curves are, on the whole, much smoother. To obtain curves without any detectable kinks when drawn on this scale would require many years of records. To demonstrate this, more than three years of records for Costa Hill were included in one frequency curve, but the final result differed little from the curve for 1949 shown in Fig. 10.

Considering the yearly velocity/frequency curves in more detail, it may be seen that both (33) Dolgarrog and (77) Bloody Foreland, have no sharply defined peak. The first is situated among many much higher hills in North Wales and these undoubtedly influence the wind conditions at the site. The irregularity at Bloody Foreland is probably due to the short time for which records were obtained. Only about 5,300 hours of records were used to plot this curve. Nevertheless, it was included because, over an extended period, this site had the highest mean wind speed of all the recorder sites.

It should be noted that at the less windy sites, the friction errors of cup anemometers probably introduce errors into the frequency curves at wind speeds approaching zero. This is in part due to the fact that the instruments used were lubricated with a fairly thick grease instead of oil. Grease was used to protect the bearings during the unusually long periods between overhaul. It was found that if only oil were used, the upper cup and cone bearings might deteriorate within two or three months at the windiest sites. As a result of using the heavier lubricant, the apparent duration of calms and of very low wind speeds is increased.

For ease of comparison all the ordinates in Figs. 9 and 10 are plotted on a percentage basis. Each figure is, in effect, a histogram. Consequently, the area enclosed by each curve is equal to the sum of all the ordinates and will thus represent 100 per cent. of each measuring period. It will be seen that, as the average wind speed increases, not only does the value of the most frequent wind speed increase, but, also, its frequency of occurrence is less. The relationship between the mean wind speed and the most frequent wind speed is discussed below.

(5.2.1) Most Frequent Wind Speeds

From the curves shown in Figs. 9 and 10, it is clear that the most frequent wind speed at any site varies with the value of the average wind speed. A curve showing this relationship for a number of hill-top sites in the New England States of the U.S.A. is shown in Ref. 25 and is reproduced in Fig. 11. Some of the points used were obtained from periods of measurement

* Use of the word "velocity" here does not conform to the convention stated in an earlier footnote. Because of long usage in this context, it is retained here.

* For a proper statistical analysis, the number of plotted points or classes should not generally be more than five times the logarithm of the number of observations, i.e., 8760 observations may be divided into 20 classes.

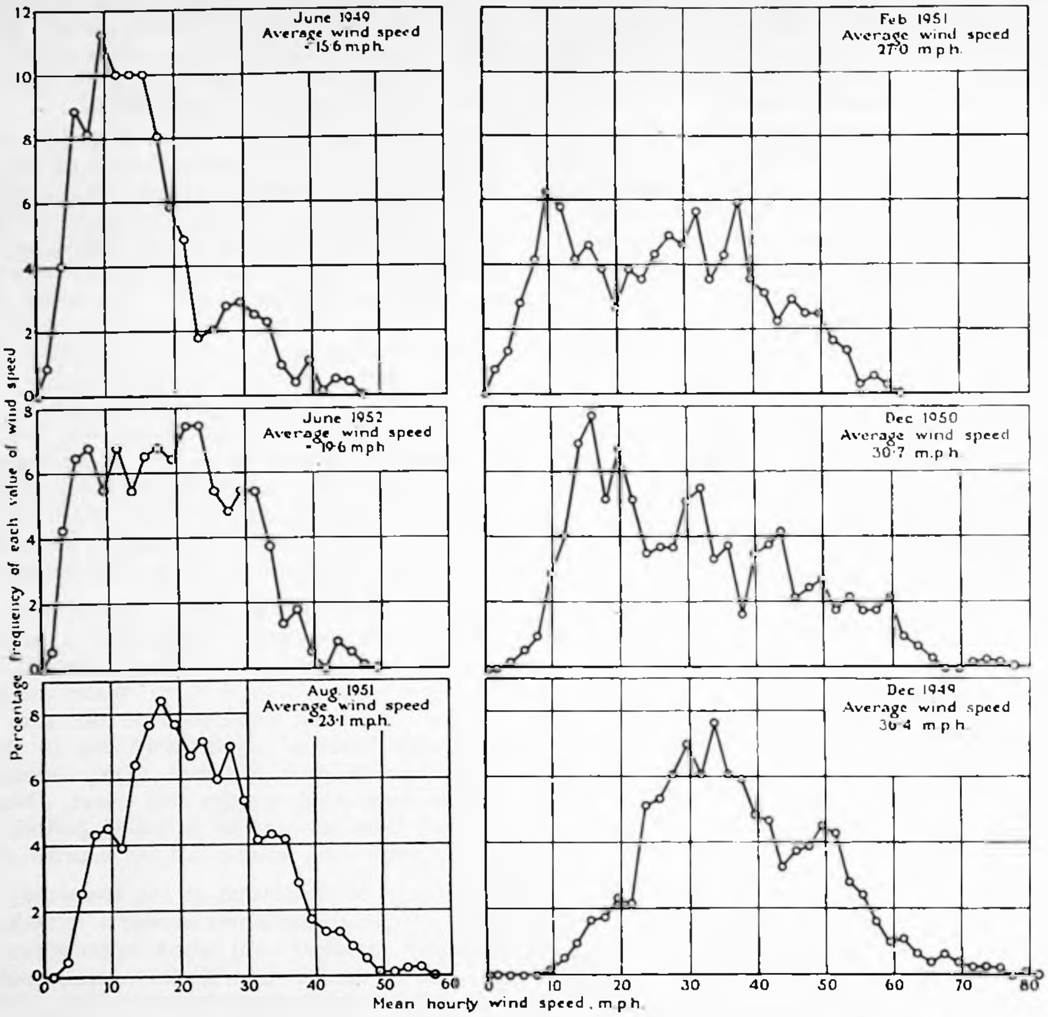


Fig. 9.—Wind velocity/frequency curves for six typical months at (37) Mynydd Mawr.

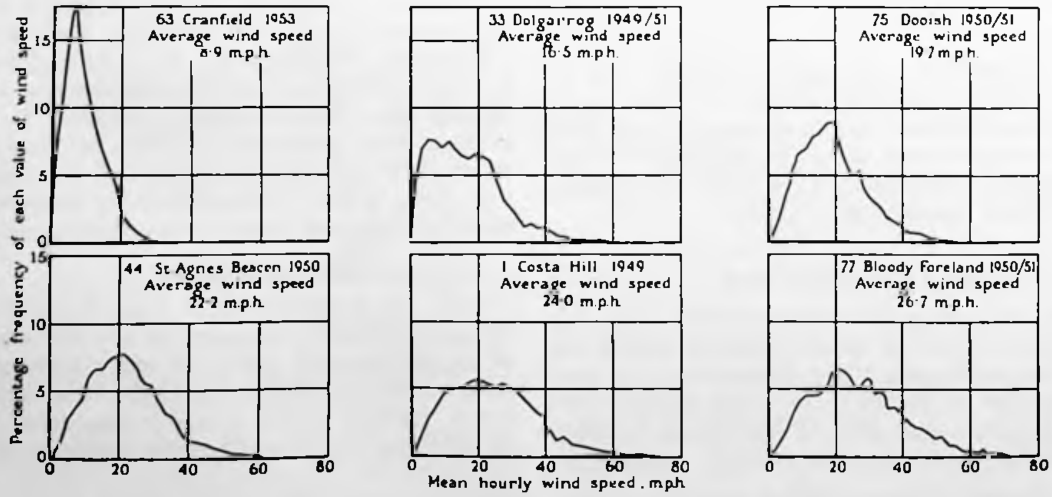


Fig. 10.—Wind velocity/frequency curves for six typical E.R.A. sites (approximately yearly periods).

Fig. 3.—Photographs of E.R.A. wind survey sites.
In the photographs shown in Figure 3, the direction of view is given in degrees. An approximate Figure is also given for the distance from the anemometer position. (See pages 15–20).

060° 1¼ miles

(1) Costa Hill

150° 1¾ miles

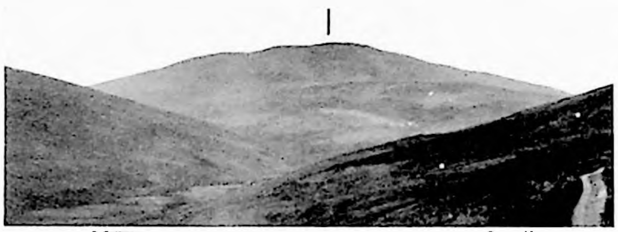
(2) Vestra Fiold

070° 1¼ miles

(4) Greenay

280° 1¼ miles

(12) Chaipaval



300° 2 miles

(20) Cnoc Moy

050° ¾ mile

(25) Pinbain

190° ¾ mile

(28) Eweside Hill

160° 3 miles

(30) South Barrule

060° ⅛ mile

(32) Holyhead Mountain

070° ¾ mile

(33) Dolgarrog

270° ⅜ mile

(34) Mynytho Common

040° ¾ mile

(35) Mynydd Rhiw

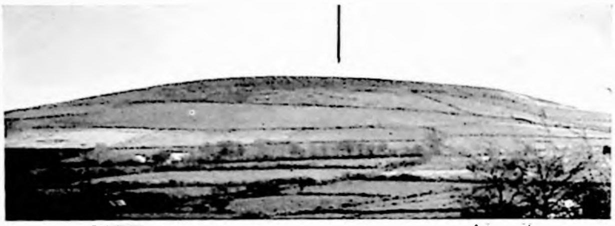
Fig. 3 (*a*)

040°   1 mile

(36) Mynydd Anelog

210°   1 mile

(37) Mynydd Mawr



090°   1½ miles

(40) Mynydd Castlebythe

070°   2 miles

(42) Rhossili Down

000°   1 mile

(44) St. Agnes Beacon

160°   ¼ mile

(46) Carn Bean

290°   1 mile

(47) Carn Brea

160°   ¾ mile

(48) Tregonning Hill

000°   100 yards

(56) Winthorpe

020°   40 yards

(59) Holy Island

140°   2 miles

(64) Slieve Gullion

190°   2 miles

(65, 66) Chimney Rock

Fig. 3 (*b*)

350° ¾ mile

(67) Slieve Donard

060° 1½ miles

(72) Knocklayd

270° 2 miles

(77) Bloody Foreland

070° 1¼ miles

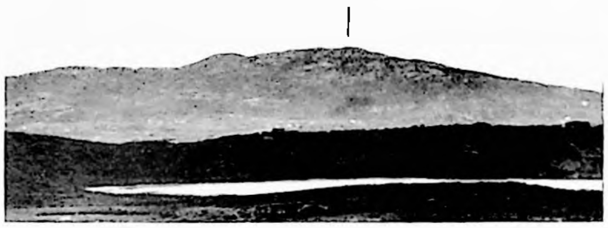
(80) Leahan

000° 1½ miles

(81) Blue Stack Mts.

200 2½ miles

(84) Knockmore



020 3 miles

(85) Tully Mountain

230° 2½ miles

(86) Errisbeg

260° 3¼ miles

(89) Mt. Eagle

280° 3¼ miles

(90) Killelan

290° 2¼ miles

(92, 93) Knockgour

200° 1½ miles

(94) Mt. Gabriel

Fig. 3 (*c*)

Fig. 27.—A modified cup-counter anemometer, Mk.2.

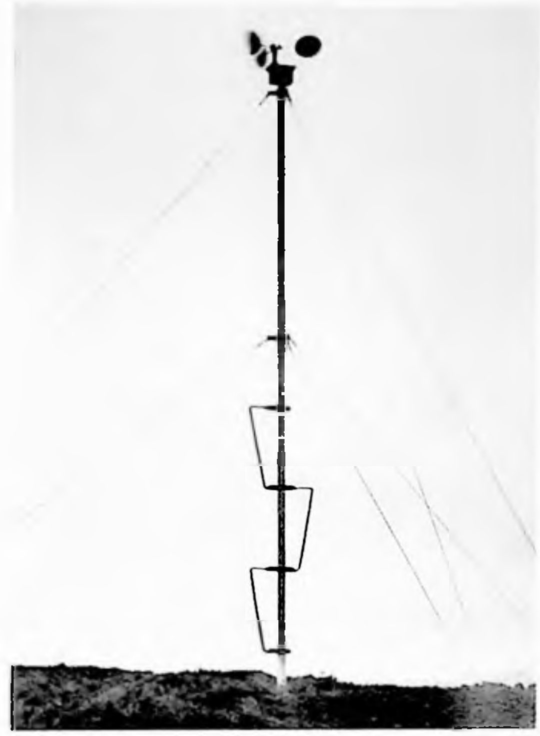


Fig. 28.—A 10-ft. anemometer pole—(30) South Barrule (Isle of Man).

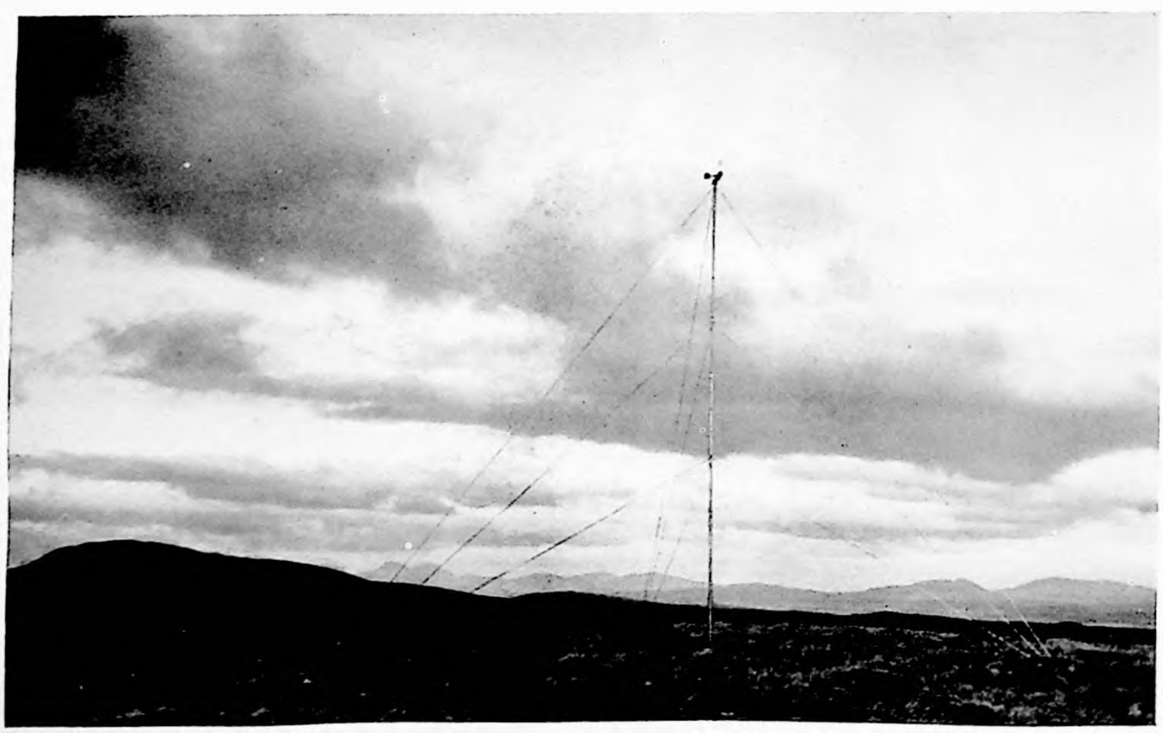


Fig. 29.—A 30-ft. anemometer pole—(17) Ben Cladville (Islay).

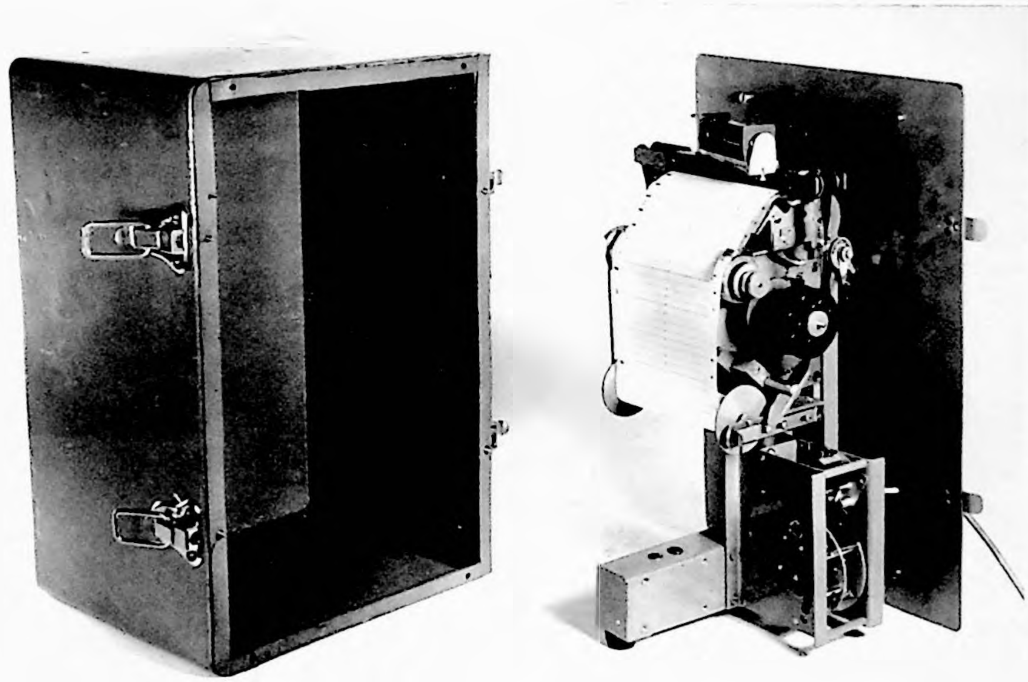


Fig. 30.—E.R.A. impulse recorder, Series 3, Mk.II.

Fig. 31.—E.R.A. impulse recorder, Series 2, Mk.IV.

