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The future of upland Britain

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31 Potential power generation from large wind turbine generators sited in upland areas of Britain

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INTRODUCTION

It is well known that the wind has been exploited as a source of energy for many centuries. It has often, however, been resorted to only when alternative sources of power or local circumstances are difficult. The lack of widespread acceptance and use can be attributed to three important factors:

(i) air is of low density and relatively large and expensive devices are necessary to recover its kinetic energy;

(ii) wind is unreliable as a steady source of power (although in the longer term it is a fairly consistent source of energy);

(iii) the power in the wind is proportional to the cube of wind speed; since average wind speed can vary substantially, even within a particular locality, careful attention to siting is critically important.

The latter two points can be particularly restricting for small plant serving an autonomous system. The effect of wind intermittency is most serious, since storage capacity or diesel reserve must be installed to ensure security of supply, and the total cost of the system may be quite high. Also, siting options are limited, being usually tied to within a few hundred metres of the load to be supplied. This limits the wind speed available and therefore the potential energy output and economics of the system. Connection of large wind turbine generators to the network offers a solution to the problems of both storage and 'optimum' siting. The need for storage can be obviated using the plant in a 'fuel saver' mode; that is treating it as a high merit power source, displacing the output from least efficient thermal stations whenever the power is available. Optimum siting is also made possible by the widespread existence in the UK of 11 000 V and 33 000 V transmission and distribution networks.

It is for these reasons that much of the Electrical Research Association's (ERA) attention during its thirty year involvement in wind power has been directed towards the problems and benefits of large network connected machines. Many of the possible sites for these machines fall within upland Britain and this paper outlines the gross potential for energy production from these sites and the factors affecting economic viability.

GEOGRAPHICAL SCOPE FOR LARGE MACHINES

Although mean wind speed is one of the factors that critically influences the economics of large machines, it is difficult to provide accurate guidance for any particular location without on-site anemometry.

Possibly the best guidance in the UK at present is provided by Caton (1976) who proposes a series of percentile isovent or isopleth maps showing wind speeds exceeded for seven durations, from 0.1% of the time to 75% of the time. Factors to be applied for individual site location and characteristics are also suggested, so that a complete velocity-duration curve can be drawn up for any location. An isovent map derived from Caton for annual mean wind speed (AMWS) including correction factors for coastal areas, is shown in Figure 1.

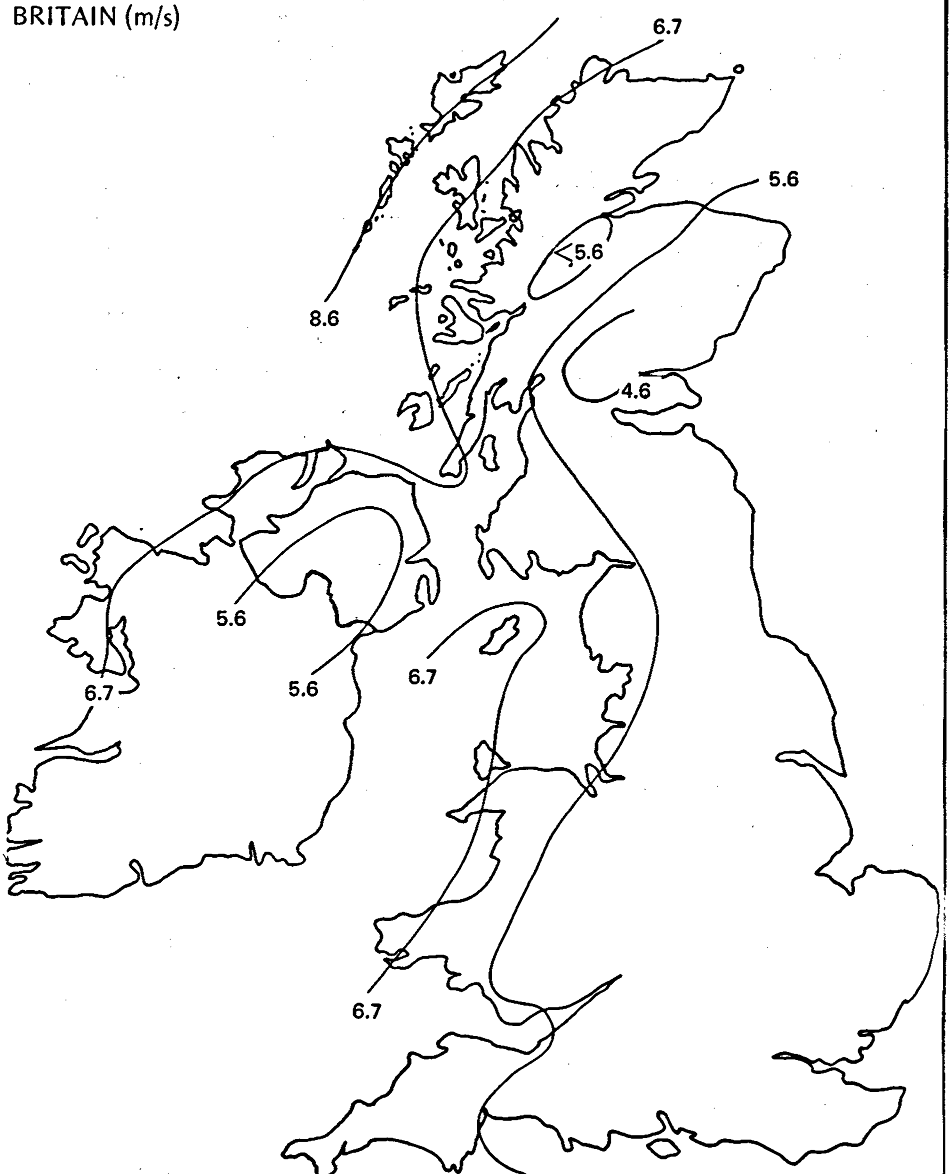
Whilst Caton's maps (taken in conjunction with the correction factors suggested for various classifications of site) are useful, they are limited (as regional surface isovent maps probably always will be) in their validity when applied to specific locations. A comparison, for instance, with the results of ERA's anemometry of hill sites (Tagg, 1957) reveals discrepancies with predictions using Caton's method. The various factors to be accounted for in assessing AMWS on coastal hills are outlined in the following section.

