ETSU L 5

Wind Energy and the Environment

H G Tolland
L A W Bedford

ETSU
for the Department of Energy

ETSU - L5

WIND ENERGY AND THE ENVIRONMENT

L.A.W. BEDFORD AND H.G. TOLLAND

INSTITUTE OF ENERGY CONFERENCE

"ENERGY AND OUR FUTURE ENVIRONMENT"

November 1983

Energy Technology Support Unit
Building 156
AERE
Harwell

October 1984

CONTENTS

	Page
Introduction	1
Machine Development	1
The Prospect for Wind Energy	2
Environmental and Other Impacts on Land	4
Visual Intrusiveness	5
Land Use	7
Ecological Impacts	8
Microclimate	8
Birds and Other Flying Lifeforms	8
Electromagnetic Interference	9
Noise	12
Safety	15
Discussion - Land Based Wind Turbines	16
Wind Energy Offshore	16
Conclusions	17
Acknowledgements	17
References	
Table 1	
Table 2	
Figure 1	
Figure 2	
Figure 3	
Figure 4	
Figure 5	
Figure 6	
Figure 7	
Figure 8	

SUMMARY

Worldwide interest in wind energy has been growing over a number of years. We describe UK wind energy activities with particular reference to the Department of Energy's programme and survey progress with large wind turbines overseas. We review the results of assessment studies which show that wind energy has the potential for supplying a significant proportion of the nation's electricity needs, at a cost which at the lower end of the estimates could probably compete with other conventionl sources.

Significant exploitation of the wind energy resource would require large numbers of machines and it is uncertain whether such numbers would in practice turn out to be environmentally acceptable. Factors which will influence this will include (not necessarily in order of importance) visual acceptabilithy and land use restrictions, ecological impacts, electromagnetic interference, noise and safety.

We review each of these aspects and conclude that for land based wind turbines the major impacts are visual intrusiveness, electromagnetic interference (particularly TV interference) and noise. These factors could be significant at all sites, other effects are likely to be site-specific.

There are a wide range of pre-existing activities and interests which may impose constraints on the location of wind turbine arrays offshore. Nevertheless when allowance is made for these, the remaining resource is comparable with total UK electricity demand and the size of the available resource need not be a constraint on interest in offshore wind power.

Wind energy and the environment

L A W Bedford and H G Tolland*

Energy Technology Support Unit, AERE Harwell, Oxfordshire OX11 ORA

Introduction

Worldwide interest in wind power as a substantial source of electrical energy has been growing over a number of years. There are major programmes in a number of European countries and the USA. Wind energy development in the UK is supported by a programme of R&D sponsored by the Department of Energy (1, 2) and coordinated with complementary activities at universities supported by the Science and Engineering Research Council, and with work by the Electricity Boards; who wish to become informed potential customers. In addition a significant level of cooperation in wind energy R&D has evolved between a number of countries mainly through the auspices of the International Energy Agency.

Machine Development

Power output from existing wind turbines range from a few kW up to a present maximum of 2-3 MW. Operating experience with MW sized horizontal axis machines already exists in Europe and the USA and this is summarised in Table 1. Machines of more advanced design are under development which would have an output of up to about 7 MW and offer the prospect of lower costs.

The UK Department of Energy programme has been concerned mainly with the ultimate development of megawatt size machines for use on land and later, possibly offshore. The high cost of diesel power in the Scottish islands has prompted the North of Scotland Hydro-Electric Board to consider wind power as a possible alternative method of generation. A 22 kW machine of Danish design has been in operation since December 1980 in the Orkneys (3). A 250 kW horizontal axis machine (Figure 1), to be followed later by one of 3 MW rating (Figure 2), will also be installed in Orkney, both machines being of British design (4, 5). All these machines are of designs suitable for the high average wind speeds encountered in the Orkneys and which are also typical of good hilltop sites in the rest of the UK.