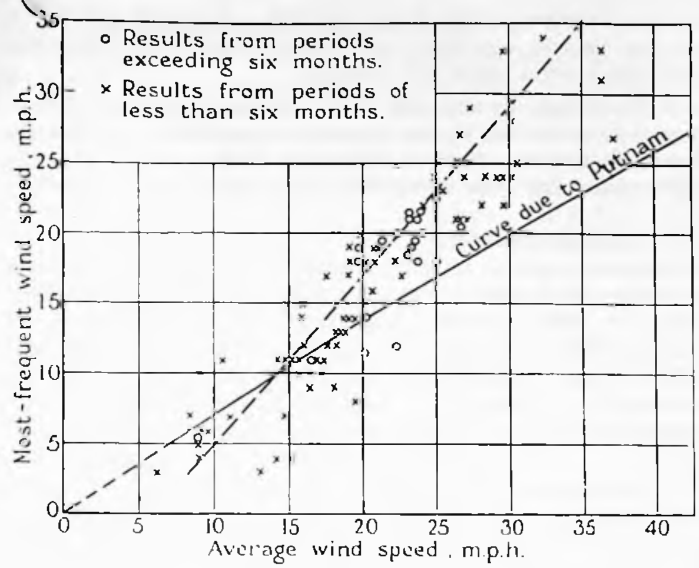


Fig. 11.—Relationship between the most frequent wind speed and the average wind speed.
The full line due to Putnam is taken from his book " Power from the Wind ", see Ref. 25.

of between two and five years' duration. The remainder were obtained from hypothetical velocity/frequency curves.

A similar treatment was attempted with the results from the E.R.A. measurements. Unfortunately, many of the velocity/frequency curves proved to be unsuitable. Either they had one or more subsidiary peaks besides the main peak, or the main peak itself was too irregular to pick out the most frequent wind speed. Both these characteristics show that the periods considered were too short to provide truly representative selections of the different wind speeds experienced at each site.

In Fig. 11, all the points marked by circles are taken from velocity/frequency curves for periods longer than six months. To extend the range at either end, shorter periods have been used and the corresponding points marked by crosses. Even allowing for the scatter of the points obtained from the E.R.A. sites, the general trend is quite different from that obtained by Putnam.

(5.3) Velocity*/Duration Curves

By summation of the data used for a velocity/frequency histogram, a second and more useful type of graph may be obtained. This is the cumulative frequency curve or " ogive " which is plotted at right angles to the conventional direction. An example of the process covering a small sample period of 80 hours is shown in Table 5, and in Figs. 12 and 13. It should be remembered that each plotted value on a velocity/frequency histogram covers all values of wind speed from 0·5 m.p.h. below the appropriate integer to 0·5 m.p.h. above. To simplify the calculations it has been assumed that half the number of hours occur both below and above each particular integer value of wind speed. It has also been assumed that only half the figure appearing as calms in a velocity/frequency table is, in fact, 0·0 m.p.h. The other half corresponds to wind speeds up to 0·5 m.p.h.

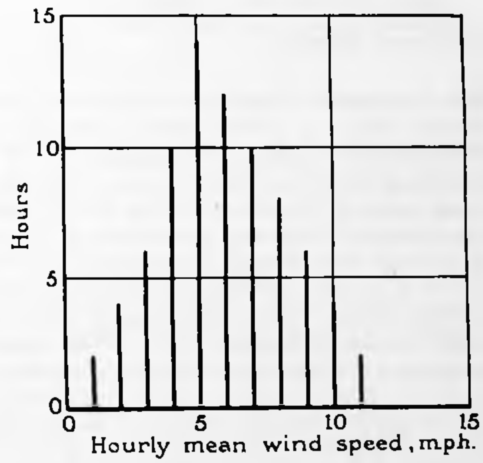


Fig. 12.—A simple velocity/frequency histogram.
This figure is usually drawn as a smooth curve.

* Use of the word " velocity " here does not conform to the convention stated in an earlier footnote. Because of long usage in this context, it is retained here.

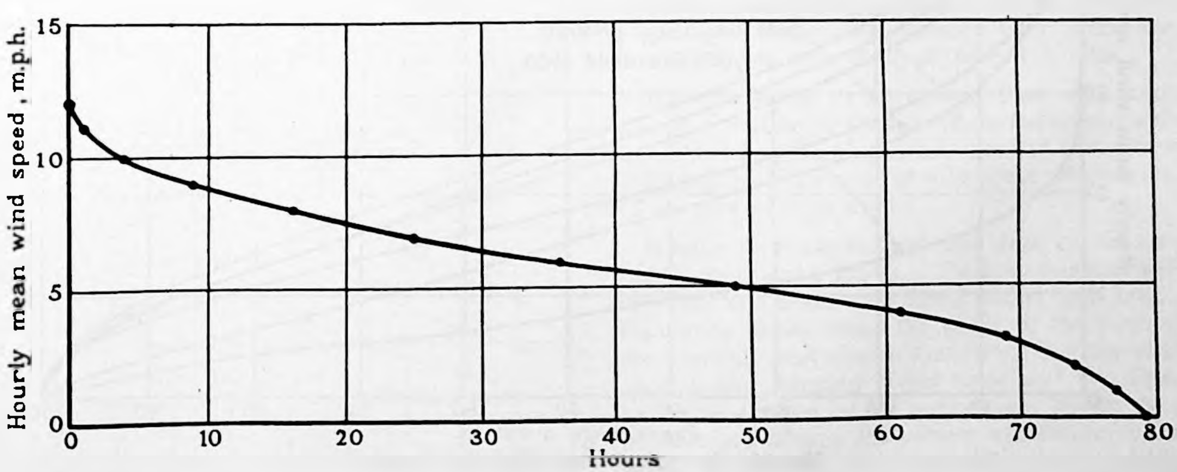


Fig. 13.—A simple velocity/duration curve.

(5.3.5) Duration of Winds within the limits of certain numbers on the Beaufort Scale

Both in England and in countries overseas information on the duration of winds of different strengths is published in the form shown in Table 6. Each observation or value of hourly mean wind speed during the year is assigned to one of the seven groups of wind speed as shown below:—

Beaufort Number 0	Less than 1 m.p.h.
Beaufort Numbers 1, 2 and 3	1 to 12·5 m.p.h.
Beaufort Number 4	12·5 to 18·5 m.p.h.
Beaufort Number 5	18·5 to 24·5 m.p.h.
Beaufort Number 6	24·5 to 31·5 m.p.h.
Beaufort Number 7	31·5 to 38·5 m.p.h.
Beaufort Numbers 8, 9, 10, 11 and 12	Greater than 38·5 m.p.h.

The table is divided into two parts; in the first part are the results from the E.R.A. sites and, in the second, those obtained from the Air Ministry Meteorological Office. The number of observations or values of mean hourly wind speed are given in each case. The duration of wind speed within each group is expressed as a percentage of the total number of observations.

(5.4) Power/Duration Curves

Velocity/frequency and velocity/duration curves show only the general characteristics of the wind at potential wind power sites. Although they indicate the relative frequencies of all the different wind speeds, they give little information about the amount of energy which might be extracted from windmills built on such sites. In the following sections, the analysis is

Table 6a.

E.R.A. WIND SURVEY RECORDER SITES

Duration of wind strengths according to numbers on the Beaufort scale

Site		Yearly period	Number of observations	Percentage duration of total number of observations (hourly mean values of wind speed) within these limits of Beaufort numbers						
No.	Name			0	1, 2, 3	4	5	6	7	8–12
1	Costa Hill	1949	8,747	0·1	19·1	16·2	17·0	18·7	14·1	14·8
1	Costa Hill	1950	6,828	0·1	19·5	18·5	19·3	16·8	12·9	12·8
1	Costa Hill	1948 and 51	6,106	0·1	16·4	18·4	20·5	19·1	13·4	12·0
6	Ward of Scousburgh ..	1952 and 53	7,552	0·01	19·4	20·0	18·2	17·0	11·8	13·6
17	Ben Cladville	1952 and 53	7,481	0·2	22·6	20·5	20·8	18·1	11·0	6·8
17	Ben Cladville	1954	7,709	0·3	22·9	19·0	19·4	17·6	11·3	9·5
20	Cnoc Moy	1950 and 51	7,899	0·06	22·8	20·5	18·0	17·9	11·5	9·2
25	Pinbain	1950 and 51	9,577	0·1	21·4	17·3	19·1	17·5	12·6	11·9
25	Pinbain	1952	6,812	0·1	21·3	19·1	19·9	16·6	9·5	13·4
33	Dolgarrog	1949 and 50	8,688	0·7	40·0	19·4	18·9	11·7	4·7	4·2
36	Mynydd Anelog	1952	6,856	0·3	18·2	18·7	18·7	19·5	12·2	12·4
36	Mynydd Anelog	1951 and 53	10,458	0·1	21·2	18·1	17·8	18·5	11·8	12·4
37	Mynydd Mawr	1950	8,760	0	16·4	16·7	16·7	20·0	13·4	16·7
37	Mynydd Mawr	1951	7,637	0·04	19·8	20·0	19·7	16·8	12·5	11·1
37	Mynydd Mawr	1949 and 50	8,756	0·01	23·2	17·7	17·2	17·8	11·2	12·8
37	Mynydd Mawr	1950 and 51	8,760	0·01	16·4	17·7	17·3	19·1	13·4	16·0
39	Foel Eryr	1949 and 50	7,961	0·06	15·3	17·5	20·4	18·8	14·0	14·0
39	Foel Eryr	1952	6,328	0·2	19·1	20·0	22·0	17·8	11·6	9·3
42	Rhossili Down	1949, 51 and 53	7,767	0·1	25·2	19·3	18·8	15·8	9·3	11·5
42	Rhossili Down	1950	8,183	0·1	18·4	19·1	19·8	18·8	11·0	12·8
42	Rhossili Down	1952	6,190	0·1	27·2	21·4	20·5	14·9	7·9	7·9
44	St. Agnes Beacon	1949	5,480	0·09	27·8	24·0	19·1	12·8	8·7	7·3
44	St. Agnes Beacon	1950	8,430	0·03	18·6	20·5	22·6	19·6	10·7	7·9
47	Carn Brea	1949 and 50	9,030	0·04	23·1	26·4	22·0	16·5	8·4	3·3
61	Dore Moor	1949, 50 and 51	10,003	0·7	63·1	25·0	9·1	1·8	0·2	0
63	Cranfield	1953	8,313	3·7	72·0	18·0	5·5	0·89	0·03	0
63	Cranfield	1954	8,760	1·0	64·6	24·7	7·4	1·9	0·3	0
68	Divis Mt.	1949, 51 and 52	5,843	0·07	17·1	18·9	18·5	18·3	13·7	13·4
72	Knocklayd	1950 and 51	6,378	0·01	19·6	19·5	20·6	19·2	10·6	10·4
75	Dooish	1950 and 51	8,533	0·13	24·6	24·7	22·4	15·9	7·5	4·7
77	Bloody Foreland	1950 and 51	5,332	0·17	15·6	13·9	18·9	18·5	14·4	18·6
80	Leahan	1950 and 51	8,958	0·13	19·1	17·4	21·2	21·0	11·4	9·8

Table 6b.

AIR MINISTRY METEOROLOGICAL OFFICE STATIONS

Duration of wind strengths according to numbers on the Beaufort scale

Name of Meteorological Office Station	Period of observation	Percentage number of hours missed	Percentage duration of total number of observations within these limits of Beaufort numbers*								
			0	1	2	3	4	5	6	7	8-12
Lerwick	1930–32	0·1	5·0		8·9	17·5	22·7	21·2	14·5	6·8	3·2
Kirkwall	1930, 31, 36–8	0·5	6·3		13·1	23·3	25·9	17·2	9·6	3·3	0·8
Bell Rock	1930–32	0	8·2		8·3	15·1	22·6	21·1	15·3	6·2	3·1
Tiree	1930–32	0	1·7	8·8	11·5	20·7	21·3	18·3	11·5	4·8	1·2
Cranwell	1921–28	3·7	2·8	11·0	20·0	29·9	22·5	7·5	2·0	0·3	0
Lympne	1922–38	3·3	0·5	5·1	19·2	32·8	23·7	10·4	4·0	0·9	0·2
Aldergrove	1927–38	0·3	0·9	15·9	24·2	29·6	21·1	6·6	1·6	0	0
Scilly	1922–7, 1930–8	3·4	0·7	3·3	10·4	18·4	24·1	19·0	13·1	5·7	1·8

* This table is derived from the Air Ministry Meteorological Office Publication M.O.M. 370—Tables of Wind Direction and Force over the British Isles.

carried a step further to produce this information with the aid of power/duration curves.

(5.4.1) **The Law of the Cube**

The power in the wind is given by $P = KAV^3$ where A is the area swept by the windmill rotor and V is the wind speed. K is a constant which varies with the units used and with the air density ρ. If ρ is taken as 0·08 lb./cu. ft. at sea level (or 1,290 grams/cu. metre), A is in sq. ft. and V is in m.p.h., then $P = 0{\cdot}0000053\ AV^3$.

The air density decreases rapidly with increasing altitude. At 8,000 ft. an average value is only about three-quarters of the value at sea level. Average values must be used, since the air density depends both on the air pressure and on the content of water vapour. The figures given in Table 7 have been calculated to show the actual power in the wind at different speeds and at different altitudes up to a maximum of 8,000 ft. It is reasonable to suppose that windmills might be operated at this altitude in hot climates where the likelihood of severe icing is remote.

Table 7

POWER IN THE WIND

Wind speed (m.p.h.)	Power in kilowatts over a swept area of approx. 8,000 sq. ft. (100 ft. dia.)				
	Sea level	2,000 ft.	4,000 ft.	6,000 ft.	8,000 ft.
10	41·6	38·7	36·0	33·3	31·0
20	333	310	288	266	248
30	1,123	1,045	971	899	835
40	2,660	2,475	2,300	2,130	1,980
50	5,200	4,840	4,490	4,160	3,870
60	8,980	8,350	7,760	7,180	6,675

(5.4.2) **Construction of Power/Duration Curves**

It has already been seen that the total area underneath a velocity/duration curve is proportional to the run-of-wind in miles. The area underneath a similar curve drawn with ordinates representing values of (wind speed)^3 will be proportional to the total energy present in the wind (see Refs. 14, 15 and 16). As it is improbable that any wind-driven generator will be constructed with a rated wind speed (see below) in excess of 40 miles per hour, it is generally unnecessary to draw a power/duration curve beyond this value. It is sufficiently accurate, as with a velocity/duration curve, to plot points corresponding to increases of 5 m.p.h. in wind speed.

(5.4.3) **Operating Limits of Wind-Driven Generators**

Using the momentum theory to calculate the maximum fraction of the energy which may be extracted by a wind turbine operating in free air gives a value for this fraction of 16/27 or 59·3 per cent (see Ref. 4). It is unlikely that any wind-rotor, built to an economic specification, could successfully extract more than 45 per cent. of the energy in the wind passing through its operating area.

In the design of such a machine, the lowest wind speed at which it will develop its full power, i.e., the rated wind speed, is first fixed. This in turn determines the cut-in speed at which the machine generates enough power to supply its no-load losses. At wind speeds higher than the rated value, the output of the machine must be limited, by the controlling mechanism, to near the rated value. Even at the very windiest site there are few hours in the year with wind speeds of over 60 m.p.h. and, in any case, it is impractical to design the machine to extract energy at the highest speeds. In the normal propeller-type of machine, the blades would be designed to furl at wind speeds greater than some particular value. The precise operating limits, which are interdependent, have an important bearing upon the initial cost of the machine. This in turn has to be considered in relation to the energy which might be produced annually. And, to complete the circle, the energy obtained is determined by the operating limits of the machine and by the wind régime at the proposed site.

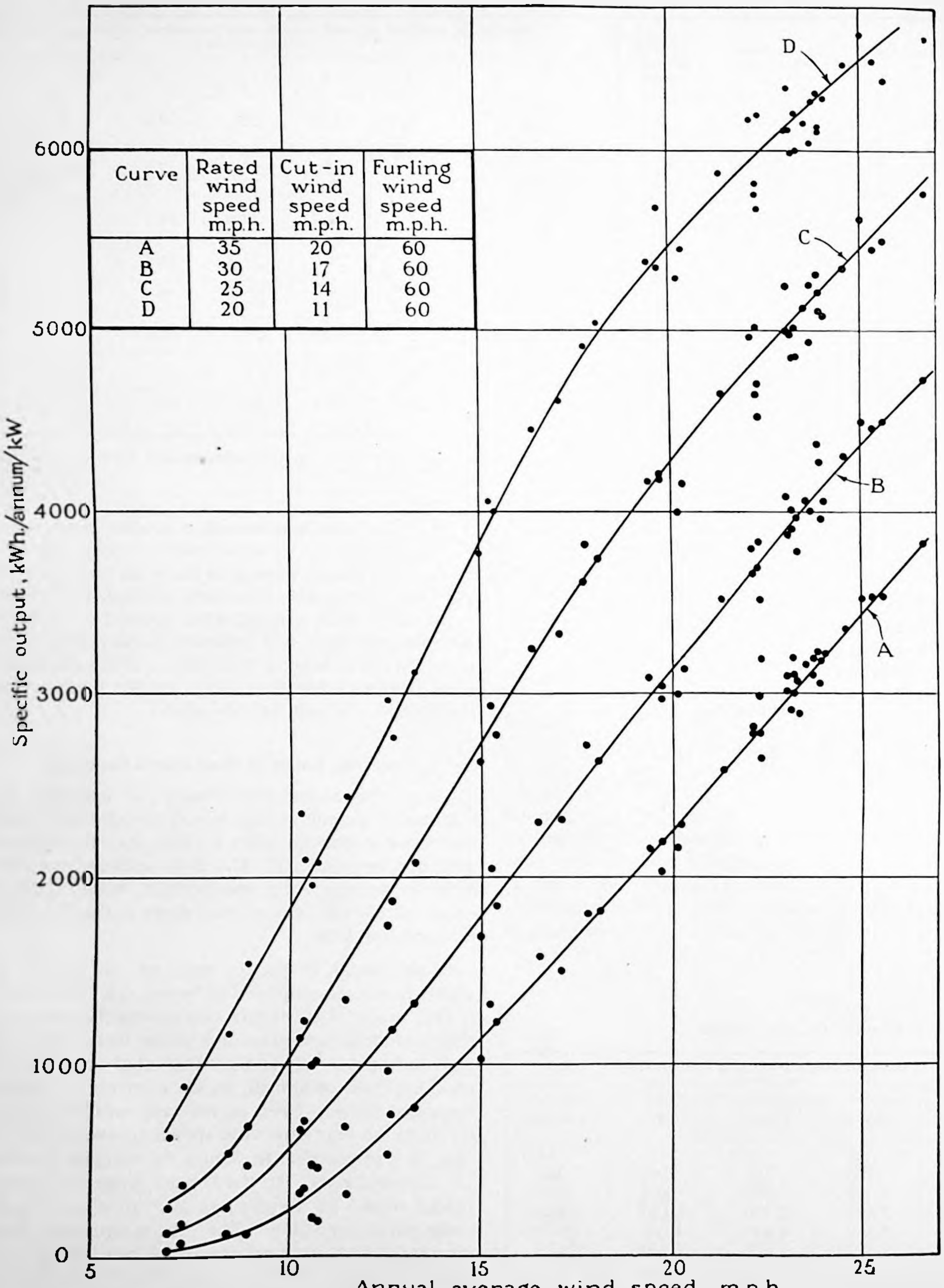


Fig. 17.—Relationship between the specific output and annual average wind speed at sites in the British Isles.