Attention to reasonably accurate prediction of mean wind speed is not purely from academic interest. The simple momentum theory of the wind turbine indicates power output (W) is given by:

$$W = \tfrac{1}{2}p \; C_p \, A \, V^3$$

where p is air density, A is turbine swept area and V is wind speed. C_p is called the power coefficient, and for large machines may be up to about 0.47. This would indicate over 70% more power in a 12 m/s wind than a 10 m/s wind, but the argument does not strictly apply to mean wind speed levels; since C_p varies with wind speed, the variation of annual energy output with mean wind speed has to be calculated from individual machine characteristics. As an example, the annual output of a 40 m diameter machine at 10 m/s and 12 m/s mean wind speed might typically be 3.6 GWh and 5.0 GWh respectively. The necessity for accurate prediction of mean wind speed within 5 to 10% is clear when attempting to justify installation of equipment.

Figure 1
LINES OF CONSTANT AMWS (ISOPLETHS) RELATING TO UPLAND BRITAIN (m/s)



Recent design and cost studies indicate that the economics of large wind turbine generators are likely to be 'marginal'. This means that only the highest mean wind speed sites should be considered as potentially viable at this stage. The significance of this for upland Britain is that the most promising areas are on the west coast of Scotland, where AMWS exceeding 12 m/s have been measured by ERA on the more exposed hill sites.

SELECTION OF INDIVIDUAL HILL SITES

The criteria which are important when assessing economic viability of siting large machines can be broadly divided into two groups:

(i) factors determining cost of plant erection and connection to the local power network;

(ii) factors influencing annual mean wind speed and hence the energy potentially available.

The importance of the first can be considerably under-estimated. The hill approach gradient and surface condition generally affect site support costs, and more specifically they have important bearing on the cost of providing site access. Local main roads must enable large items of plant to be transported to the site. The suitability of the local network (particularly the fault capacity at the nearest substations) will determine the length of connection required, which can substantially affect costs.

Although much effort has been made in the field of wind regime prediction, further advances must be made before adequate practical techniques are available; complementary to this theoretical work, certain empirical methods are undergoing development at present. ERA's hill site anemometry programme has identified certain topographical features as indicative of AMWS.

In particular, the shape of a hill exerts significant influence on wind flow. Fairly steeply graded, smoothly profiled hills exhibit higher AMWS than hills of irregular shape with many sharp changes of gradient. There appears no obvious limit on approach gradient provided levelling at the summit is sufficiently gradual to avoid detachment of the boundary layer and attendant turbulence.

The exposure of a hill relative to surrounding terrain has important bearing on the selection of large numbers of coastal sites. It is obvious that a hill foreshadowed in the prevalent directions will produce a consistently lower AMWS. It is perhaps less obvious that this local screening can considerably modify prevalent directions. The local wind direction may be one in which the profile is less attractive. Clearly shape and exposure have a complex interactive effect on wind flow and may not be judged in isolation.