The CEGB has installed a 200 kW machine at Carmarthen Bay power station as a first step in their wind power strategy. The next step in this strategy is a machine of up to 4 MW capacity. The aim is to have the machine operating at the end of 1985, suggesting that the CEGB and Orkney machines could start operating at about the same time. CEGB recently announced (6) that they will seek permission to construct their MW machine at Richborough power station, near Ramsgate, Kent.

All the machines mentioned so far are of the horizontal axis type but there may be advantages to be gained from vertical axis machines. Development overseas has so far concentrated on the Darrieus type (Figure 3); in the USA versions rated up to 500 kW are under test, while in Canada a MW sized version is under development.

The Department of Energy is supporting development of a Variable Geometry Vertical Axis machine of the type originally suggested by Musgrove (7). Considerable refinement of this concept has taken place (8) and the possibility of building a 25 m diameter prototype is being considered. This machine (Figure 4), if built, would be at Carmarthen Bay on a site offered by CEGB and would be tested over a period of two years. In addition further design work on a MW sized version would be carried out.

The Prospects for Wind Energy

From the UK viewpoint, in considering the results which have emerged so far from wind energy R&D activities, abroad as well as at home, two main questions must be addressed - how much energy is available and what is its cost likely to be.

As far as the energy resource is concerned, current assessments of wind data and possible land sites (8, 9) suggest that the amount of wind energy which might be utilised, mainly in the form of electricity supplied to the grid system could be up to 50 TWh/y, or about 20% of current electricity consumption. This would correspond to 5000 to 10 000 machines each with rotor blades of about 80 m diameter and towers of about the same height. The extent to which environmental constraints would restrain exploitation of this resource remains a major uncertainty. This aspect is discussed in detail later.

Consideration (8, 9) of possible siting of wind turbines in shallow waters offshore, where wind speeds are generally higher than over land, has led to the conclusion that the wind energy resource could amount to over 200 TWh/y. In determining this figure only areas greater than 5 km offshore and with water depths up to 50 m were considered. Other areas not included were those unlikely to be suitable because of present use, such as shipping lanes or due to unfavourable site conditions. However fishing areas were included, mainly because of the difficulty of defining their extent. Nevertheless the resource is clearly very large and probably several times greater than that which could be utilised by the electricity network from an unfirm source without major changes to the system.

Turning now to the economics of wind energy. These were considered by ETSU in some detail in 1981 (10), when comparisons were made with the other renewable energy options, eg geothermal, tidal, wave etc, as part of a strategic review for the Department of Energy.

Although no large wind turbines have yet been built in this country, cost estimates have been made based on experience with prototype MW rated machines in the US. From this information, and taking account of recent UK estimates for the Orkney machine, the ETSU study assumed for land based machines that capital and transmission costs might be in the range of £600-1300/kW installed. For offshore machines, these figures were increased to take account of the greater expected costs of offshore wind energy, resulting in an assumed cost range of £920-1930/kW installed.

In addition the costs of maintenance and operation were considered, resulting in a range of figures from 1% to 7% of annualised capital costs for land based machines. In the case of offshore machines, somewhat higher figures were assumed ranging from 2% of the (higher) annualised capital costs to about 14% based on a detailed study carried out for the wave energy programme.

To arrive at estimates for energy costs in p/kWh the study assumed 25 year life with 5% Test Discount Rate and annual energy output equal to full rated power for 25% of the time.

From Table 2 it can be seen that the projected range of costs (late 1981) are 1.9-4.3 p/kWh for land based and 3.1-7.0 p/kWh for offshore.

Thus it can be seen that wind energy has the potential for supplying a significant proportion of the nations electricity needs, at a cost which at the lower end of the estimates could probably compete with other conventional sources.

Environmental and Other Impacts on Land

The analysis of impacts has naturally concentrated on horizontal axis machines. There is already sufficient knowledge to identify the major impacts and to describe some of their effects in reasonable detail. There remains considerable uncertainty on the degree to which these impacts would in practice constrain the exploitation of wind energy, particularly on land. Also, caution is needed in interpreting the results of overseas studies because conditions overseas do not necessarily correspond to those in the UK.