It may be assumed that any proposed machine might have one of the sets of operating limits shown below.

Table 8

Windmill Operating Limits

Wind speed at which generation begins (m.p.h.)	Minimum wind speed for maximum output (m.p.h.)	Maximum operational wind speed (m.p.h.)
11	20	60
14	25	60
17	30	60
20	35	60

Even if machines are designed to operate successfully at wind speeds exceeding 60 m.p.h., the extra energy so obtained will not be large and no account will be taken of it in subsequent calculations.

Finally, over the whole operating range of wind speeds, the power produced by the machine will be a varying proportion of the actual power in the wind. This proportion is known as the *overall power coefficient* (see Ref. 16). Because different machines will have different characteristics, no attempt will be made to allow for this coefficient in the following calculations.

(5.4.4) Specific Output

At any site a windmill will only generate electricity at wind speeds above the cut-in speed. Up to the rated wind speed, the output will be proportional to the actual speed of the wind*. In higher winds than this the output will remain approximately constant at its rated value. Since the machine will be working at part capacity for long periods during a year, in addition to the periods at full output, the total energy produced will be equivalent to the energy which would have been produced had the machine been working at full capacity for a shorter period. To this period the term *specific output* has already been given (Ref. 16).

(5.4.5) Variation of Specific Output

When Ref. 16 was published, only a few annual average wind speeds were available from E.R.A. wind survey sites. The authors used these figures, together with others from Meteorological Office sites, to produce tentative curves of specific output against annual average wind speed. Since that time, many additional results have been obtained and they are now included in a new set of curves shown in Fig. 17. A fourth set of operating limits has been added, and, to preserve uniformity, in two of the previous sets of figures the cut-in wind speeds have been slightly modified.

Most of the E.R.A. sites for which values of specific output have now been obtained have annual wind speeds lying within the range of 19 m.p.h. to 27 m.p.h. Nearly all these values lie within ±4 per cent. of the four mean lines drawn through the

* The varying efficiency of any machine will influence the output obtained between the cut-in wind speed and the rated wind speed.

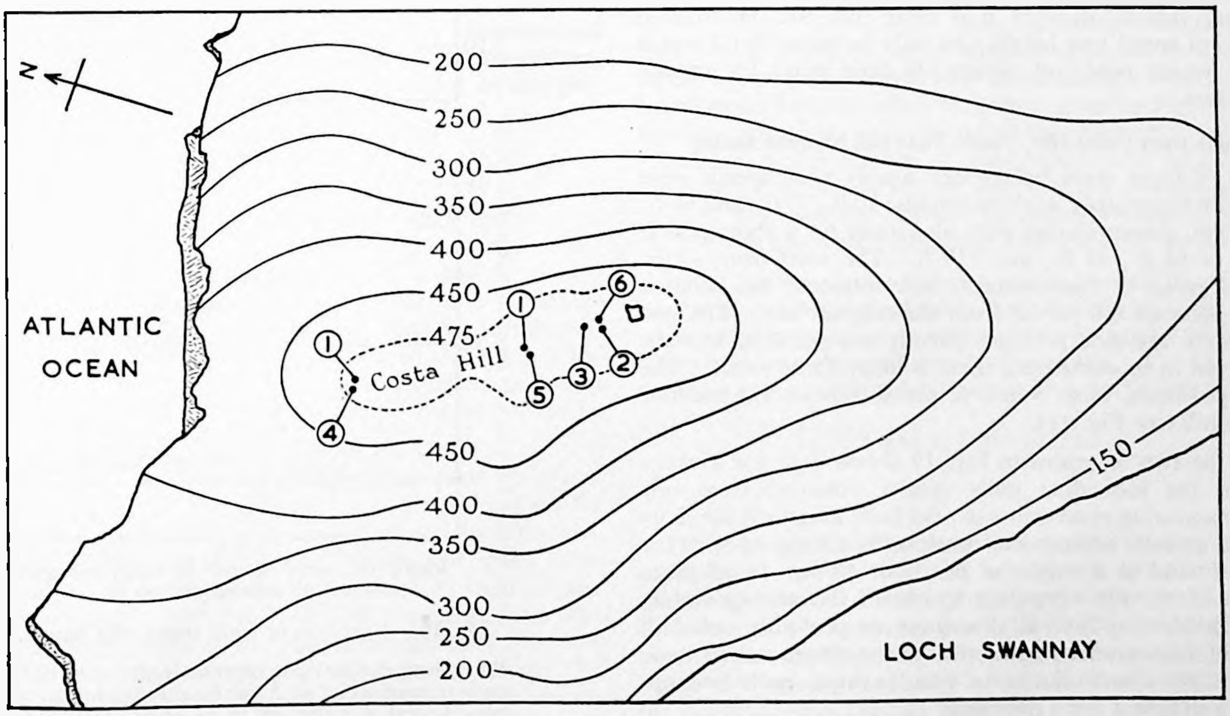


Fig. 18.—Contour plan of (1) Costa Hill, Orkney.
Scale: 1 in. = 200 yards.

(1) and (2)—Original positions of cup counter anemometers mounted on 10 ft. poles.

(2) —Actual summit of Costa Hill at an altitude of 500 ft.

(3)* —Original position of the 66 ft. pole. This was later removed to make way for the 100 kW windmill.

(4) —Subsequent position of the 66 ft. pole.

(5)* —Position of the 120 ft. measuring mast.

(6)* —Position of a cup-contact anemometer mounted on a 10 ft. pole and used with the photographic recorder.

* Positions from which results were analysed.

The contour vertical interval is normally 50 ft. with the exception that the highest contour has been drawn at 475 ft.

plotted values in Fig. 17. It is thus confirmed that the annual average wind speed for sites within the British Isles may be accepted as a measure of the potential specific output.

(5.5) Variation of Wind Speed with Height

Winds result from pressure differences in the atmosphere. Close to the ground frictional effects lead to a reduction in wind speed. As a result there is normally an increase of wind speed with height which experimental work by several investigators (see page 17, Ref. 14, also Refs. 7 and 22) has proved to be of the form:—

$$V \propto x^{\alpha}$$

where V is the wind speed, x, the height above ground, and α is an exponent which varies according to the prevailing conditions.

Sutton (Ref. 31) has calculated values for the exponent α from observations at Leafield. He found considerable diurnal variation. Typical values during the summer were about 0·17 at midnight to 0·07 in the afternoon. In winter, the variation was less. Values of 0·12 were obtained at night, and of 0·08 in the afternoon. It has been shown that extreme values of up to 0·63 occur during very large temperature inversions (see Ref. 12). Barkat Ali (Ref. 2) observed an extreme value of 0·9 during the small hours of the morning at Agra. Sutton stated in a later report (see Ref. 32) that the diurnal variation in temperature gradient influenced the diurnal variation of turbulence in the lower levels of the atmosphere, and hence the value of the exponent α. The nature of the ground surface also had an important effect upon the gustiness, whereas the height and mean wind speed influenced it to a lesser degree. With all these contributory factors at work it is clear that the relationship between wind speed and height can only be stated for average conditions which need not necessarily hold good for instantaneous values.

(5.5.1) Results from Costa Hill, Vestra Fiold and Mynydd Anelog

At each of these three hills, mean hourly wind speeds were obtained, simultaneously, at three heights: 10 ft., 33 ft., and 66 ft. At Costa Hill, measurements were also made for a short period at heights of 58 ft., 88 ft., and 118 ft. The mast from which this second group of measurements was obtained, was situated at a short distance (80 yards) from the original site. The two sets of results are not perhaps directly comparable, but the error involved in so comparing them is likely to be small. The two mast positions, Nos. 3 and 5, are shown on the contour plan of the hill (see Fig. 18).

Each of the two diagrams in Fig. 19 shows both the average results and the individual daily results obtained from one particular measuring mast and site. In both diagrams the daily run-of-wind at each anemometer position is compared with the daily run-of-wind at a height of 66 ft. or 88 ft. In all cases 20–30 days of records were used to obtain the average value, so that winds blowing from all directions are probably included. Thus the different relationships shown in the diagrams are made up of unknown combinations of relationships, each one applicable to a different wind direction.

The scatter of the points may be due in part to interference caused by the supporting masts, particularly in winds having large vertical components. Nevertheless, it does emphasise the fact that there is no one relationship applicable to any particular hill. At Costa Hill it may be noted that the wind speed is generally higher at 88 ft. than at 118 ft. Results from the shorter mast at Vestra Fiold do not provide any evidence of a reduction in wind speed with height.

At Mynydd Anelog, analysis was complicated by the fact that anemometers at opposite ends of each platform produced different results. On the lower platform the wind speed at the eastern end was usually greater than that at the western end. The opposite was true of the upper platform. In each case the difference varied slightly with direction but was approximately

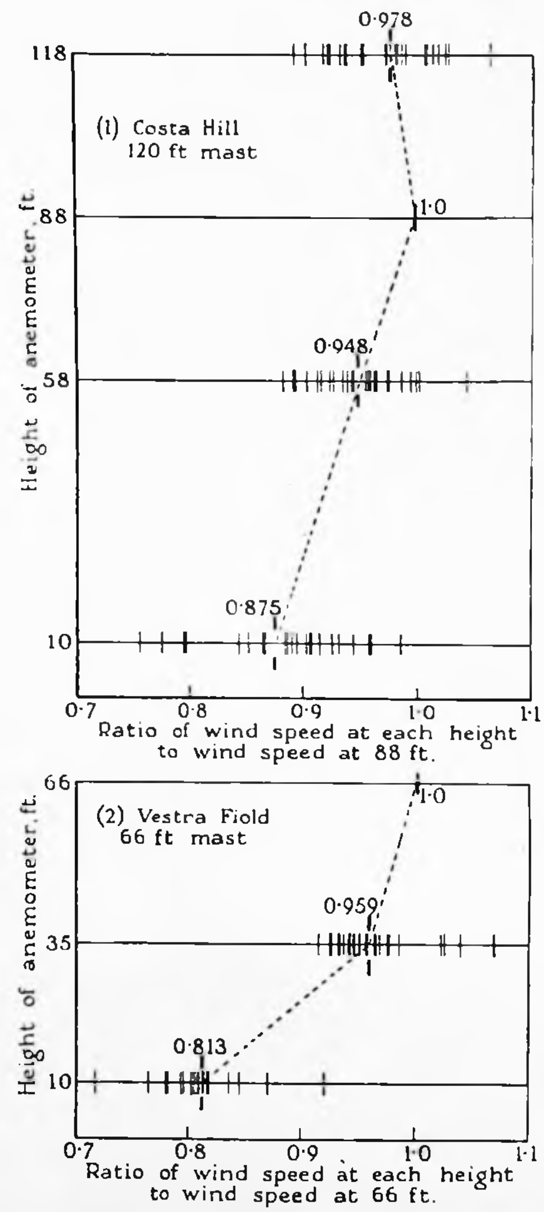


Fig. 19.—Variation of wind speed with height.

Each short vertical line represents the ratio of the daily run-of-wind at a particular height, to the run-of-wind at either 88 ft. or 66 ft. The single bold lines at each height represent the average ratios for the period of the analysis.

5 per cent. This discrepancy still showed even after the anemometers had been changed during normal maintenance visits. From some directions there was considerable interference by the mast or wind direction indicator on the down-wind anemometer, but this effect was fairly easy to eliminate.

The contours of Mynydd Anelog are approximately oval with the major axis running almost north-west and south-east. The hill is conical in general shape with steep slopes on the eastern and western sides and much shallower slopes to the north and south. On the top there is a flattened area some 50 yards across which slopes gently downwards to the north-west. The summit is a small hillock on the south-eastern edge of this flattened area, and the foot of the mast is about 6–8 ft. below the summit of the hill and some 40 ft. away to the WNW. No detailed survey of the top of this hill has been carried out as it was for Costa Hill, but from the foregoing description, it will be realised that the windflow over Mynydd Anelog is likely to be even more complex than over the much smoother surface of Costa Hill. With only limited information available, no definite conclusions can be reached on the change of wind speed with height over the former hill. However, during a typical period of four months from 6th May to 6th September, 1951, average wind speeds at each of the three levels were:—

66 ft.	22·3 m.p.h.
35 ft.	21·8 m.p.h.
10 ft.	21·2 m.p.h.

The long-term overall effect is thus one of steady increases in wind speed with increasing height over the summit of the hill. From certain directions, however, the wind over the hill may have a maximum speed at some level below 66 ft.—the height of the highest anemometer on the mast.

Gradients varying from a very steep slope to a gentle incline are represented on one or other of the three hills. In addition there is a wide variation in gradient on each hill. Diagrams and photographs are shown in Figs. 2 and 3. Clearly little information can be extracted from the results about the effect of any particular slope on the flow of wind over a hill.

Effect of Direction

Although the run-of-wind recorded from each anemometer position is an integrated total, the information on wind direction is confined to spot readings taken every hour or half hour from a wind vane. In gusty winds the vane oscillates considerably and it is thus a matter of chance whether the directions indicated represent the mean direction of flow of the wind. Only if the directions remain sensibly constant over an extended period of several hours is it probable that the indications are representative of the actual wind direction during that time.

On this assumption, some records obtained from the 66-ft. mast in its earlier position on Costa Hill were analysed in greater detail. The results extended from 22nd February to 28th June, 1949. Periods were selected during which the wind blew steadily within ±15° of four main directions at right angles. These directions—60°, 150°, 240° and 330° measured from true north—corresponded to winds blowing either across or down the length of the ridge. The hourly mean wind speeds measured by anemometers at 10 ft. and 35 ft. were compared, hour by hour, with the corresponding hourly mean wind speeds at 66 ft. Between 70 and 150 hours of records were used to obtain the two average ratios for each main wind direction. From the results it was obvious that the values obtained for the direction 240° would have to be ignored, because of interference by the wind direction indicator on the results obtained at 66 ft.: the two instruments were only about 5 ft. apart. It appeared probable that the errors in wind speed might be as large as 50 per cent. for some directions of wind near 240°.

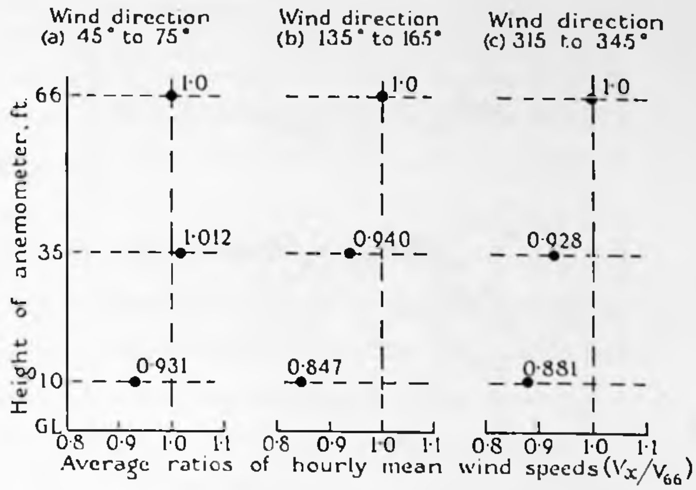


Fig. 20.—Variation of wind speed with height for three wind directions over Costa Hill.

Each of the plotted points represents the average ratio of the hourly mean wind speed (V_x) at a particular height to the corresponding hourly mean wind speed at 66 ft. (V_{66}). Wind directions were selected to coincide with winds blowing either across or along the ridge. The analysis included periods in 1949, when the wind blew steadily within ±15° of each of the four main directions. The results from the direction 240° have been discarded because of interference with the wind-flow past the 66 ft. anemometer by the wind direction indicator.

A similar effect was noticed on the anemometer down-wind of the mast at the 35 ft. level. Here the tubular mast is only about six inches in diameter, yet the effect upon the down-wind anemometer about 5 ft. away was considerable. Fortunately this interference does not affect the results given in Fig. 20. The six average ratios have been plotted in this diagram to give a visual indication of the change of wind speed with height for each direction of wind. It will be seen that the average wind speed at 35 ft. is greater than the corresponding average wind speed at 66 ft. when the wind is blowing from the N.E. across the ridge.

When the wind was blowing down the length of the ridge similar results were obtained in both directions. The change of wind speed with height x, appeared to be similar to the change which has been observed over level country. The four values of the exponent α, obtained by substitution in the formula:—

$\frac{V_{66}}{V_x} = \left(\frac{66}{x}\right)^\alpha$, lie between 0·095 to 0·15.

Effect of Wind Speed

The records were then examined to find whether the actual strength of the wind had any effect upon the change of wind speed with height. For this purpose, periods when the wind was blowing steadily from any one of the eight directions shown in Fig. 21 were selected. As with the previous analysis, the hourly mean wind speeds at either 10 ft. or 35 ft. were compared with the corresponding values at 66 ft. The individual values of these ratios have been plotted against the hourly mean wind speed at the 66 ft. level in Fig. 21.

It is interesting to note the change in the mean values of the ratios $\frac{V_{35}}{V_{66}}$ and $\frac{V_{10}}{V_{66}}$ for the direction 235°–245° (which was ignored in the previous analysis). It was not possible to plot many of the higher ratios of the two wind speeds for this direction, but the remaining ones clearly show the amount of

Table 9.