A third feature indicative of high AMWS of relatively consistent direction is the condition of vegetation. This depends upon climate, but hills which support a healthy growth of trees or bushes are unlikely to experience appreciable wind speeds. Alternatively, if a hill is covered by clipped scrub and trees sparse, stunted and showing marked 'flagging', relatively high AMWS may be expected.

It is evident that no single group of factors may be scrutinised in isolation with reliable result, and when all factors are considered in combination with many plant design variants, substantial analytical effort is required. ERA is presently exploring possible applications for computer modelling techniques in this field.

Depending upon the weighting given to each of the factors, the number of hill sites which are suitable in upland Britain varies between about 1000 and 2000, with a hill-top AMWS in the region of 8 to 12 m/s (at 10 m height above the hill).

Table 1

A PROJECTION OF NUMBER OF SITES AND INSTALLATIONS POSSIBLE FOR UPLAND BRITAIN OF DIFFERING AMWS (m/s)

	AMWS				
	8	9	11	12	Total
Number of sites	580	330	150	40	1100
Number of installations	1200	670	310	80	2260

A sample projection representing 1100 sites in upland Britain is shown in Table 1; the number of machines installable and the distribution with AMWS is indicated. (The number of machines per site is based upon a minimum spacing of 10 turbine diameters to avoid wake effects and interference).

GROSS ENERGY POTENTIAL

In order to estimate the annual energy production from an installation, it is necessary to know, in addition to AMWS, the frequency of occurrence of different wind speeds throughout the year. This information is usually presented as a velocity-duration curve (see Figure 2). ERA has found the shape of this curve to be relatively invariant for large numbers of sites.

Combining the velocity-duration curve with the plant power-wind speed characteristic (Figure 3) results in the power duration curve (Figure 4) for an installation. The area beneath this curve represents annual energy output.

A report published recently by the Department of Energy (Bird & Allen, 1977) admits to the uncertainty of 'optimum' machine size and hence large scale installation cost. Increasing the size of a machine raises the annual energy output, but attendant upon this are certain cost penalties. Of particular importance are potential increases in haulage, site access and support costs associated with larger

Figure 2
TYPICAL PROFILE OF A VELOCITY DURATION CURVE

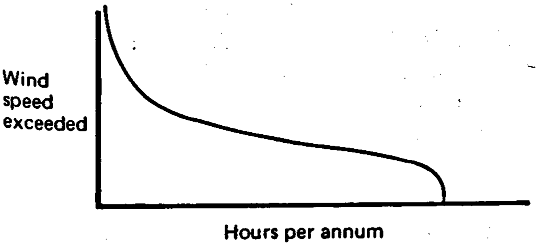


Figure 3
POWER-WIND SPEED CHARACTERISTIC FOR TYPICAL PLANT

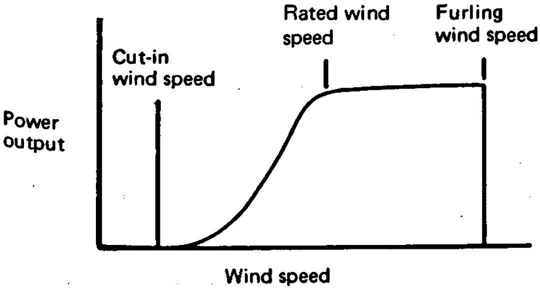
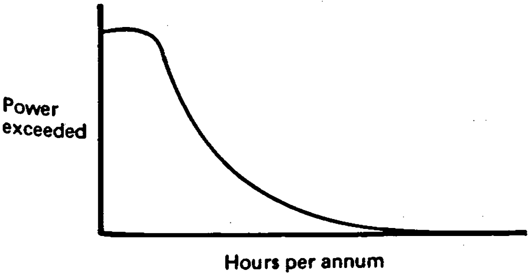


Figure 4
POWER DURATION CURVE



components and material quantities. Such cost penalties may escalate considerably in areas of particularly poor amenity.

Consequently it can be misleading to undertake estimates of energy production for large regions based on one machine size. Using methods described above, annual energy outputs for different machine sizes and AMWS have been estimated, and are presented in Table 2. Very wide ranges of output both for different machine sizes and AMWS are evident.