Significant exploitation of the wind energy resource would require large numbers of machines. In considering the contribution wind energy might make to future energy requirements (11), ETSU considered a ceiling of 7.5 GW of wind energy on shore. This would require 1500-3000 wind turbines. Taking the area of England and Wales as 150 000 km^2, the average density of 3000 wind turbines, assuming that they were generally dispersed over the countryside and not clustered together in wind farms, would be one every 50 km^2. This would mean that the average distance between machines would be about 7 km, or just over four miles. On this simplified basis one might therefore expect to see a wind turbine within about two miles looking in any direction. This may not be considered particularly intrusive visually (11). If the wind turbines were spaced on a grid 10 diameters (say 0.75 km) apart, on wind farms, the total land area occupied would be about 5300 km^2. If there were 20 such wind farms, each would be of area 265 km^2 and of side about 16 km if square in plan. It should be possible to find 20 areas where such wind farms may be environmentally acceptable (11). The two cases, ie widespread dispersion of wind turbines and concentration into a few wind farms, represent extreme views. Both were thought to be credible and to stand a chance of being environmentally acceptable (11).

Whether such numbers of wind turbines would in practice turn out to be environmentally acceptable remains uncertain. Factors which would influence this will include (not necessarily in order of importance) visual acceptability and land use restrictions, ecological impacts, electromagnetic interference, noise and safety. These are reviewed in the following sections.

Visual Intrusiveness

Public acceptability of wind turbines is likely to be strongly influenced by visual impact. This is at present difficult to quantify; the impact depends on subjective judgements including the value of the landscape, the aesthetic design of the machine and perhaps the observer's views on energy matters and other subjects. Individual large turbines will be visually dominant for a radius of at least 1 km and possibly extremely dominant for a 500 m radius (12). However, inspection of photomontages of arrays of 10 turbines suggests that an observer is conscious of about three machines, at least for a flat landscape.

Public response to wind turbines in Sweden (13) and the USA (14) has so far been very positive and encouraging. Indeed the 2 MW MOD-1 machine at Boone, North Carolina was a tourist attraction (15, 16) until it was dismantled in 1983. However, these attitudes appear to be based in the main on small numbers of machines rather than arrays and may not be representative of public attitudes to large numbers of machines. These results could indeed be influenced by the novelty value of early machines.

The rotating blades of the wind turbine could present visual problems. If the wind turbine blades subtend an angle greater than that of the sun, a rotating shadow pattern will be produced which is likely to be visually intrusive. Caution suggests it may be prudent to ensure that there are no dwellings which could lie in the umbra of the rotating shadow (17). Also, the motion of the blades would probably increase the impact compared with static structures. It would exaggerate their size and, particularly for two bladed machines, would give the illusion of non-constant rotational speed which may be disconcerting. The significance of this is uncertain.

The proportions and styling of modern wind turbines are capable of an elegance of their own and it is important that this is achieved. Attitude surveys (14) suggest a preference for tubular towers rather than lattice towers. This seems to be confirmed by the world-wide design choice for elegant tubular designs.

Useful landscaping would probably be confined to treating the infrastructure and to screening in the immediate vicinity of points of view, residents' houses, etc.

Land Use

A wind turbine would itself use very little land and power transmission would probably be by 11 kV wood pole line as is common in rural areas. A transformer and possibly a small building for instrumentation may be required; alternatively these might be placed in the base of the tower. There seems to be no reason why the area right up to the base of the tower should not be used for agriculture (17). If a metalled road to the site is needed this would have rather more land use impact. Some local land-owners could regard it as a benefit if it improves access to part of a farm (17). Even if a metalled road is not required, access of heavy vehicles to the site during construction would be necessary.

Some categories of land can probably be ruled out immediately for wind turbines. Provisionally these would probably include National Nature Reserves, Ministry of Defence land, National Parks, Areas of Outstanding Natural Beauty, Heritage Coasts and National Scenic Areas (Scotland) and urban land. Perhaps forest should also be ruled out while Sites of Special Scientific Interest and the Agricultural land classification would presumably be lesser constraints.