Monthly and Annual Average Wind Speeds Overseas

KEY PART I—SOURCES OF RECORDS
(Column 7)

AG From the Official Year Book of the Commonwealth of Australia, No. 38, 1951. (Ref. 40.)
BWS Base Weather Station Patrick, AFB Climatological Section. (Unpublished.)
CMS British Caribbean Meteorological Service. (Unpublished.)
CSC Climatic Summaries for selected meteorological stations in Canada, Newfoundland and Labrador. By C. C. Boughner and M. K. Thomas, Vol. II, Publ. Dept. of Transport, Meteorological Division, Toronto, 1948.
EPW "Electric Power from the Wind," by P. H. Thomas (Federal Power Commission, 1945).
EVU "La Energia del Viento en el Uruguay," by Emanuele Cambilargiu. (Ref. 6.)
F "Wind Research in Israel, Report for 1953," by J. Frenkiel. (Unpublished.) (Ref. 11.)
HW "Windkraftwerke," by Hans Witte, Publ. Rudolf A. Lang Verlag, Pössneck, 1950.
IV "Il Problema Italiano dell'Utilizzazione del Vento" by Renzo Vezzani. Estratto degli Annali dei Lavori Pubblici (già Giornale del Genio Civile)—1942, XX, Fasc. 3.
IWD "Wind Data for Wind Mills," India Meteorological Department. (Ref. 35.) (At most of the sites for which results are published, Robinson cup anemometers were originally used, but these have been replaced recently by similar instruments manufactured in India. At a few sites, Beckley's anemographs were originally used, but these have been replaced by Dines pressure tube anemographs.)
K "Větrné Motory a Elektrárny," by F. Kaspar (trans. Wind Motors and Power Stations). Elektrotechnický Svaz, Prague, 1948.
SW Studiengesellschaft Windkraft, No. 3, April 1954. (Ref. 8.)
TEC Trinidad and Tobago Electricity Commission. (Unpublished.)
TWA "The Trade Winds of the Atlantic Ocean," Meteorological Office, 1910.
U Unpublished.
UEV "Utilização da Energia Dos Ventos," by E. A. Brun and T. Oniga. Instituto Nacional de Tecnologia, Rio de Janeiro, 1952.
WM World Meteorological Organization, Technical Note No. 4.
WSA "Surface Winds of South Africa," Weather Bureau, Department of Transport, Pretoria 1949.

KEY PART II—INSTRUMENTS
(Column 8)

A Anemograph.
AB Anemobiagraph.
AC Anemocinemograph.
CA Combined anemograph, Miguel Venturino.
CI Counter type instrument.
DA Dines anemograph.
FA Friez anemocinemograph.
FU Fuess universal.
PA Papillon registering anemometer.
RA Robinson cup type anemometer with recording anemograph.
RDM Data obtained either by Robinson cup anemometers, Dines pressure tube anemometer or Machin cup anemometer.
SA Single anemograph.
SI Siap.
ST Steffens Hedde.
WI Wild type instrument (rather inaccurate).

1	2	3	4	5	6	7	8	9													
								Average wind speed in m.p.h.													
Country and name of site	Lat.	Long.	Alt. (ft.)	Height of An. (ft.)	Period of Records (yrs.)	Source of Records	Type of inst.	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	
CANADA																					
1. Victoria, B.C.	48°25′N	123°20′W	228	50	24	CSC	RA	12·4	11·6	11·6	11·7	12·0	12·3	11·9	10·6	8·7	8·9	10·7	12·8	11·3	1
2. Churchill, Man.	58°47′N	94°11′W	44	45	13	CSC	RA	14·6	14·6	14·2	14·2	13·4	12·0	11·4	12·8	16·1	17·1	16·9	14·9	14·4	2
3. Cape Hopes Advance, Q.	61°03′N	69°36′W	240	25	8	CSC	RA	19·1	18·9	17·9	17·5	15·4	14·4	16·2	17·7	20·8	23·8	24·2	20·5	18·9	3
4. Sable Island, N.S. ..	43°56′N	60°02′W	25	40	15	CSC	RA	21·2	20·7	20·1	17·7	14·6	13·6	12·8	12·9	15·2	17·5	19·4	21·2	17·2	4
5. Resolution Island, N.W.T.	61°18′N	64°53′W	127	12	15	CSC	RA	18·4	18·1	16·8	16·8	14·4	13·0	12·6	12·9	14·8	17·7	18·9	18·2	16·1	5
6. Torbay, Newf.	47°37′N	52°44′W	463	20	4	CSC	RA	19·4	18·3	20·4	16·6	15·9	16·3	16·1	15·3	16·2	18·5	17·2	20·2	17·6	6
UNITED STATES OF AMERICA																					
7. Av. of 20 stns., New Eng.	—	—	—	—	—	EPW	—	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	7
WEST INDIES																					
8. Nassau, Bahamas ..	25°05′N	77°21′W	15	34	43	BWS	—	8·8	8·8	8·8	8·8	6·9	6·1	5·6	6·1	5·6	7·8	8·8	9·2	7·6	8
9. Havana, Cuba	23°08′N	82°22′W	79	—	41	U	—	7·3	7·4	7·7	7·8	6·8	5·9	5·6	5·4	5·4	7·2	7·6	7·4	6·8	9
10. San Juan, Puerto Rico ..	18°29′N	66°06′W	99	—	13	U	—	11·2	11·0	11·3	11·2	10·7	12·2	12·5	11·8	9·4	7·8	8·8	10·2	10·6	10
11. Bridgetown, Barbados ..	13°10′N	59°30′W	180	—	8	U	—	12·5	13·6	12·4	12·4	12·8	13·6	12·4	9·8	8·1	7·5	8·4	10·6	11·2	11
12. The Fort, Tobago ..	11°12′N	60°40′W	452	10	1	TEC	CI	11·1	11·4	11·4	10·6	10·9	10·5	8·6	8·3	7·2	7·1	7·0	9·4	9·5	12
13. French Hill, Tobago ..	11°12′N	60°40′W	—	15	1	TEC	CI	11·4	11·9	12·1	13·9	13·5	13·9	11·4	10·7	9·7	11·4	11·1	11·4	11·9	13
BRAZIL																					
14. Cabo Frio	22°53′S	42°02′W	10	—	10	UEV	—	12·7	11·4	11·7	10·2	10·4	11·0	11·7	15·1	15·5	14·7	15·7	12·6	12·7	14
15. Fernando-Noronha, Pernamb.	03°50′S	32°25′W	333	—	—	HW	—	15·2	13·4	12·7	14·3	15·2	17·0	17·9	17·0	16·1	15·9	15·4	14·5	15·4	15
16. Recife, Pernamb. ..	08°01′S	34°51′W	197	—	—	HW	—	13·6	13·0	11·6	12·5	15·9	14·5	13·6	13·6	14·5	13·6	13·0	12·5	13·6	16
17. Santa Victoria do Palmar, R.G.	33°33′S	53°23′W	—	—	—	HW	—	12·3	11·4	11·6	11·2	10·1	11·2	10·7	12·8	13·6	13·6	13·0	13·4	12·1	17

Table 9—*continued*

1 Country and name of site	2 Lat.	3 Long.	4 Alt. (ft.)	5 Height of An. (ft.)	6 Period of Records (yrs.)	7 Source of Records	8 Type of Inst.	9 Average wind speed in m.p.h. Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	
URUGUAY																					
18. Santa Isabel	32°46′S	56°32′W	260	—	5	EVU	WI	10·4	10·0	10·8	9·4	10·2	10·9	10·7	11·9	13·5	12·9	12·8	12·0	11·3	18
19. Melo	32°22′S	54°12′W	362	—	5	EVU	WI	8·6	9·2	7·7	7·3	6·7	6·8	7·5	9·7	9·0	9·9	9·5	9·0	8·4	19
20. La Calera	33°15′S	54°28′W	197	—	5	EVU	WI	7·8	6·9	7·1	6·0	5·9	6·4	6·1	7·7	7·5	9·0	8·6	8·7	7·3	20
ARGENTINE																					
21. Buenos Aires	34°35′S	58°29′W	82	—	39	WM	FA	7·0	→	←	8·1	→	←	7·6	→	←	6·3	→	←	7·6	21
22. Puerto Madryn	42°46′S	65°02′W	20	—	39	WM	SA	10·1	→	←	11·2	→	←	8·8	→	←	8·8	→	←	10·1	22
23. Santa Cruz	50°01′S	68°34′W	361	—	39	WM	SA	10·1	→	←	11·9	→	←	13·2	→	←	10·1	→	←	11·2	23
24. Rio Gallegos	51°36′S	69°20′W	—	—	—	HW	—	9·3	10·5	8·9	9·9	8·4	8·8	9·8	10·0	11·0	10·1	10·3	10·2	9·8	24
FALKLAND ISLES																					
25. Darwin	51°49′S	58°58′W	—	—	1	U	CI	11·7	14·7	13·3	12·3	11·3	12·1	11·8	13·0	14·2	12·1	13·6	12·1	12·7	25
26. North Arm	52°06′S	59°20′W	—	14	1	U	CI	10·4	12·0	10·7	15·5	17·3	13·9	14·6	15·4	14·7	13·7	16·6	10·9	13·8	26
27. Fox Bay, West	51°58′S	60°06′W	—	—	1	U	CI	12·0	11·1	11·5	10·5	12·5	9·3	11·1	10·0	12·9	12·8	13·0	13·0	11·7	27
28. Port Stanley	51°42′S	57°52′W	168	45	1	U	CI	20·0	19·4	19·3	20·0	24·2	18·2	17·3	20·9	15·9	15·9	20·4	21·2	18·6	28
GIBRALTAR																					
29. North Front	36°09′N	05°21′W	10	—	4	WM	DA	13·2	→	←	12·6	→	←	11·2	→	←	11·0	→	—	12·1	29
FRANCE																					
30. Paris (Eiffel Tower) ..	48°51′N	02°20′E	112	1,000	20	U	—	22·8	22·0	20·8	19·6	18·7	17·0	16·6	17·9	18·4	20·8	20·7	22·0	19·8	30
31. Brest	48°24′N	04°30′W	—	—	13	U	—	—	—	—	—	—	—	—	—	—	—	—	—	16·5	31
32. Perpignan	42°42′N	02°50′E	164	56	13	U	—	—	—	—	—	—	—	—	—	—	—	—	—	15·7	32
BELGIUM																					
33. Uccle (observatory) ..	50°48′N	04°21′E	328	—	30	OEEC	—	11·1	10·9	10·7	10·0	8·2	7·6	7·5	7·6	7·1	8·4	9·6	11·0	9·2	33
GERMANY																					
34. Heligoland	54°11′N	07°53′E	184	69	3	SW	ST	16·6	17·5	15·2	13·7	12·6	10·8	12·8	9·8	14·8	18·6	19·7	17·7	15·0	34
35. Quickborn	53°44′N	09°53′E	43	230	5	SW	SI	17·2	16·8	16·1	15·9	13·9	13·4	13·7	12·8	14·1	15·0	15·5	16·1	15·0	35
36. Brocken (Harz)	51°48′N	10°37′E	3,750	92	5	SW	FU	25·8	28·9	22·9	22·7	19·3	18·2	18·4	20·6	19·8	23·8	25·4	26·9	22·6	36
37. Kahler-Asten	51°11′N	08°30′E	2,770	86	5	SW	FU	19·7	18·4	16·4	17·3	14·3	13·0	13·5	13·9	13·7	15·7	18·4	18·8	16·1	37
38. Kalmit	49°19′N	08°05′E	2,220	103	4	U	ST/FU	20·8	18·4	15·0	15·2	13·4	13·9	13·7	12·8	13·7	16·4	16·8	15·9	15·5	38
39. Feldberg (Schw.) ..	47°52′N	08°00′E	4,900	56	5	SW	FU	22·0	20·6	20·6	19·5	15·5	15·0	13·9	14·8	15·0	17·3	21·7	22·6	18·2	39
NORWAY																					
40. Utsira	59°18′N	04°53′E	—	20	10	U	DA	20·5	19·5	16·0	14·5	13·0	14·5	12·5	14·5	15·5	18·0	19·5	20·0	16·0	40
41. Hellisøy	60°45′N	04°43′E	—	20	10	U	DA	17·5	17·0	13·5	10·5	10·5	11·0	9·5	10·5	13·5	14·0	15·5	16·0	13·5	41
42. Ona	62°52′N	06°33′E	—	20	10	U	CI	18·5	17·5	14·5	11·5	11·0	11·5	10·5	10·5	13·0	13·5	16·0	15·5	13·0	42
43. Nordøyan	64°48′N	10°33′E	—	20	10	U	CI	22·0	21·5	18·5	15·5	14·0	13·0	11·5	13·5	17·0	18·0	20·0	20·5	17·0	43
44. Andenes	69°19′N	16°07′E	—	20	10	U	CI	16·0	15·5	14·0	11·0	10·5	10·0	7·5	7·5	11·5	12·5	12·5	14·0	12·0	44
FINLAND																					
45. Kökar (Äland)	59°56′N	20°56′E	36	31	—	U	—	16·8	14·6	15·0	12·3	12·3	10·8	11·4	11·4	12·3	15·2	17·5	18·8	14·1	45
RUSSIA ..																					
46. Moscow	55°45′N	37°37′E	—	—	10	K	—	10·8	10·6	10·3	9·6	9·7	8·9	8·9	8·6	9·1	9·9	10·3	10·1	9·7	46
CZECHOSLOVAKIA																					
47. Prague (Petrin)	50°05′N	14°25′E	—	—	—	K	—	11·2	11·6	15·5	11·8	12·4	11·9	13·7	13·5	11·1	14·2	12·0	16·0	13·0	47
48. Prague (Karlov) ..	50°05′N	14°25′E	—	—	1	K	—	6·7	6·2	5·7	10·0	7·2	7·4	6·5	6·4	7·2	6·4	6·2	5·1	6·7	48
ITALY																					
49. Lido di Roma	41°54′N	12°28′E	10	49	3	IV	—	12·6	10·2	11·2	9·5	8·8	7·1	8·1	7·1	7·7	10·7	·3	10·7	9·4	49
50. Oristano	39°54′N	08°30′E	63	78	3	IV	—	16·0	16·0	13·1	13·3	10·9	6·1	6·6	7·1	6·5	7·5	7·	9·5	9·9	50
51. Brindisi	40°38′N	17°56′E	43	43	3	IV	—	10·9	12·2	13·6	9·8	9·6	10·2	11·2	11·2	9·9	10·4	11·2	12·6	11·1	51
52. Monte Cimone	44°11′N	10°46′E	7,095	53	3	IV	—	25·6	20·3	23·7	22·1	23·0	20·2	16·0	11·8	19·2	23·5	28·0	24·1	21·4	52

Table 9—*continued*

1 Country and name of site	2 Lat.	3 Long.	4 Alt. (ft.)	5 Height of An. (ft.)	6 Period of Records (yrs.)	7 Source of Records	8 Type of inst.	9 Average wind speed in m.p.h. Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	
ISRAEL—including stations of former Palestine Met. Service																					
53. Mt. Canaan	32°59′N	35°30′E	3,070	—	8	WM	DA	13·5	→	←	13·5	→	←	15·0	→	←	11·2	→	←	13·2	53
54. Misgav Am	33°14′N	35°33′E	2,760	10	1	U	CI	17·0	18·6	16·4	16·8	14·1	19·0	17·2	19·0	18·6	13·4	13·0	12·8	16·3	54
55. Mt. Scopus (Jerusalem)	31°47′N	35°13′E	2,630	—	5	F/WM	DA	11·8	10·5	11·0	10·0	10·8	11·9	13·6	11·5	9·7	8·6	6·8	8·9	10·4	55
56. Aquaba Bay	29°33′N	34°58′E	10	20	2	WM	AB	8·3	→	←	12·8	→	←	12·8	→	←	11·9	→	←	11·4	56
ARABIA																					
57. Aden	12°50′N	45°01′E	13	7	—	IWD	—	9·9	10·6	11·8	11·1	7·9	6·5	7·3	7·5	6·7	9·0	9·0	9·2	8·9	57
58. Perim	12°30′N	43°00′E	—	—	—	IWD	—	14·5	14·0	14·1	13·1	10·0	9·8	11·2	10·1	8·8	13·5	14·7	14·1	12·3	58
IRAQ																					
59. Baghdad	33°20′N	44°24′E	112	—	—	IWD	—	10·0	10·7	11·9	11·3	8·0	6·3	7·4	7·4	6·7	9·3	9·4	9·4	9·0	59
PERSIA																					
60. Jask	25°45′N	57°45′E	13	40	5	IWD	—	8·1	9·0	8·7	8·3	8·3	8·7	9·7	9·5	8·2	7·1	6·6	7·5	8·3	60
61. Bushire	28°59′N	50°50′E	13	49	5	IWD	—	7·5	7·8	8·3	7·5	7·5	9·1	7·1	6·1	5·7	5·2	6·1	6·5	7·1	61
INDIA																					
62. Jodhpur (Rajputana)	26°18′N	73°01′E	737	48	—	IWD	A	6·9	6·8	6·9	6·8	10·7	12·6	12·1	9·1	7·3	4·8	4·5	6·1	7·9	62
63. Madras	13°00′N	80°11′E	53	73	—	IWD	A	11·0	9·5	9·6	11·1	11·8	11·9	10·8	10·7	10·0	8·7	12·3	12·5	10·8	63
64. Deesa (Bombay)	24°15′N	72°12′E	—	62	—	IWD	A	6·0	5·9	6·0	6·4	9·1	11·4	10·5	8·4	5·6	4·6	5·0	5·4	7·0	64
65. Bombay	18°55′N	72°54′E	—	58	—	IWD	A	6·6	7·0	7·2	7·1	6·7	9·4	11·6	9·9	7·0	6·1	6·3	6·5	7·6	65
66. Dwarka (Bombay)	22°13′N	68°58′E	—	19	—	IWD	—	8·2	8·7	9·4	9·6	11·4	13·1	14·9	12·6	8·5	6·9	7·3	7·5	9·8	66
67. Puri (Orissa)	19°48′N	85°52′E	—	29	—	IWD	—	6·2	8·5	10·6	12·5	13·3	12·1	11·3	9·9	8·1	6·4	5·7	5·8	9·2	67
68. Port Blair (Andaman Is.)	11°41′N	92°43′E	—	27	—	IWD	—	8·5	7·1	5·9	5·9	8·6	13·7	15·9	13·4	10·4	8·6	8·4	9·1	9·5	68
CEYLON																					
69. Hambantota	06°07′N	81°08′E	62	11	—	IWD	—	9·9	9·3	7·4	6·6	9·9	11·4	11·5	11·8	11·5	8·7	6·4	7·7	9·3	69
PAKISTAN																					
70. Karachi (Manora)	24°08′N	67°08′E	72	36	59	IWD/WM	—	6·2	6·8	8·2	9·7	11·6	12·7	12·8	11·9	10·0	6·6	5·3	5·9	9·0	70
71. Karachi (Drigh Road)	—	—	72	25	—	IWD/WM	—	6·6	7·1	8·5	10·0	13·5	15·5	15·8	15·3	13·3	7·3	5·9	6·2	10·4	71
BURMA																					
72. Victoria Point	09°58′N	98°35′E	154	6	—	IWD	—	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	72
73. Akyab	20°08′N	92°53′E	16	19	—	IWD	—	6·1	7·0	7·2	7·7	8·4	10·9	11·4	10·0	7·8	6·6	5·5	5·7	7·9	73
74. **Hong Kong**	22°30′N	114°00′E	—	—	—	WM	—	8·5	→	←	9·9	→	←	7·9	→	←	8·8	→	←	8·7	74
JAPAN																					
75. Seburi Yama	—	—	3,460	—	9	U	—	20·6	20·4	22·2	22·0	20·0	18·4	20·2	17·1	19·1	20·6	21·4	20·6	20·4	75
AUSTRALIA																					
76. Perth (W.A.)	31°57′S	115°51′E	210	71	30	AG	RDM	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	76
77. Sydney (N.S.W.)	33°52′S	151°12′E	138	58	26	AG	RDM	8·9	8·1	7·5	7·0	6·8	7·1	7·2	7·4	8·0	8·2	8·5	8·9	7·8	77
78. Adelaide (S.A.)	34°56′S	138°35′E	140	75	30	AG	RDM	9·9	8·8	8·3	8·0	8·1	8·3	8·5	9·2	9·2	9·8	9·9	9·9	9·0	78
79. Melbourne (V.)	37°49′S	144°58′E	114	93	30	AG	RDM	8·8	8·3	7·9	7·3	7·5	7·7	8·9	8·4	8·6	8·3	8·4	8·6	8·2	79
80. Hobart (T.)	42°53′S	147°30′E	177	40	30	AG	RDM	8·0	7·2	6·8	6·7	6·3	6·2	6·5	6·8	7·9	8·2	7·9	7·6	7·2	80
NEW ZEALAND																					
81. Wellington	41°16′S	174°47′E	—	35	3	U	—	9·3	9·7	8·9	8·1	8·0	8·2	7·5	8·2	9·3	10·2	10·1	9·5	8·9	81
SPANISH MOROCCO																					
82. Sania Ramel	35°35′N	05°24′W	33	—	14	WM	AC	9·9	→	←	11·0	→	←	10·1	→	←	9·2	→	←	10·1	82
SPANISH SAHARA																					
83. Villa Cisneros	23°41′N	15°54′W	20	—	9	WM	—	13·0	→	←	17·5	→	←	22·4	→	←	16·4	→	←	17·2	83