Table 2

ANNUAL ENERGY OUTPUT FOR DIFFERENT MACHINE SIZES AT EACH AMWS

AMWS (m/s)	Annual energy output (GWh)		
	40 m diameter	60 m diameter	80 m diameter
8	2.1	4.7	8.3
9	2.9	6.4	11.4
11	4.4	9.8	17.4
12	5.0	11.3	20.1

Table 3

BREAKDOWN OF TOTAL ENERGY PRODUCTION FOR UPLAND BRITAIN

AMWS (m/s)	Energy produced at each AMWS (GWh)		
	40 m diameter	60 m diameter	80 m diameter
8	2520	5640	9960
9	1943	4288	7638
11	1364	3038	5394
12	400	904	1608
Total	6227	13 870	24 600
Proportion of national electricity generation (%)	2	5	9

Tables 1 and 2 may be combined to give amalgamated energy production estimates for upland Britain, and Table 3 shows this breakdown together with national totals; the totals have also been expressed as a percentage of total national electricity production. The unreliable nature of wind generated energy limits the amount of conventional thermally generated energy it might displace on the supply network; it is presently thought that about 10% of electrical energy production could be met by large wind turbine generators without creating difficult control and stability problems.

TARGET COSTS FOR LARGE MACHINES

Since wind turbine installations may not be classified as 'firm' generating capacity, their cost effectiveness must be judged simply by the worth of energy produced. This is dependent on the cost and amount of fuel displaced in lower efficiency thermal generating stations and the uncertainty of these quantities, which exhibit both daily and seasonal fluctuation, has already been indicated. Consequently, it is at this stage possible only to bound a range of energy values.

Table 4
ESTIMATED ANNUAL VALUE OF ENERGY PRODUCED BY MACHINES OF DIFFERENT SIZES

AMWS (m/s)	Annual value of energy produced (£1000)					
	40 m diameter		60 m diameter		80 m diameter	
	1.1p/kWh	1.25p/kWh	1.1p/kWh	1.25p/kWh	1.1p/kWh	1.25p/kWh
8	23.1	26.2	51.7	58.7	91.3	103.7
9	31.9	36.2	70.4	80.0	125.4	142.5
11	48.4	55.0	107.8	122.5	191.4	217.5
12	55.0	62.5	124.3	141.2	221.1	251.2

The annual worth of energy production shown in Table 2 has been estimated at 1.1 and 1.25p/kWh. Table 4 gives this information, each figure representing the annual return on investment for its respective installation. The simplest of accounting techniques would produce target installation costs by multiplying each annual energy worth by the plant life. However, this practice takes no account of the decreasing worth of capital with time.

The discounted cash flow method facilitates such adjustments. A constant discount rate of 10% has been applied to each annual energy worth figure in Table 4, over an assumed plant life of 20 years. The resulting target capital costs for each installation are presented in Table 5. It is apparent that wide cost variations are afforded by the ranges of AMWS and machine size.

First taking energy produced at a value of 1.1p/kWh; a 40 m machine installed at an 8 m/s site should not exceed a capital cost of £216 000. An 80 m machine installed at a 12 m/s site might justify a cost of £2.1 million. At the higher energy value of 1.25p/kWh these target costs rise to £240 000 and £2.3 million respectively.

Table 5

APPROXIMATE TARGET CAPITAL COSTS FOR MACHINES OF DIFFERENT SIZES

AMWS (m/s)	Target capital costs (£1000)					
	40 m diameter		60 m diameter		80 m diameter	
	1.1p/kWh	1.25p/kWh	1.1p/kWh	1.25p/kWh	1.1p/kWh	1.25p/kWh
8	216	245	484	550	855	971
9	299	339	659	749	1174	1334
11	453	515	1009	1147	1792	2037
12	515	585	1164	1322	2071	2352

Note: The above costs were produced using the discounted cash flow method assuming a 20 year life and 10% discount rate.

CONCLUSION

While the target costs for a 40 m machine (see Table 5) are unlikely to be achieved, recent design and cost studies for larger machines (particularly 60 m diameter) indicate that there is a distinct possibility that the target costs are fairly realistic.

Two important problems need to be resolved if upland Britain is to be used to any extent for the generation of electricity from the wind. The first problem concerns the uncertainty of public reaction regarding the effect on the environment. This is a highly subjective and sometimes emotive issue; reactions will probably not be significant until a substantial number of machines are proposed; the full nature of public objection or support will only be gauged at the planning application stage and it is not appropriate at this stage to speculate. The second uncertainty is technical feasibility and reliability of large network connected machines; many large machines have been built and operated on a network, but only one has demonstrated adequate robustness and reliability over a prolonged period. It is to be hoped that increasing pressure for conservation of fuels will result in modern prototypes and a persistent programme of development to demonstrate adequate reliability.

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