Another question is how far away from habitation would it be necessary to place wind turbines. Many of the impacts (visual amenity, noise, electromagnetic interference) and safety considerations would in principle set minimum distance. Unfortunately at present there is no clear guidance from consideration of these various factors on what this minimum distance should be. For initial investigations in the UK, the CEGB have suggested an arbitrary minimum of 500 m from the nearest dwelling though other countries (eg Sweden) have adopted 200 m as the nearest distance (17). The arbitrary 500 m distance adopted for planning purposes is seen as reasonable, at least until more experience with wind turbines is gained (17).

Ecological Impacts

Microclimate. A wind turbine generator would induce minor changes in wind speed, turbulence, temperature, available moisture and various other wind-influenced atmospheric parameters. The extent of changes would depend on machine design but are expected to be quite small (18). This has been confirmed in preliminary measurements made around the MOD-0 machine (19). Such small effects are not considered likely to induce measurable secondary effects to flora and fauna, including agricultural species.

The enhanced turbulence in the wake of a wind turbine at a height of several dozen metres will be less than ambient turbulence at ground level, and will also be small compared to natural variations. A CEGB assessment indicates that aircraft should, in general, be discouraged from approaching closer than about six diameters when the machine is operating (17), and the hazards to birds from the microclimate effects will be no more than from tall buildings. There should be little effect on the dispersion of flue gases from nearby chimneys.

Birds and Other Flying Lifeforms

The major areas of concern appear to be collisions with the wind turbine and its tower and the effect noise might have on birds. The significance of birds, bats and insects colliding with the rotating blades of a wind turbine will depend on location, time of day, season and prevailing climatic conditions (18). Birds with a habitat close to the machines learn to avoid obstacles in their own territory and so would not normally be expected to be at risk (17). Thus the main danger would be to migratory birds of various type. Migratory songbirds are more likely to be affected on dark foggy nights during the peaks of migration in the spring and autumn. Daytime migratory birds can be expected to avoid the blades, as would most nightime migrants in fair weather (18). At the inland MOD-0 site in Ohio in normal conditions migrating birds such as waterfowl fly between about 400 and 700 m (19). Some songbirds fly at 150-300 m, but it has been estimated that only 10-20% of all migrating birds fly below about 200 m. Since the maximum height reached by the blade of a 100 m diameter machine would be $\sim$175 m, the likelihood of migrating birds being killed in normal conditions would seem to be fairly low, but the applicability of these results to the UK is currently uncertain (17).

In adverse conditions, birds sometimes descend to lower altitudes, and there is evidence that they can be disoriented by lights and fail to take evasive action. The momentum of birds, unlike insects, implies they would neither be swept into nor away from the blades by the deflection of the airstream imposed by the rotor (18). The placement of wind turbines on bluffs or headlands may impose a somewhat greater risk since birds tend to soar on rising air currents (17).

Manning (17) presents calculations which show that even if birds do fly through the area swept by the blades, the incidence of them being struck is fairly low. This seems to be borne out by experience both in the USA and elsewhere. For example, in Denmark small birds have been observed to fly safely through the rotors of operating wind turbines at the Risø test centre. Thus evidence to date suggests that wind turbines present a negligible hazard to birds.

Bird monitoring studies are being carried out by the RSPB for the Orkney machine, work commencing prior to any site development. This programme of work arose from concern that the construction period as well as the operating of the machines together with the noise produced could adversely affect the established pattern of habitation at and around the site. This includes sections of land which RSPB operate as bird sanctuaries. It has to be recognised that many attractive wind power sites are also of interest to bird lovers, making independent assessments desirable.

Electromagnetic Interference

A windmill can give rise to electromagnetic interference by creating two transmission paths, the direct path and the scattered path. Since the blades of a wind turbine (the scatterer) move, the phase of the scattered signal varies with time. The combination with the direct ray produces alternate destructive and constructive interference and the signal at the receiver is modified by a predominantly amplitude modulation. Machines on or close to the line of sight produce amplitude modulation of the signal, those off it can create a periodic multipath signal. The amount of interference is site specific and also depends on the electromagnetic system being considered.