Table 9—*continued*

1 Country and name of site	2 Lat.	3 Long.	4 Alt. (ft.)	5 Height of An. (ft.)	6 Period of Records (yrs.)	7 Source of Records	8 Type of Inst.	9 Average wind speed in m.p.h. Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	
ANGOLA																					
84. Luanda	08°49′S	13°13′E	148	—	22	WM	DA	8·3	→	←	7·8	→	←	6·9	→	←	8·7	→	←	8·1	84
UNION OF SOUTH AFRICA																					
85. Beaufort West	32°19′S	22°38′E	2,849	50	8	WSA	DA	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	85
86. East London	33°02′S	27°52′E	285	50	5	WSA	DA	10·4	9·8	9·5	9·5	10·5	10·6	10·7	10·9	11·5	12·4	11·9	11·9	10·8	86
87. Pietersburg	23°56′S	29°29′E	4,244	50	9	WSA	DA	7·9	7·0	5·8	5·2	5·7	6·0	6·2	6·8	9·1	10·1	9·4	8·7	7·3	87
88. Port Elizabeth	33°57′S	25°37′E	181	50	8	WSA	DA	12·2	11·8	11·5	10·8	9·6	10·0	10·2	11·0	12·6	13·3	13·3	12·9	11·6	88
89. Victoria West	31°24′S	23°09′E	4,163	50	4	WSA	DA	9·8	9·3	7·6	7·0	7·5	6·9	8·2	8·4	10·3	10·6	10·5	10·2	8·8	89
90. Wingfield	33°54′S	18°32′E	55	50	5	WSA	DA	11·9	11·6	11·1	8·2	7·7	7·3	7·9	8·1	8·5	10·5	10·7	11·0	9·5	90
KENYA & TANGANYIKA																					
91. Tabora	05°02′S	32°49′E	4,150	—	13	WM	DA	7·4	→	←	10·1	→	←	13·2	→	←	11·9	→	←	10·8	91
92. Equator	00°00′S	35°33′E	9,100	—	13	WM	DA	14·8	→	←	12·8	→	←	8·1	→	←	13·0	→	←	12·2	92
MADAGASCAR																					
93. Diego-Suarez	12°17′S	49°18′E	95	—	10	WM	CI	10·7	→	←	16·1	→	←	22·6	→	←	24·6	→	←	18·6	93
94. Fort Dauphin	25°02′S	46°58′E	26	—	10	WM	CI	11·2	→	←	11·2	→	←	14·6	→	←	13·0	→	←	12·5	94
SUDAN																					
95. Wadi Halfa Aerodrome	21°50′N	31°18′E	550	—	3	WM	DA	9·6	→	←	10·1	→	←	10·3	→	←	9·6	→	←	9·9	95
96. Khartoum Aerodrome ..	15°36′N	32°33′E	1,260	—	3	WM	DA	9·8	→	←	10·1	→	←	10·8	→	←	8·1	→	←	9·7	96
EGYPT																					
97. Matruh	31°21′N	27°12′E	82	55	2	WM	DA	12·1	→	←	11·4	→	←	9·2	→	←	9·8	→	←	10·8	97
98. Alexandria	37°12′N	29°57′E	-7	50	2	WM	DA	9·4	→	←	9·2	→	←	10·3	→	←	7·2	→	←	9·0	98
99. Port Said	31°17′N	32°14′E	3	59	2	WM	DA	10·5	→	←	13·6	→	←	9·8	→	←	10·3	→	←	11·2	99
100. Cairo	30°08′N	31°24′E	230	66	2	WM	DA	10·3	→	←	9·8	→	←	8·1	→	←	9·2	→	←	9·4	100
LIBYA																					
101. Tripoli	32°45′N	13°15′E	5	72	3	IV	—	11·2	9·4	9·5	10·3	10·3	9·2	8·0	8·9	9·5	8·4	10·6	10·5	9·7	101
102. Benghazi	32°10′N	20°10′E	49	23	3	IV	—	10·9	10·8	10·4	11·7	11·0	10·0	9·1	8·7	7·3	7·8	8·7	9·2	9·6	102
TUNISIA																					
103. Cap Bon	37°04′N	11°02′E	361	—	5	WM	A	15·7	→	←	14·3	→	←	10·3	→	←	12·3	→	←	13·2	103
104. Bizerte	37°14′N	09°49′E	7	—	5	WM	A	10·3	→	←	11·2	→	←	11·4	→	←	9·6	→	←	10·8	104
105. Sfax	34°43′N	10°41′E	69	—	5	WM	A	10·5	→	←	11·2	→	←	9·6	→	←	9·6	→	←	10·3	105
ALGERIA ..																					
106. Aoulef	27°04′N	01°04′E	930	—	4	WM	PA	9·4	→	←	11·0	→	←	10·8	→	←	10·6	→	←	10·3	106
CANARY ISLANDS																					
107. Arrecife	28°58′N	13°31′W	33	—	8	WM	AC	11·0	→	←	14·1	→	←	18·3	→	←	11·6	→	←	13·9	107
108. Gando	27°56′N	15°23′W	20	—	11	WM	AC	10·8	→	←	13·7	→	←	20·8	→	←	12·8	→	←	14·7	108
109. Izaña	28°19′N	16°29′W	7,750	—	12	WM	AC	15·2	→	←	16·4	→	←	14·6	→	←	13·0	→	←	14·8	109
110. Cotillo	28°40′N	10°19′W	39	—	2	WM	CC	15·0	→	←	14·3	→	←	18·2	→	←	13·4	→	←	15·5	110
111. Asomadas	27°45′N	14°17′W	4,500	—	1	WM	CC	19·0	→	←	16·8	→	←	16·8	→	←	13·9	→	←	16·6	111
CAPE VERDE ISLANDS																					
112. São Vincente	16°54′N	24°04′W	49	—	5	WM	—	11·0	→	←	13·2	→	←	11·9	→	←	9·8	→	←	11·9	112
113. Praia	14°55′N	23°31′W	111	—	10	WM	—	15·2	→	←	14·8	→	←	10·8	→	←	10·8	→	←	13·0	113
114. **St. Helena**	15°55′S	05°44′W	—	—	—	TWA	—	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	114
115. **South Georgia**	54°30′S	37°00′W	—	13	2	U	—	18·4	23·7	15·9	23·5	17·2	15·0	16·8	13·4	13·0	13·9	15·0	15·0	16·8	115
116. **Kerguelen**	49°30′S	70°00′E	—	53	1	U	—	20·6	21·7	19·9	16·4	17·7	20·8	17·0	20·2	20·4	18·2	17·7	19·9	19·3	116

diurnal variation in the wind flow. These conditions could arise when, as in certain places in India for example, the wind speed may be relied upon to increase during the middle part of the day. Naturally, to take advantage of this constancy, arrangements must be made to accept the energy at the times when it is available.

(6.1) Monthly and Annual Average Wind Speeds

The information shown in Table 9 has been obtained from a large number of sources (see column 7). These are listed in the key preceding the table. Annual average wind speeds and, in many cases, monthly average wind speeds, are given for a large number of sites all over the world. In a few cases, three-monthly average values of wind speed are given in place of the more usual monthly values. At only very few of these sites were measuring installations made with the object of determining the suitability of the site for wind power. For this reason, they are often situated in positions with a poor exposure to winds from different directions. In some cases it is probable that the figures given represent only instantaneous values of wind speed at more or less regular times during the day. When possible, the type of anemometer used has been indicated together with the latitude and longitude (where known), the height of the site above sea level, the height of the anemometer above the ground and, finally, the duration of records. This last figure may include periods which are not consecutive in time. No great accuracy is claimed for the figures of height and wind speed as many of them may have been converted more than once from their original units of measurement to those of feet and miles per hour in which they are now given.

Before considering the results in detail it should be remembered that these figures of wind speed are not strictly comparable one with another for several reasons. In the first place, a wide variety of instruments has been used. It is, therefore, most probable that their characteristics will be different in normal fluctuating winds. Even two cup anemometers of the same design but having rotors of different masses give different results in fluctuating winds, in spite of their having identical calibrations in steady winds. With anemometers of such dissimilar types as the Dines pressure tube instrument, the Robinson cup anemometer and the windmill type of instrument, the scope for variation in the result for the same wind flow is much greater. Another point which should be remembered is that a long period of records from a single site may show a gradual lessening in the annual average wind speed. This may be due to the growth of trees or an increase in the number of buildings surrounding the measuring site. Furthermore, the figures quoted in Table 9 will, only occasionally, have been obtained from a site which may be considered to be among the best to be found in the vicinity. It is much more probable that the figures will represent a site which must be classed as " fair " or " relatively poor ". Experiences in the British Isles have shown that, in extreme cases, good sites can be found having average wind speeds twice as high as those at a nearby Meteorological Office station. There seems little reason to doubt that this will also be the case for many of the sites quoted.

From the values of monthly and annual average wind speeds shown, it is clear that the western coast of the British Isles is one of the windiest in the world. This is confirmed in Fig. 7 of Ref. 25 on which are marked lines of equal potential energy output above the oceans. The information shown has been calculated from about fifty years of United States Weather Bureau records from ships at sea, and has been extended to include some coastal districts known to be very windy. Outstanding amongst these areas is one which covers the extreme eastern part of Canada, the New England States and Newfoundland. There appears to be a similar area on the eastern coast of Asia which includes Japan and the Kamchatka peninsula of the U.S.S.R. The set of results from Japan, given in Table 9, bears this out.

Due to the general circulation of the atmosphere from west to east around the earth, the western coasts of continents are invariably windy. The northern Norwegian coast is outstandingly so and, even further south, good sites may be found in northern Germany, France, Spain and Portugal. The west of Canada is also known to be very windy. In the southern hemisphere good sites for wind power may be found in Chile, South Africa, New Zealand and parts of Australia.

Isolated communities—including research bases and the like—situated far from any source of power, will be among those to benefit from the introduction of wind-driven electric generators. Many such island communities are found in the windiest parts of the oceans—St. Helena, South Georgia and the Falkland Islands may be taken as typical examples. Even some of the more accessible islands as, for instance, the Canary Isles, which are not thought to be particularly windy, have surprisingly high annual average wind speeds at some sites. It is, of course, impossible to judge how representative these are without knowing much more about the measuring installations.

Israel may be taken as an example of a country lacking natural energy resources. Long term records of winds over that country were not encouraging. However, a wind survey was inaugurated in 1953 and the first results obtained were very satisfactory. (Ref. 11).

Clearly, the figures quoted in Table 9, and other records of a similar type, play a limited part in the assessment of the potentialities of wind power overseas. Only with a background of experience of measurements made under many different conditions is it possible to examine existing records, and the methods by which they were obtained, and to arrive at a conclusion as to how nearly they may be considered to represent the best sites which may be found in the vicinity.

(6.2) Velocity/Duration Curves

In considering the velocity/duration curves obtained from the E.R.A. sites in the British Isles, it was seen, in Section (5.3.3), that they were all substantially similar in shape. Those sites having a fairly low annual average wind speed were characterized by very few winds exceeding 25 m.p.h., and by long periods of very low wind speeds. For example, at (63) Cranfield, the hourly mean wind speed was less than 8 m.p.h. for 50 per cent. of the year and greater than 25 m.p.h. for only about 1 per cent. of the year. A good site having an annual average wind speed of 25 m.p.h. might have hourly mean wind speeds below 8 m.p.h. for only some 10 per cent. of the year and above 25 m.p.h. for nearly 50 per cent. of the year.

For comparison, several velocity/duration curves for sites overseas have been drawn in Fig. 23. It will be seen that many shapes are represented in this figure.

For convenience, each curve may be examined by considering each of its three component parts as shown in Fig. 24. The three types of curve representing the higher range of wind speeds at each site are shown in the diagrams (*a*), (*b*) and (*c*). It is usual for a very windy site to have a type (*a*) curve at the upper end of its velocity/duration diagram. The Falkland Islands and Heligoland, both exposed island sites, show this characteristic very well. Inland, at a less windy site, curve type (*b*) is more common—see Potsdam. Cranfield (see Fig. 14) exhibits the

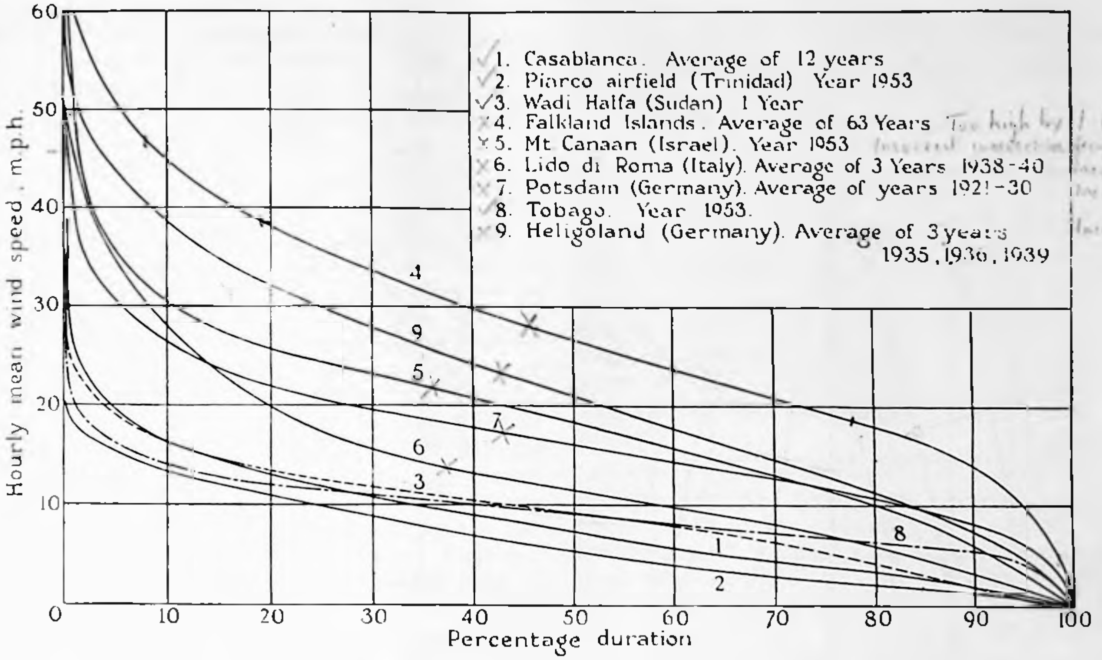


Fig. 23.—Velocity/duration curves for various sites overseas.

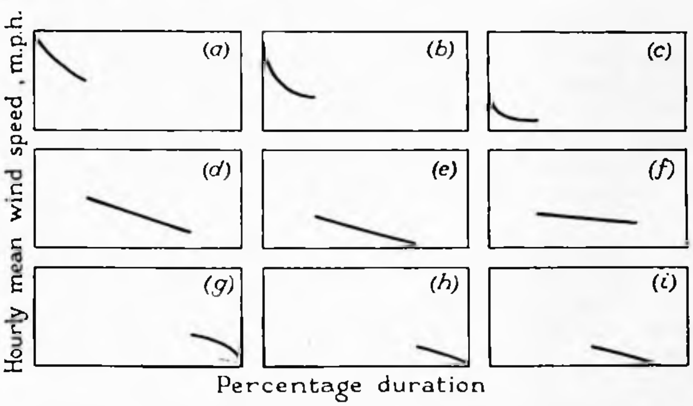


Fig. 24.—Characteristics of wind velocity/duration curves.

(*a*) A windy site having long periods of high wind speeds.
(*b*) Only occasional periods of high wind speeds.
(*c*) Practically no high wind speeds.
(*d*) A windy site having a large range of wind speeds.
(*e*) Average wind speed fairly low, but a wide range of wind speeds exhibited. (This type of curve may be exaggerated by an insensitive anemometer.)
(*f*) Long periods of very steady wind speeds.
(*g*) A windy site with calms occurring only very infrequently.
(*h*) Fairly long periods of very low wind speeds (a sensitive recording instrument in use).
(*i*) Long periods of calms (an insensitive recording instrument in use).

characteristics of curve (*c*). This site has a low annual average wind speed and very high winds seldom occur. Such conditions are common to low level inland sites which are seldom subjected to gales.