The level of the interfering signal is dominated by the scattering area, or radar cross section of the wind turbine (17). The most important parameter here is simply the projected area, or radar cross-section, of the wind turbine. Also of paramount importance is blade material, conducting blades being more likely to cause interference than insulating ones (17).

Much work on television interference has been carried out in the USA (20-25) and this has recently been reviewed by Manning (17). Television interference arises either because the wind turbine lies between the transmitter and receiver, when a periodic variation in signal strength is manifested as a variation in picture brightness, or when periodic reflections from the blades give multipath interference which can be manifested as an irritating flickering ghost on the picture. The sound signal appears to be immune from interference effects.

Figure 5 gives an indication of the area around a wind turbine which might suffer interference. The large area is from the analysis of Senior and Sengupta (18) who assumed an isotropic receiving aerial. The standard British aerial, the Yagi array, has considerable directivity and when the CCIR (1963) recommendation (26) on directivity is incorporated into the analysis the area over which interference is to be expected becomes much smaller, and this is also shown in Figure 5 for the case when the transmitter is effectively distant from the wind turbine (17). The boundary shown is that between the areas where interference was judged 'acceptable' and 'severe' (23) but note that the situation is not clear-cut and some subjective judgement is involved (17).

Public attitudes are likely to be influenced by the frequency of disruption seen by an individual viewer. In front of the wind turbine interference is only experienced when the wind turbine is in certain specific orientations. The results of Sengupta and Senior (20) suggest that an individual consumer in front of the wind turbine might experience TV interference some 5-10% of the time (17). In the area behind the wind turbine TV interference could be experienced some 50% or more of the time in those areas where interference occurs.

The UK YJ 625 line PAL system employs a different modulation scheme to that used in the USA so that modulation thresholds and hence the size of the interference zone may differ. The UK PAL system generally gives a better colour picture than the USA NTSC system so British viewers may be more critical. Against this, the PAL system is generally less susceptible to distortion.

The siting of wind turbines would need to take account of TV relay stations and the links between them. Such stations are features of remote areas, often the areas suited to wind turbines.

In general methods to ameliorate the disruption to TV signals are readily available (17). These include reorientation of domestic aerials where a suitable alternative signal is available, cable TV systems or a new repeater station. The cost of such measures is likely to be a small proportion of the cost of an individual machine, and probably even smaller in the case of an array of wind turbines.

Where significant TV interference appears possible, pre-emtive action may be considered to avoid putting the acceptability of wind machines at risk. This is well illustrated with the Orkney machine. The area around Burgar Hill was known to be one with poor reception. As a result of studies by British Telecom and the BBC, it was concluded that TV interference was possible and this could be avoided by installing a repeater station. This would give better signal reception than at present and at the same time enable the effect of the wind machine to be assessed without affecting the TV viewers.

Microwave communication links are, generally speaking, high capacity line of sight communications between fixed points using directional dish antennae (17). Because of the highly directional nature of the antennae, interference is only likely if the wind turbine is on or close to the line of sight. This fact and the difficulty and cost of remedial measures suggests that wind turbines should be sited to avoid causing any interference.

Sengupta and Senior (22) studied VOR (variable omni-direction and range) and the doppler variant DVOR. They concluded that the errors in bearing caused by the rotating blades were much less than those caused by the tower and hence the machine could be treated as a static scatterer. Other navigation systems such as instrument landing systems could be affected but appear not to have been studied seriously (17).

Noise

Noise could be a serious consequence of wind energy particularly in the relatively crowded British Isles. Noise sources during construction are well understood and standard methods can be used to minimise nuisance. However, work on noise from industrial plant is not applicable to operating wind turbines. This is due to the presence of background wind noise, the probable inability to control noise generation and the distinctive spectrum of wind turbine noise.

Noise from wind turbines may conveniently be split into three components:

- machine noise from the gearbox, generator etc. This should be amenable to conventional soundproofing;
- aerodynamic noise;
- infrasound from blade/tower interactions.