The steep middle part of the duration curves for both Potsdam and the Falkland Islands represents a wide range of wind speeds —see curve (*d*). On the other hand, the curve for Tobago shows long periods of low but steady winds—curve (*f*)—a well-known feature of that area. The intermediate curve (*e*) is frequently caused by an insensitive recorder which tends to read low in very low wind speeds. The lower end of a velocity/duration curve is also often distorted by this characteristic of the recording instrument. A sensitive cup anemometer will show a much shorter period of calms than will a Dines anemograph, which is insensitive to the lower wind speeds. However, those concerned with operating wind-driven generators will be interested only in the total period of winds below the *cut-in* wind speed. Any well-exposed site is much more likely to exhibit the characteristic of curve (*g*) than that of curve (*i*).

(6.3) The Diurnal Variation of Wind Speeds

An analysis of hourly mean wind speeds to reveal the diurnal variation has been carried out for several sites in the British Isles (see Section 5.6). Only at low level sites, during one or two of the hottest months of the year, has this been found to reach a significant figure. Similar results for shorter seasonal periods at several sites overseas are given in Fig. 25. Unfortunately, considerations of space prevent more than a representative selection from being included. (See Refs. 6, 8, 24, 35, 38 and 39).

In the four sections of Fig. 25, each smoothed curve is drawn through the points representing consecutive average hourly mean wind speeds during the day. The plotted points may be slightly inaccurate in some cases because they have been extracted from results presented graphically in the references mentioned above. The times given for each site are probably local and are each related, in a different way, to local solar time. That most of the sites are situated in the southern hemisphere is coincidental.

It will be seen immediately that very large variations in mean wind speed take place, during the hotter months of the year. Hobsonville may be considered as an example. The measuring site is situated on a flat headland 60 ft. above sea level and the anemometer is 35 ft. above ground level (see Ref. 24). The effect of land and sea breezes is slight. A layer of cold air frequently accumulates at the surface during the night

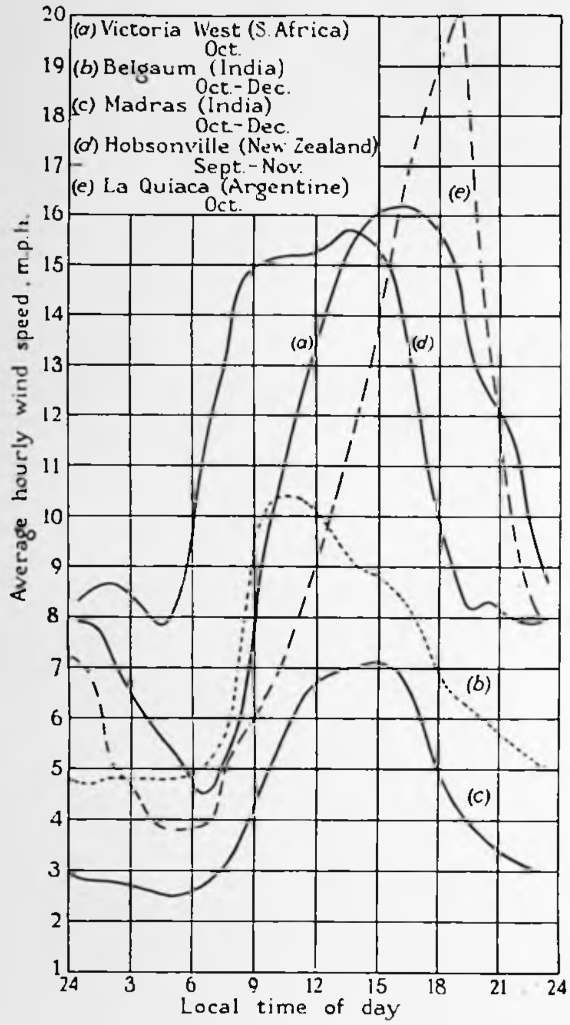


Fig. 25.—Diurnal variation of seasonal average hourly wind speeds for several representative sites overseas. Reproduced from Refs. 24, 35, 38 and 39.

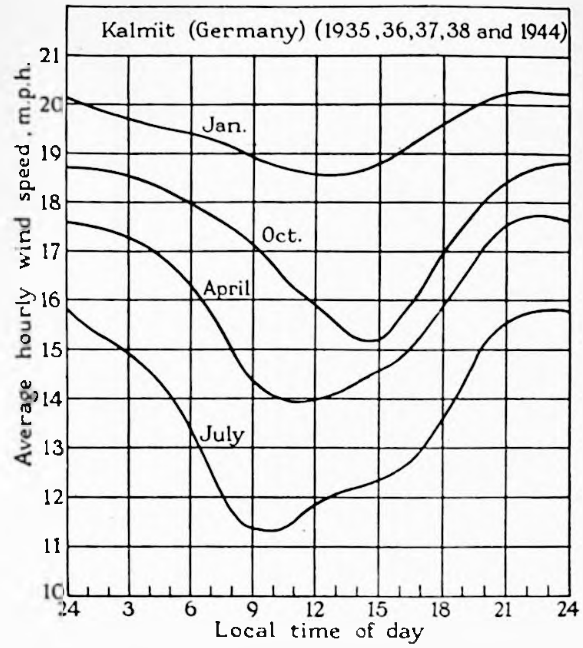


Fig. 26.—Diurnal variation of monthly average hourly wind speeds at Kalmit, Germany. Reproduced from Ref. 8.

when long periods of calms are very common. During the day, however, much greater wind speeds are experienced, as thermal turbulence enables energy to be transferred from the higher levels of airflow. Similar conditions are to be found at other low level sites.

At sites where turbulence in the airflow is caused by obstructions, the diurnal variation is either much less marked or else entirely absent. Many examples may be found amongst the E.R.A. sites and also amongst those which are described and for which results are given in Ref. 8.

In this reference there are also several examples of sites which exhibit a reversal of the normal diurnal variation of wind speed. Four typical monthly curves from Kalmit in South-West Germany are given in Fig. 26. The site is on top of an isolated conical-shaped hill with fairly steep slopes on every side. It is clear that the height of the anemometer places it within the level of the airflow which is slowed down during the day. The actual variation is not large but it is significant during every month of the year. A similar set of results is given for Colonia, Uruguay, in Ref. 6. Unfortunately, a description of the measuring site is not included.

(6.4) Measurement of Wind Speed and Power in the Wind

The information given in the three previous sections has clearly shown the need for comprehensive measurements of wind speed in any region in which the use of wind power is contemplated. Although measurements which have already been made are of undoubted value in estimating the general magnitude of the wind in any area, the great variety of instruments used makes direct comparison of one site with another very difficult. Experiences on the E.R.A. wind survey have convinced the investigators of the value of such a survey. While it was carried out, several types of recording instrument were constructed specially for the work and were later modified in several ways. Descriptions of the two final types of instrument are included in Appendix 2. The experiences gained in the use of anemometers and recording instruments show that great care must be exercised in their choice.

At many stations regular observations of wind speed have been made continuously for long periods without reference to any instrument. An experienced observer, such as a lighthouse keeper or coastguard, can estimate the strength of the wind by reference to its effect upon fixed and moving objects. With practice, an accuracy of 10 per cent. or better may be achieved consistently. In these circumstances, the modified Beaufort scale is most frequently used to express the strength of the wind.

A variety of physical effects have been utilized to measure the speed of the wind. They include the use of a quantity of material disintegrating by nuclear radiation, the semi-conductor effect in thermistors and the cooling effect of air passing over heated wires. There are four distinct types of anemometer which are made commercially and are available for use.

The Dines pressure tube anemograph has already been mentioned and is representative of the group of instruments using a pitot tube head. In these, the pressure difference between the air in the "static" and "velocity" tubes is measured. The Dines anemograph has been used as a standard anemometer by meteorological services all over the world. Because of its high cost, and the need for a building in which to house the recorder, it is unsuitable for use in a wind survey. Undoubtedly records already produced by this type of instrument are of great assistance to those who have to consider the development of different regions for wind power.

Cup anemometers have long been used as standard wind measuring instruments both in this country and overseas. The design of most of these instruments is substantially similar. Although rotors having different rates or factors* are used, the main dissimilarity between instruments is their response to fluctuating winds. (See Appendix 1). The three types of instrument used on the E.R.A. wind survey are also described. The rotors, which are made up of three modified conical-shaped cups, have a factor of nearly 2·98 over most of the working range. As an example of the uncertainty of the calibration of instruments used to obtain early wind records, Ref. 35 may be mentioned. Up to the year 1911, the factor of the cup anemometers used in India was taken as 3·0. In that year the factor was found to be more nearly 2·2, and all earlier records had subsequently to be corrected using the new factor. Overseas, rotors having four hemispherical cups are still widely used although they are gradually being superseded by the modern three-cup design which is generally more consistent in performance.

Windmill anemometers, of which only a few types are available commercially, have an advantage over cup anemometers, in that they do not tend to over-read in fluctuating winds. Their main disadvantage is that the rotor must be maintained at right-angles to the air flow. There are, therefore, errors involved in using this type of instrument in gusty conditions when the wind direction is constantly changing, and consequently there may be some doubt about the accuracy of the results obtained. It may be argued that a windmill would be unable to follow rapid changes in wind speed and direction and that for this reason results given by this type of instrument would be of great value in predicting the output which might be obtained from a windmill. In practice, however, no existing windmill-type anemometer is likely to have response characteristics identical with those of any windmill unless specifically designed with that purpose in mind.

The final group of instruments may be collectively termed pressure-actuated instruments, since they all attempt to measure the wind pressure upon stationary objects placed in the air stream. In the main, they are designed for some particular measuring application and are not generally suited to continuous measurements. Examples of such instruments are the bridled-cup anemometer, the pressure plate anemometer and the E.R.A. gust anemometer.

(6.4.1) An Instrument for Measuring Power

An interesting development of the cup anemometer has been described by P. Ailleret (Ref. 1). This instrument has been used extensively on wind-power surveys both in France and in North Africa.

The anemometer rotor has four cups which are greatly elongated in the vertical direction. Each cup is in the form of half a cylinder closed by a quarter-sphere at each end. The overall length or, more correctly, height, of the cups is about 27 inches and the width or diameter of the half-cylinder is about 2½ inches. The centres of the cups rotate about a circle approximately 6½ inches in diameter. They drive a small, permanent-magnet type a.c. generator which is housed in the base of the instrument. Except at starting, the torque required by the generator is very small. The factor of the cups is nearly 2·0 and remains constant over a wide range of wind speeds. The generator is connected directly to a modified kilowatt-hour meter. The voltage and frequency of the output are directly proportional to the speed of the wind. The electrical circuit is so arranged that the meter integrates a quantity proportional to the cube of the wind speed and hence proportional to the power in the wind. The indicating dial is calibrated in kilowatt-hours per square metre. The actual calibration shows that the instrument starts to operate in winds of between 6 and 7 m.p.h., and follows the cubic law very closely up to about 30 m.p.h. Above that speed, however, the errors increase progressively until the reading is about 30 per cent. low at 56 m.p.h.

Undoubtedly, this instrument is labour-saving in use as it provides a measure of the energy in the wind at any site without the necessity of any attention other than an occasional visit to take a reading. But, at windy sites, which are those likely to be developed first, the inaccuracy at the upper end of the wind speed range is very inconvenient. Even if the accuracy were maintained up to the highest wind speeds frequently encountered at a particular site, considerable additional information about the wind régime at that site would still be required, because the integrated total of the energy in the wind is composed partly of energy derived from winds with speeds above the rated value of a windmill. The proportion of such winds remains doubtful unless previous investigations have clearly established the shape of the velocity/duration curves for the region being studied.

The utility of the French instrument would be considerably enhanced if it were fitted with a device which would control the output voltage of the generator to a value corresponding to the rated wind speed of any projected windmill. An additional refinement would be to provide a cut-in contact to connect the generator to the meter only when the voltage exceeded a value corresponding approximately to the cut-in speed of the windmill. With these modifications the instrument would give a much clearer indication of the potential value of any windmill site, but the prior fixing of the rated wind speed would be a considerable disadvantage.

(7) CONCLUSION

The main purpose of this report has been to present the results of the E.R.A. wind survey up to the end of 1954 and to do so in such a way that the report may be used as a handbook. Since the previous report (Ref. 16) was published, the investigators have seen no reason to alter or modify their views on the procedure to be adopted in carrying out a wind survey.

The preliminary results published in the earlier report have been further assessed and are brought up-to-date. In particular, it has been confirmed that, in the British Isles at least, the annual average wind speed obtained from the run-of-wind over a year may be accepted as a measure of the energy available at any windmill site. The relationship is shown in Fig. 17. Special recording apparatus may be dispensed with when investigating the potential value of any new site in the British Isles. It is sufficient to use a simple counter type of anemometer which needs to be read only at infrequent intervals.

It has also been shown that, if the wind speed is measured over the three summer months, the annual average wind speed may be deduced to within about 2 m.p.h. This may prove to

* The factor of cup anemometers is given by the ratio of the speed of the wind to the linear speed of the centres of the cups.

be useful when quick comparisons of one site with another are required. The basic fact supporting these conclusions is to be found in the similarity of the velocity/frequency and velocity/duration curves of windy sites. Several examples of these have been given, upon which potential operators of wind-driven plant may base their design specifications. A further extension of the results, which depends upon the similarity of wind régimes, is to be found in the curves illustrating the duration of winds above and below certain wind speeds. From these it is possible to predict the number of hours in a year when the hourly mean wind speed will be in excess of the cut-in speed of a windmill. To forecast the total time during which a windmill will actually be working requires more information than is at present available on the variation in wind speed which takes place within the unit of one hour.

Clearly, further analysis is needed of the different types of short-period changes which take place in the wind flow, both over level ground and over hill-top sites. It is only insofar as they assist in such analysis that measurements of wind direction in the British Isles appear to have importance, since no particular wind direction is frequent enough to warrant the consideration of a non-orientating windmill.

The study of the change of wind speed with height is closely linked to the study of air turbulence of both mechanical and thermal origin. Hitherto, it has been thought that turbulence is undesirable on account of the demands which it makes on the strength of any structure which is subjected to it. There appear to be reasonable grounds to suppose that there may be a greater amount of energy available at hill top sites which are regularly subjected to a small amount of turbulence than similar nearby sites which have a smoother air flow. Unfortunately this turbulence may, in itself impose further operating problems. More information about this aspect of wind power will be available when the actual output of a windmill has been compared in detail with the structure of the wind passing through the swept area of its blades.

It has long been realised that different designs of windmill, although nominally rated for the same output from the same swept area in the same steady wind, may actually produce quite different outputs when operating in normal gusty conditions. This discrepancy may be explained by the differing response of the two designs to fluctuating winds. It is hoped that with the aid of gust anemometers developed by the E.R.A., studies will shortly be undertaken to determine the proportion of the available energy which can be extracted from gusty winds by different types of machine. In this connection, a study of the detailed structure of the wind forms the basis of a separate report (see Ref. 34).

From the results of the general wind measurements already made overseas, it is apparent that there are many regions where wind power might be developed successfully. References have already been given in which the economic possibilities are assessed. Little more can be said without first investigating the local wind régimes and the local energy resources. A report (Ref. 18) describes the progress of a pilot survey made specifically to consider what energy resources already exist in, and what use could be made of energy supplied to, a typical under-developed area.

When the development of wind power is under consideration in any new area, experience has shown that it is essential to make careful preliminary measurements of local wind régimes, both at a low level and at a height comparable with the hub height of a wind-driven generator. Only by adopting this procedure will it be possible to avoid such disappointing results as have occurred in the past from time to time. This is particularly important when what might be termed "marginal areas" are under consideration, many of which exist in the lower latitudes. Measurements already made for such sites frequently exhibit a pronounced diurnal variation, and it is essential to find out to what height this variation is continued before planning to make use of it. Disappointing results due to lack of careful preliminary investigations must be avoided if the steady development of wind power is to be maintained. Even in the present age, at the beginning of the development of nuclear power, there is an undoubted need for the parallel development of wind power. Each has its particular role to fill. And it should not be forgotten that nuclear energy is derived from expendable resources, albeit large, whereas wind power makes use of the inexhaustible supply of energy from the sun. Furthermore it is unlikely, in the foreseeable future, that the exploitation of nuclear power will prove economic for very small installations.

(8) ACKNOWLEDGMENTS

The Authors' thanks are due to the Director of the Air Ministry Meteorological Office for permission to publish the information given in Tables 4 and 6b, and also to the Electricity Supply Board, Dublin, who have done so much to help in obtaining the information on wind speeds in Eire. With over a hundred sites scattered widely over the British Isles, it is impossible to name and thank all those who have contributed to the work of the wind survey.

Permission to make wind measurements has been freely given by the owners of sites to which the local operators have made regular weekly visits, often in appalling weather conditions. This co-operation, without which the survey would have been impossible, is acknowledged with gratitude.

The author would also like to thank Mr. E. W. Golding for his untiring encouragement and assistance, Mr. A. H. Stodhart, who did much of the installation of instruments and early analysis of results, and his other colleagues in the E.R.A. who manipulated the many pages of necessary but rather uninteresting figures.

APPENDIX 1

Anemometers and Supporting Structures used on the Wind Survey

When the wind survey of the British Isles was initiated, no propeller type of anemometer was both readily and cheaply available in this country. On the other hand, cup anemometers had long been manufactured by several firms. These instruments tend to over-estimate mean wind speeds in gusty winds but they were, in the main, sufficiently accurate for the purpose of the survey. Although several designs were available, the investigators decided to use anemometers of the Air Ministry Meteorological Office pattern throughout. These have a common form of rotor with three modified conical beaded-edge cups, each five inches in diameter. The cups are mounted on horizontal arms attached to a central vertical spindle. The radius of the path traversed by the cup centres is 6·3 inches.

The ratio of the distance travelled by the wind to the distance travelled by the cup centres has a mean value of 2·98. No calibration corrections are necessary as the wind speed indicated by these instruments is within ± 1 m.p.h. of the true wind speed throughout the range. A full description of one type of anemometer used on the wind survey—the *cup-contact anemometer; Mk. III*—is given by G. E. W. Hartley (see Ref. 21). In this type of instrument, the vertical spindle is arranged to tilt a mercury switch at intervals, and so make an electrical circuit between the two terminals. The mechanism is such that twenty contacts are produced for every mile of wind passing the anemometer. Normally, these contacts are integrated by a recorder (see Appendix 2). For reliable operation, it is necessary to mount cup-contact anemometers within 2° to 3° of a truly vertical position. In addition, the supporting pole should hold the anemometer steady even in the highest winds to prevent the mercury switch making spurious contacts. Unfortunately, at wind speeds above about 60-70 m.p.h., this proved to be impossible when using the light portable poles constructed for the E.R.A. wind survey. For this reason it was impossible to produce any reliable figures for the maximum run-of-wind during any one hour. Undoubtedly, wind speeds well in excess of 70 m.p.h. were recorded occasionally, but their actual magnitude remains unknown. Any conventional windmill would certainly be designed to furl at these high speeds and it is, therefore, sufficient to quote their duration where known.