Some experience of the generation of aerodynamic noise by wind turbines is available from extrapolating data from helicopter rotors (17), although at present there do not appear to be any definitive documents available in the literature. Nevertheless, the major aerodynamic noise source appears to obey the equation established for jet noise (27, 28).

$$\text{Total Sound Power} = 10 \log_{10} (nU^6 bd) + \text{Constant} \qquad (3)$$

where n is the number of blades

U the relative velocity between blade and wind at 70% span

b blade chord

d diameter of machine.

Infrasound is a problem specific to machines with the rotor downwind of the tower. It is caused by interaction between the blades and the tower wake. The problem depends on the detailed geometry of the machine and proagation depends on local topography. It has caused problems with the MOD-1 machine at Boone in the USA (7) where it was found the problem could be reduced, though not eliminated, by reducing the speed of rotation. There is a cost for this measure in terms of lost output.

Manning (17) reviews a number of noise measurements, mainly in the USA but including the British Lawson-Tancred machine (Figure 6). Measurements on the MOD-1 machine concentrated on the infrasound problem (7) rather than the overall noise measurements. Perhaps the most germane are the MOD-2 measurements taken by Hubbard et al (29) for the machine on Goodnoe Hills (Figure 7). Overall sound levels from the MOD-2 were relatively high and the noise was dominated by aerodynamic noise generated by the rotor.

The amount of data so far is sparse, even Hubbard's measurements span only three days. A large amount of low frequency noise appears to be common to all machines and these propagate through the atmosphere much more efficiently than higher frequencies. Distance attenuation, at 6 dB per doubling of distance, seems to be the only important source of attenuation but relying on this may severely limit the number of wind sites (17).

Anomalous propagation, ie effects other than inverse square law, atmospheric absorbtion and screening may need to be taken into account.

Topographical effects would have to be treated on a site specific basis. Wind shear can cause shadow zones upwind of the rotor while downwind noise levels can be enhanced.

It seems noise from wind turbines cannot be ignored and that any problems which arise from aerodynamic noise are likely to prove fairly intractable (17). The noise produced by wind turbines must be judged against the background level prevailing while the wind is blowing. This is contrary to the usual case where background levels are measured under calm conditions at night. Wind turbines, unlike conventional noise sources, have a spectrum which peaks at low frequencies (see Figures 6, 7). Such noise is important because; unlike high frequency it is not subject to atmospheric absorbtion; is very easily diffracted round obstacles rendering screening ineffective; and it can cause resonance in buildings, making objects rattle or vibrate. Levels at which nuisance can occur are not well defined and there is the additional problem that it can cause distress though not audible in the conventional sense (17).

The spectral characteristics of the noise from wind turbines are of a type for which there is little subjective data or experience (17). Research in the USA on the development of noise criteria is currently underway (29) but as yet no specific criteria have been derived. Work by Iredale (30) on low frequency noise standards has been incorporated into CEGB standards (17). These reduce noise levels by 20 dB at 31 Hz compared to standard NR curves (and progressively less up to 250 Hz) but are not directly applicable to wind turbines since they are designed for windless days. They are capable of development (17).

The characteristics of wind noise together with a consideration of likely machine spacing and minimum distance from habitation suggest that any noise criteria developed for a single machine can also be applied to an array (17). From the point of view of noise, an array should be acceptable if each individual machine is acceptable (17).

Safety

A possibility which cannot be ignored is that part or all of a wind turbine blade may become detached and fly off. The probability of this happening can be kept to a minimum by good design techniques, monitoring, inspection and good quality assurance. The consequences of such unlikely events have been examined by CEGB (18) and others (31).

If the accident occurs when the load is lost and the brakes have failed, the final speed of the rotor is determined by aerodynamic considerations unless a lower limit is given by the tensile strength of the material. The distance of travel of any missile, if produced, is limited by drag and may be around 300-700 m. However, not all missiles would be thrown this distance and a Monte Carlo simulation gives a probability of a fragment being thrown more than 300 m of around 5% (17). This must, of course, be multiplied by the low probability that a fragment is formed.

Structural failure of the tower is considered unlikely except in the case of a very rare blade fracture. It would involve hazard in a circular area centred on the tower with a radius of the tower height plus the length of a blade.

In some areas icing would be a problem and this has been reviewed by Mortimer (32). The variability of weather conditions and the probability of icing, suggest each case should be considered on its merits. The prevention of ice formation in all circumstances is probably not possible and some form of ice detection is probably necessary (17).

The requirements for aircraft safety would need to be considered. The blade tip for a large wind turbine could be 130 m or more above ground level at its highest point and so presumably there would be siting limitations close to airfields.

Discussion - Land Based Wind Turbines

It is probably reasonable to conclude that the major impacts of land based wind turbines are visual intrusiveness, electromagnetic interference (particularly TV interference) and noise. These effects could be significant at all sites, other impacts are likely to be site specific.

Wind Energy Offshore

The possibility that wind energy exploitation on land could be severely restricted by environmental factors led to consideration of siting structures offshore. Provided they are located far enough offshore, environmental intrusion is likely to be less severe than for land based machines. Work by Taywood Engineering and CEGB (33) shows that even taking into account environmental and other constraints on deployment offshore, the remaining resource is very large.

There are a wide range of pre-exisitng activities and interests which may impose constraints on the location of arrays of wind turbines offshore. The study examined siting constraints, wind availability, alternative spacings between wind turbines and appropriate machine energy yield. The whole of the continental shelf within UK waters starting 5 km offshore was examined. Areas with water depth less than 10 m or greater than 50 m were excluded on technical grounds. Attention was concentrated on the marine activities which appeared to be least compatible with arrays of wind turbines and therefore likely to rule out siting of arrays in large areas of UK offshore waters. The study identified areas which were either 'probable' or 'possible' areas for wind turbine arrays and evaluated extractable resource in each category and mapped the probable and possible areas (Figure 8).

The mapping is based on those constraints such as military zones, shipping clearways and aggregate dredging concession zones which are relatively well documented. Some constraints such as oil and gas production installations, submarine cables and some types of waste dumping affect well defined but small areas. These were not mapped but are expected to have only a marginal effect on the size of the exploitable resource. The remaining resource size, possibly up to 230 TWh/year, is comparable with total UK electricity demand. The exploitable offshore resource is therefore considerably larger than the electricity supply system is likely to be able to absorb economically. Certainly the size of the available resource need not be a constraint on interest in offshore wind power.

Conclusions

Wind energy has now reached the point where multi-MW machines are being constructed and some experience is being gained with their use overseas. Such experience will shortly be gained in the UK. For wind energy to make a serious contribution to UK energy supply, reliable performance and acceptable costs must be demonstrated to the satisfaction of the electricity supply industry.

On land the size of the exploitable resource could be constrained by visual intrusiveness, electromagnetic interference and noise. These are in the main problems for land based machines and are less severe offshore where the available resource is very large. Thus cost points towards onshore installations, but many other factors point offshore. Presumably experience with the developing technology and its environmental implications will help to delineate these problems more clearly.

Acknowledgements

The authors wish to thank both the Department of Energy and the UKAEA for their permission to publish this paper.

Opinions expressed are those of the authors alone and should not be construed as those of the Department of Energy or the UKAEA.

References

1 L A W Bedford et al, Wind Energy R&D in the United Kingdom, 4th International Wind Energy Workshop, Washington, October 1981

2 R G S Skipper and L A W Bedford, The UK Programme on Wind Energy, British Wind Energy Association Wind Energy Symposium, Reading University, March 1983

3 W M Somerville, W G Stephenson, An Appreciation of the 10 m Wind Matic Aerogenerator Operating on Orkney. Proc Third British Wind Energy Association Wind Energy Conference, Cranfield, April 1981, pp 120-127

4 D Lindley and W G Stephenson, The Horizontal Axis Wind Turbine Project on Orkney. Proc Third British Wind Energy Association Wind Energy Conference, Cranfield, April 1981, pp 16-32

5. P B Simpson et al, The 3 MW Orkney Wind Turbine, British Wind Energy Association Wind Energy Symposium, Reading University, March 1983