Occasionally, during the early stages of the wind survey and at some particularly inaccessible site, a cup-contact anemometer was used on a 10 ft. pole at the top of the hill. Twin field telephone cables, up to half a mile long, were then taken from the instrument down the hillside to some more convenient spot. Here, one of the E.R.A. *seven-figure electrical counters* was used to integrate the impulses produced by the anemometer. The run-of-wind total could then be read from the lower slopes of the hill by the local observer.

The electrical counter was a modified message register housed in a small metal box. Three extra number wheels were added to the normal complement of four wheels so that up to $9{,}999{,}999 \times 1/20$ miles could be accommodated before the counter returned to zero. A sensitive high-speed relay, also housed in the box, was connected between the anemometer and the counter. When energized by six $1\frac{1}{2}$-volt bell cells, the counter would work successfully with a line resistance of over 200 ohms.

The cup-counter anemometer Mk. II was the type of instrument most frequently used on the wind survey. An integrated total of the miles of wind passing the anemometer is indicated directly on the six-figure revolution counter driven by the central spindle. A total of 9,999·99 miles is indicated before the number train automatically restarts at zero.

During the later stages of the survey a *long-term cup counter anemometer* (Fig. 27) was found to be more economical and reliable than the combination of a cup-contact anemometer with a seven-figure electrical counter. This instrument was made by fitting a 10 to 1 reduction gear box to the main driving spindle of a standard cup-counter anemometer. Apart from the construction of the gear box itself, only a small amount of machining was needed on the body of the anemometer to provide three smooth surfaces for the fixing lugs of the gear box. The modification simply increased, by a factor of ten, the number of miles of wind which could be integrated by the number train before it returned to zero, thus removing any likelihood of the readings being misinterpreted if the normal period between them were exceeded for any reason. Such a gap might be caused by winter snow or fog conditions for instance, or by the illness of the local observer. The maximum permissible period between readings has been shown to be about a month—see Section (4.1).

Response of Cup Anemometers

In this report, the readings from all three integrating instruments described above have the same form—an integrated total of the run-of-wind, in miles. Similar results are also obtained from the combination of cup-contact anemometer and recorder, by adding together all the recorded values of hourly mean wind speed.

All four combinations of instruments use the same modified conical form of three-cup anemometer rotor assembly, as described earlier. For the practical purposes of the wind survey, the friction or instrument loading of each anemometer may be considered to be similar over the more important range of measurements, i.e., upwards of 5 m.p.h. Thus it has been assumed that in any normal fluctuating wind, all four installations will produce substantially similar readings.

It was realised at the beginning of the wind survey that in a fluctuating wind there was a doubt about the accuracy of the readings of a cup anemometer. Schrenk (Ref. 28) calculated that the amount of over-reading by an anemometer with hemispherical cups might be as high as 20 to 30 per cent. in extreme artificial conditions. Experiments by Scrase and Sheppard (Ref. 29) suggested that use of the modified conical cups, now standardized by the Meteorological Office, might result in significantly smaller errors. Still later, Deacon (Ref. 9) refuted this suggestion. His own work showed that in fluctuating winds both hemispherical and conical cup anemometers tended to over-read by similar amounts. It was agreed that the error could be reduced by making the cups as light as possible, consistent with adequate strength.

In experiments carried out at Costa Hill (Ref. 16), a comparison was made between the readings of a Dines pressure tube anemograph, a cup-contact anemometer and recorder, and a newly developed balsa-wood windmill anemometer.* In a continuous period of 24 hours, it was seen that the mean hourly wind speeds recorded by the cup-contact anemometer differed by only one mile per hour from the speeds recorded by the other two instruments. The agreement was in fact closer than was shown as the figures were only given to the nearest mile per hour.

In discussing the errors of cup anemometers in fluctuating winds, it should be remembered that these instruments, which are cheap to produce, are unlikely to be replaced by more accurate anemometers for several years to come. Until that time, most measurements made to ascertain the wind power potentialities of any site will, if only for economic reasons, be made with cup anemometers. It is, therefore, important to compare the performance of prototype windmills with the outputs calculated from cup anemometer readings. Only then will it be possible to predict accurately the amount of energy which may be expected from any potential windmill site.

Anemometer Supports

In Section (5.5.1) it was shown that the frequently observed relationship between the wind speed at different heights over level ground did not apply to hill tops. It was found that the normal relationship showing an increase of wind speed with height applicable to level ground might be reversed in certain conditions. It was thus incorrect to assume a knowledge of the wind speed at any particular height by reference to the known

* A description of the balsa wood windmill anemometer appears in another report (Ref. 34). It has a rotor assembly of four very light balsa-wood paddle wheels which rotate about a horizontal axis. The spindle is held in line with the wind by a single tail fin. The rotor drives a small permanent-magnet electric motor, the rotational speed of which may be measured electronically or by photographic means. The instrument is designed to follow changing wind speeds with great accuracy.

wind speed at some other height. For this reason, it was impossible to assess the relative value of different hills, from the point of view of wind power, unless measurements of the wind were made at the actual height of the rotor of any proposed machine. In the circumstances, the best that could be done was to specify a common height of exposure for all anemometers.

The Beaufort scale relates its effects to the uniform anemometer height of ten metres (33 feet) which is widely used throughout the world. More practical considerations fixed the height of the instruments used on the E.R.A. wind survey. Where all weights had to be carried up the hills it was desirable that the poles should be as short and as light as possible, and yet sufficiently rigid to hold the instruments steady in high winds. The height finally chosen for all cup-counter anemometers was 10 ft. and the usual height for cup-contact anemometers with recorders was fixed at 30 ft.

At first, wooden poles were used, but later a more convenient design was evolved using light aluminium tubing $1\frac{3}{4}$ inches in diameter. Three easily made steps were attached to the lower end. A length of half-inch gas thread fixed to the upper end provided a support upon which the body of the anemometer was screwed. The pole was held upright by six guy wires each tensioned by a small screwed strainer. The guys, running in three directions, were attached three to the top and three to the centre of the pole. The three anchorages were formed by short lengths of angle iron, pointed at one end so that they might easily be driven into the ground. This design (Fig. 28) resulted in a very rigid pole capable of withstanding the strongest gales and yet light enough to be carried easily by two men.

Thirty foot Anemometer Poles

The first cup-contact anemometers were mounted on a very light but very stiff form of lattice mast, made in 15 ft. sections, two of which were bolted together to hold the anemometer at a height of 30 ft. above the ground. Later the anemometers were mounted on 30 ft. long aluminium poles. A photograph of one of these is shown in Fig. 29. The design is similar to that of the 10 ft. pole except that it is split into three sections for ease of carrying. Nine guys, each tensioned by a strainer, are attached to the pole in three groups of three. At their lower ends, one guy from each group is attached to each of three anchorages formed by driving angle iron pickets into the ground. Occasionally, in soft ground, it is necessary to reinforce a single picket by wiring it back in tandem with a second, to provide a more secure anchorage. As in the design of the 10 ft. poles, the anemometer is screwed on to a length of half-inch gas thread fixed to the top of the pole. Two-core flexible cable insulated with polythene and sheathed with P.V.C. is used to connect the anemometer mercury switch with the recorder. It is strapped to the pole with hose pipe clips or insulation tape. No provision is made for climbing the pole as a team of three men can lower and re-erect it in a matter of minutes.

APPENDIX 2

Recording Instruments used on the Wind Survey

The methods of recording the indications of cup-contact anemometers have been developed continuously since the first instruments were used in Orkney in 1948. It will be appreciated that the conditions obtaining on a wind-swept hilltop are very different from those to be found in a laboratory. The instruments were to be used on hills whose summits were often covered in cloud. At sites on the west coast, frequent on-shore winds would bring salt-laden air and even sea spray to hasten corrosion. To keep the instruments dry, either by constructing walk-in shelters or by providing a source of heating, would have increased the cost of the survey many times over. Only at one site was it possible to use a mains supply of electricity. This was at Costa Hill, Orkney, the site of the first 100 kW windmill installed in Britain. On first considering the problem, it might be thought convenient to obtain an electricity supply from batteries charged by small wind-driven generators, but experience has shown that they are not normally designed to withstand the severe conditions frequently encountered at such exposed sites. The only alternatives appeared to be in the use of wet or dry Léclanché cells or batteries charged by small petrol electric sets. Thus, it will be realised how essential it was to limit, as much as possible, the electricity requirements of any instruments used.

Previous experience with pen and ink recorders had shown them to be unsuitable for use in such conditions. No other commercial recording instruments needing only a small power supply were available, so that entirely new instruments had to be designed and built specially for the work.

Photographic Recorder

Two instruments of this type were originally built for use in Orkney, as mentioned in Section (2.1). They have been described in an E.R.A. report (Ref. 27). Briefly, the design allows for the use of four or five cup-contact anemometers and the indicator of a remote indicating wind vane. The contacts produced by the anemometers were integrated by message registers. The wind direction indicator was modified by the substitution of a thin aluminium disc for the pointer. The disc, suitably marked with an angular scale, and the message registers were all housed in line on one side of a light-tight box. At hourly or half-hourly intervals they were illuminated for a few seconds, and a photograph was taken of the figures on a strip of recording paper. A prism, together with a normal lens, provided a convenient means of obtaining an image in the correct sense. The photographic recording paper was driven by clockwork, the message registers were energized by wet Léclanché cells and the two bulbs used to illuminate the figures were run from a 12 volt accumulator. Although this equipment proved to be most reliable in use, the accumulator needed frequent recharging and the Léclanché cell elements had to be renewed approximately every year. In addition, the use of a photographic method of recording imposed inconvenient restrictions upon the handling of the records.

Impulse Recorder, Series 3, Mk. II

In order to avoid all these disadvantages, the first E.R.A. impulse recorder was developed to use, as the marking medium, an inked typewriter ribbon. The original Series 1 impulse recorder (Refs. 15 and 16) was modified through seven different Mark numbers and is now designated the " E.R.A. impulse recorder, Series 3, Mk. II " (Fig. 30).

Basically, the recorder consists of a standard eight-day clockwork mechanism which is arranged to drive a paper chart at a rate of three inches per hour. A self-contained dividing mechanism is used to produce one electrical impulse for every forty impulses arriving from the anemometer. It will be remembered that each impulse from the anemometer represents one-twentieth of a mile of wind, so that each impulse from the dividing mechanism represents the passage of two miles of wind past the anemometer position. As each impulse occurs, it energizes a solenoid which, in turn, moves a marker arm to press a typewriter ribbon against the chart and so make a small dot. The ribbon is driven continuously by the clockwork motor to prevent its being dried out at any one spot. On the resulting records, the mean wind speed is obtained by counting the number of spaces between the dots, which occur on each three inch length of chart. The chart itself is 4½ inches wide and allows up to four channels to be recorded side by side. It is provided with time marks, but only so that it may be set on the recorder—any other scale marks are unnecessary.

The marker solenoids are modified Post Office (Type 3000) relays mounted horizontally. A small metal arm is fixed to the armature which is held in its unoperated position by a light spring. The frames of the solenoids, up to four in number, are fixed to a removable saddle which also carries the inked ribbon across the paper chart by means of two small pulley wheels and two small guide pins. The distance of each marker arm above the paper and inked ribbon is adjusted by means of shims underneath the screws fixing the frame of the solenoid to the saddle. Once this height has been set to obtain legible dots no further adjustment is required. A plug and socket electrical connection is provided to enable the complete saddle and marker solenoids to be removed bodily from the recorder clock. This greatly facilitates changing the paper charts every week. At the same time as the paper chart is replaced, the inked ribbon is re-wound from the take-up spool back onto the stock spool.

Provision is also made for mounting up to four of the dividing mechanisms on the pressed steel chassis. The electrical connections are made by means of plugs and sockets, whilst the dividing mechanism is held in position by captive screws. The design ensures that the units are easily replaced on the site by unskilled operators, should this be necessary. It also allows an interchange of units having different dividing ratios to provide for the recording of impulses from other types of instrument—for example from impulsing kilowatt-hour meters.

The dividing mechanism is illustrated diagramatically in Fig. 33. The operating solenoid of the unit is wired in series with a 6–8 volt d.c. supply usually obtained from four or five large dry Léclanché cells. When the mercury switch in the anemometer closes, the solenoid is energized and the armature moves the ratchet wheel, together with the disc carrying the contact pins, through 1/120 of a revolution. The same movement closes the contact of a small micro-switch which is wired in series with a second set of normally open contacts. The spring leaves of this pair of contacts are controlled by two pivoted arms which are lifted together by each of the contact pins carried in the rotating disc. The two arms are of the same length, but the ends may be displaced relative to each other so that one arm falls off a pin before the other, and makes the contact. Two adjustments are provided—one to fix the absolute position of the arms relative to the steps in the movement of the contact pins, and the second to fix the relative displacement of the ends of the two arms themselves. This mechanism is exactly the same as that used on many well-known time switches. In operation, the standard divider mechanism with three contact pins produces one outgoing impulse, through the two sets of contacts wired in series, for every forty impulses arriving from the anemometer. Furthermore, the length of the single outgoing impulse is the same as that of the corresponding incoming impulse from the anemometer. This is an essential feature of the recorder and is necessary to prevent an excessive discharge of the dry batteries.

Both the marker solenoid and the dividing mechanism solenoid have fairly high inductances which result in high transient voltages appearing across the dividing mechanism and anemometer contacts respectively. These transient voltages are suppressed by small metal rectifiers which greatly increase the life of the contacts.

The design of the dividing mechanism also caters for the inclusion of a sensitive high speed relay in the electrical circuit between the anemometer mercury switch and the operating solenoid, thus enabling the recorder to be operated at the end of a long line connecting it to the anemometer.

Once one of these instruments had been set up and the clock adjusted to run correctly, it was found to give satisfactory service for many months and, in some cases, for over a year. Most of the troubles experienced could be attributed to faulty handling

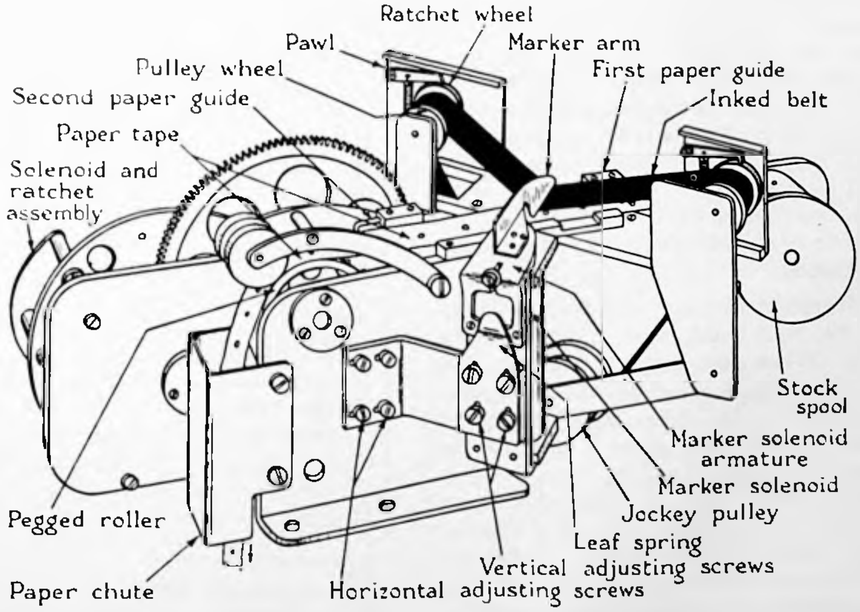


Fig. 32.—Construction of E.R.A. impulse recorder, Series 2.

of the recorders. Many of the operators were unused to manipulating fairly delicate equipment and their task was not eased by the conditions under which they often had to work. In spite of these hazards, this type of impulse recorder was used successfully to obtain most of the records up to the end of 1954.

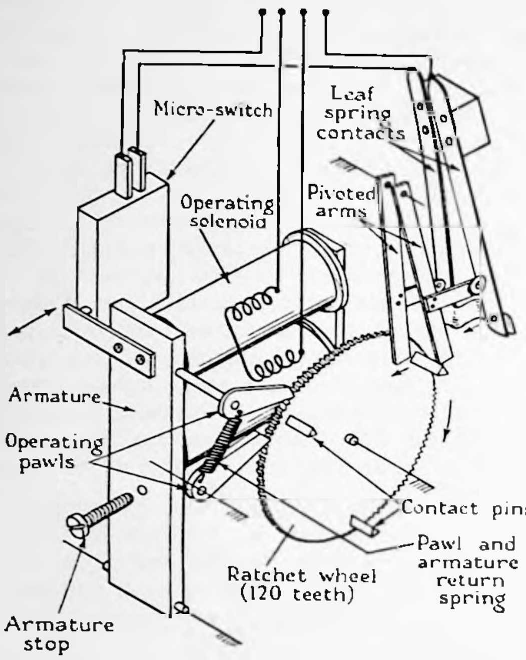


Fig. 33.—A diagram of the dividing mechanism used with the E.R.A. impulse recorder, Series 3.

Impulse Recorder, Series 2, Mk. IV

Early in 1953, efforts were made to evolve an even simpler recorder. It was designed primarily to be foolproof in the hands of anyone inexperienced in handling such instruments. The latest version is the E.R.A. Impulse Recorder, Series 2, Mk. IV (see Fig. 31). The main parts of the recorder are shown in Fig. 32. It will be seen that it has the same type of solenoid pawl and ratchet wheel unit as was used in the divider mechanism of the Series 3 impulse recorder. The solenoid is wired in series with the anemometer mercury switch and is energized by four or five dry Léclanché cells. As in the Series 3 recorder, operation of the mercury switch causes the ratchet wheel to turn through 1/120 of a revolution. In this case the intermittent movement of the ratchet wheel has been transmitted by a simple gear wheel and pinion to a special pegged driving wheel conveniently obtained from a standard recorder clock. The gear ratio is so chosen that in the normal instrument the circumference of the driving wheel moves at a rate of one inch for every sixteen miles of wind passing the anemometer.

Paper charts, ½ in. wide and 65 ft. long, were obtained with perforations to match the nine small pegs equally spaced around the driving wheel. When placed on the recorder, the unused chart is held on a free running spool which may be seen on the right hand side of Fig. 32. The loose end is led through two paper guides, over the driving wheel and out through the bottom of the recorder case by means of a chute. It is held in contact with the pegs of the driving wheel by a light aluminium roller. No provision is made to re-roll the chart; it is allowed to fall loosely into a box. Two small ball bearings are used on the main driving wheel spindle and another is used on the solenoid ratchet wheel spindle to reduce friction as much as possible.

A marking solenoid is mounted on one side of the body of the recorder. The armature is held in its unoperated position by a light spring. A marking arm fixed to the armature projects diagonally over the paper tape. An endless inked typewriter ribbon is passed at right angles to, and underneath, the marking arm, and thence round the body of the recorder via three small pulley wheels. The two upper pulley wheels are allowed to turn in only one direction by means of small pawls and ratchet wheels. The third and lower pulley wheel merely serves to tension the inked ribbon.

The marker solenoid is wired in series with a time switch and also with the same dry cells which are used to energize the main driving solenoid. When the time switch operates, the marking arm presses the inked ribbon against the paper, makes a small dot and simultaneously moves the inked ribbon round a short distance. This movement prevents the ribbon from drying out at any one spot.

In some of the recorders, provision has been made for operating the instrument at the end of a long line connecting it to the anemometer. Total line resistances of up to 200Ω are permitted by the use of a sensitive high speed relay between the anemometer mercury switch and the main operating solenoid. The relay is brought into operation by means of a change over link. High transient voltages are prevented from appearing across the main operating solenoid by means of a small metal rectifier which remains in circuit both during normal operation and also when the relay is connected. In this type of recorder the marker solenoid is energized only once every hour by the time switch and it was therefore not considered necessary to protect the time switch contacts.

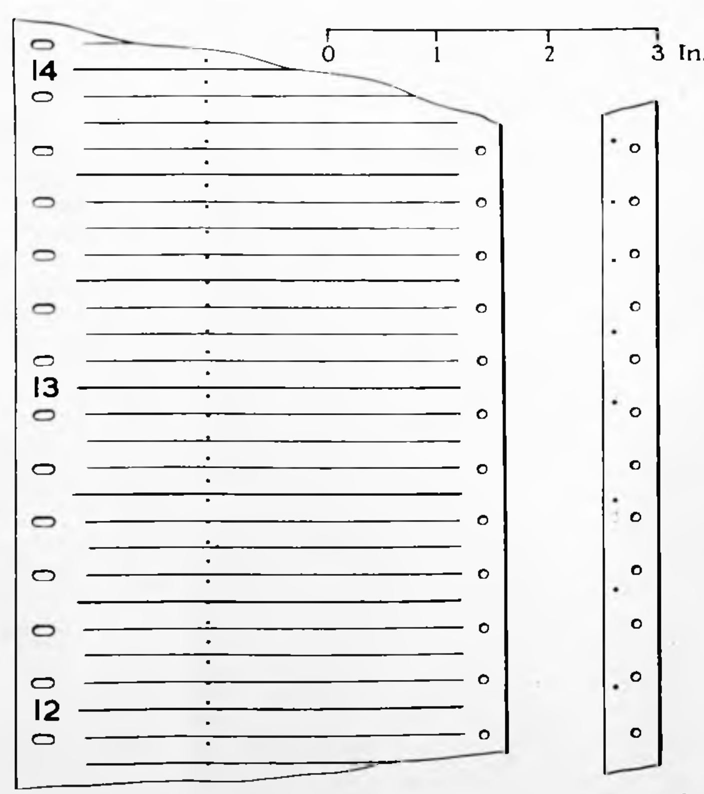


Fig. 34.—Sections of records produced by the E.R.A. impulse recorders, (*a*) Series 3, and (*b*) Series 2.

On the records obtained from this type of instrument, the distance between each successive dot when measured in sixteenths of an inch gives the mean wind speed directly in miles per hour. A special chart analyser has been made. It has a transparent marked scale, hinged to a platform and suspended between two chart spools each fitted with a handle. In use, the chart is transported across the platform from one spool to the other and each mean wind speed is read off on the scale in turn.

The 65 ft. chart lasts for over a fortnight at any site with a mean wind speed of 30 m.p.h. Since the movement of the chart is directly proportional to the wind speed, it lasts for correspondingly longer periods of time at less windy sites.

Some of the larger types of dry Léclanché cells used with this recorder have sufficient capacity to last from four to six months. In some conditions found on the wind survey thay have had an even longer life. To avoid loss of records due to the complete discharge of the batteries, the operators were usually instructed to replace them when the voltage dropped below about one volt per cell. A small voltmeter controlled by a switch is permanently wired across the battery terminals to enable the operator to make this measurement.

In use, this type of recorder has been found to be extremely reliable. The absence of any method of re-rolling the chart has resulted in a very simple mechanism—an important advantage when the instrument is placed in the hands of an unskilled operator.

No trouble has been experienced in this country during calm periods which might result in the hourly dots being printed very close together. It is possible to resolve two dots made only " 3/20ths of a mile " apart. Such low hourly mean wind speeds rarely occur; so far during the wind survey no example has been found.

Undoubtedly the main reason for the reliability of this method of recording lies in the fact that the time switch requires no attention other than the winding of the clockwork mechanism once a month. Indeed, a similar time switch incorporated in one of the photographic recorders mentioned earlier has given perfect service on different hill sites for six years. During this time the clockwork movement has received no attention whatsoever.

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S.P.(E.I). 110

To see pl.

[signature]
3/x/58

H.E.S. 111

I have only glanced through the publication, it would appear that the F.Is is an ideal plan for such units: but to the best of my knowledge none are in production as yet.

[signature] 6-10-58.

112.

H.E.S.

108 – 111 f. i. p.

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B.U. 30/11 (...)
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113

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WINDMILL RESEARCH STATION
HIGH STREET
CRANFIELD
BLETCHLEY, BUCKS.
TELEPHONE: CRANFIELD 391

YOUR REFERENCE

OUR REFERENCE JRT/MP

4th September, 1958.

P. A. Canning, Esq.,
Chief Meteorological Officer,
Meteorological Service,
Falkland Islands.

METEOROLOGICAL OFFICE FALKLAND ISLANDS 30 OCT 19..

Dear Mr. Canning,

I have been examining the wind records from Sapper Hill and Port Stanley, which you kindly sent to us last year. You will, of course, already have noticed the consistency of the wind régime on the hill site. The variation in average wind speed is slight - 23.5, 24.4 and 24.2 m.p.h. during each of three years - and the differences between the velocity/duration curves are correspondingly insignificant.

On reading your letters, it is clear that you have not seen our recent report C/T 115. I am, therefore, ~~enclosing~~ sending you a copy. You will notice that for the sake of consistency, we have slightly modified our method of obtaining figures of specific output from wind records. When comparing sites, we do not normally take any account of the overall power coefficient, or indeed of its variation, since it will be peculiar to only one particular design of windmill.

In examining your results, I have taken an average of the three years of records from Sapper Hill, and I have applied our standard method of analysis to them. This is shown on the attached sheets. The figures of specific output for different rated wind speeds are in close agreement with the results obtained from sites within the British Isles, as shown by Fig. 17 in C/T 115.

The results from Sapper Hill are not strictly comparable in detail with results from our own survey, since you used a cup generator anemometer and recorder. For instance, this type of installation is particularly insensitive to low wind speeds as shown by your tables of figures. Very few hours are registered with average wind speeds below 4 m.p.h., whereas the duration of calm periods is quite large. To some extent this may be due to the method of analysis. I know that it is particularly difficult to decide accurately what average windspeed each hour of the recording represents.

As you say in your letter, the results are very encouraging, and show that there is ample wind at Sapper Hill for electrical generation by wind power to be a reasonable proposition. The only unknown is the cost of suitable plant.

At the risk of being tedious, may I repeat what is only simple arithmetic? You have a site which may well provide over 4000 kWh of energy per annum for each kilowatt of installed capacity. Annual charges may be taken as 10% - a not unreasonable figure. If you can purchase wind driven plant for £100 per kilowatt, then each unit of energy produced will cost 0.6d. It is, of course, assumed that a load exists to absorb all the energy available.

You have a good site at Sapper Hill where a suitable machine should give you the output you expect. Because of local conditions, the annual charges might be a little higher. The problem remains that of finding a wind driven generator to produce energy at a competitive price.

We at Cranfield have recently completed a series of tests on a 25 kilowatt machine constructed by Dowsett Holdings Ltd., of Tallington, Stamford, Lincs. It has now been removed to the Isle of Man for further tests on a much windier site. As at Cranfield, it will be operated in parallel with the main electricity supply network. We hope to be able to carry out further tests on this machine during the coming winter. I mention this because I have reason to believe that this firm is actively engaged in developing other and larger wind driven plant suitable for network or isolated operation. It is possible that one of the machines they are intending to produce may be suitable for conditions in the Falkland Islands.

I hope that you will find my comments helpful, and I look forward to hearing more of your progress in this work.

Yours sincerely,

J R Tagg

J. R. Tagg.

YEARS 54/55 55/56 56/57 Vf | Vdi 1 1 2 | % | mph | SAPPER HILL (FALKLAND Is) 8/115

KNOTS	54/55	55/56	56/57	Vf	Vdi 1	Vdi 2	%	mph	DEC	YEAR
				–	23637	23637	100	0		
0	68	142	70	80	23357	23497	99.5	0		
1	21	1	0	22	23335					
2	11	7	9	27	23308	23322	98.5	2.3		
3	32	24	26	82	23226					
4	20	42	68	130	23096					
5	74	128	96	298	22799	22948	96.8	5.8		
6	120	155	178	453	22346					
7	181	225	191	597	21749					
8	113	167	143	423	21326					
9	139	145	118	402	20924					
10	158	182	233	573	20351	20637	87.3	11.5		
11	236	249	241	726	19625					
12	212	242	216	670	8955					
13	295	315	341	951	8004					
14	262	310	264	836	17168					
15	331	316	268	915	16253	6710	70.7	17.3		
16	316	268	305	889	15364					
17	370	341	368	1079	14285					
18	341	286	314	941	3344					
19	337	244	321	952	2392					
20	314	349	405	1068	1324	1858	50.1	23.0		
21	290	261	321	872	0452					
22	281	270	322	873	1579					
23	259	241	330	830	3749					
24	271	258	344	873	7876					
25	245	284	271	800	7076	7476	31.6	28.8		
26	278	281	272	786	6290					
27	225	232	206	663	5627					
28	217	188	185	590	5037					
29	189	144	178	571	4526					
30	224	152	214	590	3936	4231	17.9	34.6		
31	181	169	165	515	3421					
32	164	117	130	411	3010					
33	144	130	142	416	2594					
34	136	130	123	389	2205					
35	80	102	84	266	1939	2072	8.75	40.3		
36	93	113	88	294	1645					
37	70	74	106	250	1395					
38	54	55	74	183	1212					
39	51	65	54	170	1042					
40	54	73	82	209	~~918~~ 833	1038	4.4	46.0		

LEA 301/a

	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
41	33	34	57	124	709								
42	26	19	38	83	626								
43	30	40	25	95	531								
44	16	15	30	61	470								
45	18	20	26	64	406	438	1·8	51·8					
46	21	20	27	68	338								
47	16	12	24	52	286								
48	20	9	11	140	146								
49	7	9	11	27	119								
50	7	13	18	38	81	100	·42	57·5					
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54	3	0	6	9	25								
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LEA 301/b

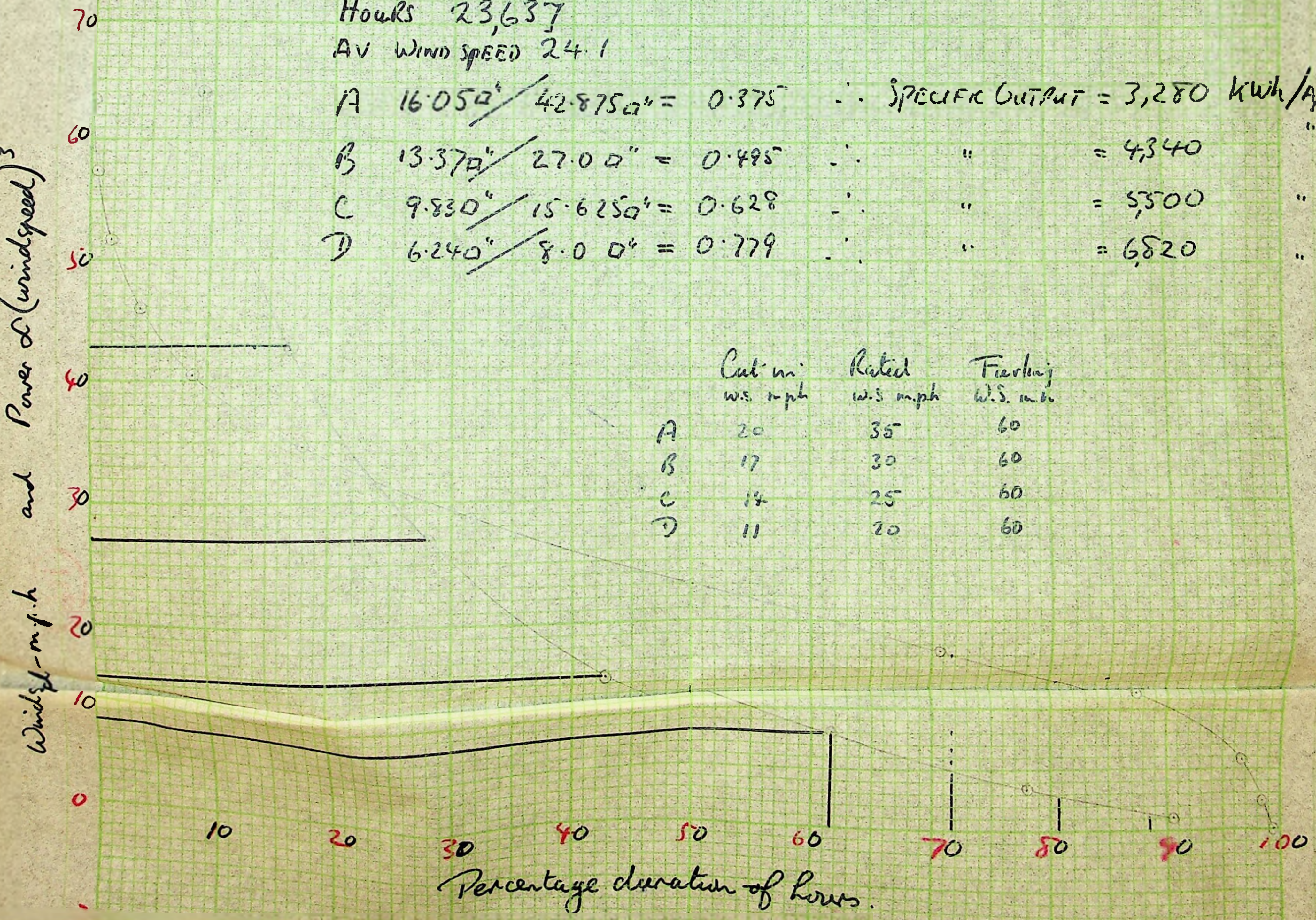
SAPPER HILL
(FALKLAND IS.)

AV of YEARS 1954/5/6/7 (3yrs)

HOURS 23,637
AV WIND SPEED 24·1

A 16·050"/42·875a" = 0·375 ∴ SPECIFIC OUTPUT = 3,280 KWh/A/KW
B 13·370"/27·00" = 0·495 ∴ " = 4,340 "
C 9·830"/15·625a" = 0·628 ∴ " = 5,500 "
D 6·240"/8·00" = 0·779 ∴ " = 6,820 "

	Cut in W.S. m.p.h	Rated W.S. m.p.h	Feathering W.S. m.p.h
A	20	35	60
B	17	30	60
C	14	25	60
D	11	20	60



H.C.S.

Please see 113-116 which arrived by ~~this~~ mail. We obviously have an ideal site at Sappers Hill, but the old problems remain. (a) Waste during the day & shortage coming at night (b) ~~[illegible]~~ there is no suitable equipment in production.

P.R.B. 4/11/58

118.

Noted - thank you. [illegible] 12 months or [illegible] [illegible] [illegible]

[illegible]

[illegible]

[illegible]

B.a. 6/11/59

DIRECTORS
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119

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U.K. Trade Correspondent,
c/o the Colonial Secretary,
Stanley,
Falkland Islands.

-4 NOV 1958

120 Lab Cino see
& 121 seen.
122

Dear Sir,

On the advice of the Export Services Branch of the Board of Trade we are sending you under separate cover, by air mail, a number of brochures describing a windpower generator which we hope to market in your area.

The Dowsett Organisation has long been aware of the need for a device to supply cheap electrical energy to the many isolated communities throughout the world. Windpower is a natural application in inaccessible areas where the cost of diesel fuel is exceptionally high, and where the distance from a generating source is such as to make the cost of transmitted energy prohibitive.

A machine which produces 31 KVA at 415/240V, 3 phase, 50 cycles/sec. in a wind speed of 25 m.p.h. has been perfected and is now in production. Since the force of the wind in your territory is sufficiently high to make the utilisation of such a machine an economic proposition we feel certain the wind generator will be of interest to establishments in the outlying districts.

From enquiries received to date it would appear that the following are most interested in the application of windpower:-

1. Government Departments such as the Ministries of Commerce, Economic Affairs, Power, Defence and Communication.

2. Engineers in charge of electricity supply undertakings.

3. Area mains engineers.

4. Industrial and Scientific Research Organisations.

5. Persons living in isolated establishments.

6. General merchants and importers.

continued/......

continued/.......

We would greatly appreciate your help in bringing our product to the notice of such interested parties, and thank you for your kind assistance in our venture.

Further copies of the brochure will be sent on demand.

Yours faithfully,
for and on behalf of
DOWSETT HOLDINGS LTD.,

H. L. JEFFERIES.

K.L.V. 118

Bu.
6/11/59.

126.

Record.

15. C.M.O. is considering sending this to Fox Bay. On H.C.S.'s instructions I informed C.M.O. by note that the cost of dismantling & freight must not result in the busting of the vote Head VIII Item 3.

[signature]
28/2/59

15/3
~~26/2/60~~

B.U. on ~~26/11/59~~

[signature]
28/?/59.

Hcs

127.

118.

This file keeps coming up periodically to K.I.V. - the file may now be P.A.?

P2

15/3/60.

Spoke

B.E. 15.3.61

128

SPF

Would you please vet this file when you next come.

13/3/61

Shadow File

30/3/61.