6. CEGB Press Information, PR765, Site Chosen for Large Wind Turbine, 16 May 1983

7 P J Musgrove and I D Mays, Development of Variable Geometry Vertical Axis Windmill, Proc 2nd International Symposium on Wind Energy Systems, Amsterdam, 1978

8 D J Milborrow et al, The UK Offshore Wind Power Resource, 4th International Symposium on Wind Energy Systems, Stockholm, September 1982 (organised by BHRA)

9 ETSU Report, The UK Wind Energy Resource, to be published

10 Strategic Review of the Renewable Energy Technologies - An Economic Assessment, ETSU R13, HMSO, 1982

11 Contribution of Renewable Energy Technologies to Future Energy Requirements, ETSU R14, HMSO, 1983

12 A Bergsjo, K Nilsson and E Skarback, Wind Power in the Landscape, 4th International Symposium on Wind Energy Systems, Stockholm 1982

13 I Carlman, Wind Energy Potential in Sweden: The Importance of Non-Technical Factors, 4th International Symposium on Wind Energy Systems, Stockholm 1982

14 Public Reactions to Wind Energy Devices, National Science Foundation, 1977, Survey Research Laboratories, University of Illinois

15 J L Collins and R H Poor, Experience and Assessment of the DoE/NASA MOD-1 2000 kW Wind Turbine Generator at Boone, North Carolina, presented at 5th Washington Wind Energy Workshop

16 D T Swift-Hook and R H Taylor, Wind Energy in the US, CEGB Report RD/L/N60/80

17 P T Manning, The Environmental Effects of Wind Turbines, CEGB Report TPRD-GS/E/1/82

18 S E Rogers et al, Evaluation of the Potential Environmental Effects of Wind Energy System Development, Battelle Colombus Laboratories, Columbus, Ohio, 1976, ERDA/NSF/07378-75/1

19 S E Rogers et al, Environmental Studies Related to the Operation of Wind Energy Conversion Systems, Battelle Columbus Laboratories, 1977

20 T B A Senior, D L Sengupta and J E Ferris, TV and FM Interference by Windmills, 1977, final report for ERDA prepared under Contract 3 (11-1)-2876 DoE/TIC-11348

21 T B A Senior and D L Sengupta, Wind Turbine Generating Siting and TV Reception Handbook, 1978, technical report no 1 for DoE under contract EY-76-S-02-2846, A001

22 D L Sengupta and T B A Senior, Electromagnetic Interference by Wind Turbine Generators, 1978, final report no 2 for DoE under contract EY-76-S-02-2846, A001

23 D L Sengupta and T B A Senior, 1979, Proc IEEE, Vol 17 No 8, pp 1133-1142

24 D L Sengupta, T B A Senior and J E Ferris, TV Interference Tests on Block Island RI, technical report no 3 for DoE under conract EY-76-S-02-2846, A004

25 B C Brock, The Scattered EM Field Due to Rotating Blades of Horizontal Axis Wind Machines, Sandia Lab Report, SAND 79-0434, 1979

26 CCIR (1963), Recommendation No 19 of the Committee Consultatif de Radio Internationale

27 D N Keast and R C Potter, US DoE Report EV-0089, 1980

28 H H Hubbard, D P Shepherd and G F W Grosveld, NASA Contractor Report 165 752, 1981

29 K P Shepherd, D G Stephen and G F W Grosveld, Development of Wind Turbine Noise Criteria, presented at 5th Washington Wind Energy Workshop

30 R A Iredale, Steam and Gas Turbine Noise, symposium on noise from prime movers, Southampton, 1973, organised by British Acoustical Society

31 B Montgomerie, Horizontal Axis Wind Turbine Blade Failure, Blade Fragment Six Degrees of Freedom Trajectory, Site Risk Level Prediction, 4th International Symposium on Wind Energy Systems, Stockholm, 1982

32 A R Mortimer, A Review of the Icing Problem for Aerogenerators, Wind Engineering, 4, 1980, no 4, pp 183-191

33 Taywood Engineering and CEGB, Offshore Wind Energy Assessment, Phase IIa Study, 1982, 2

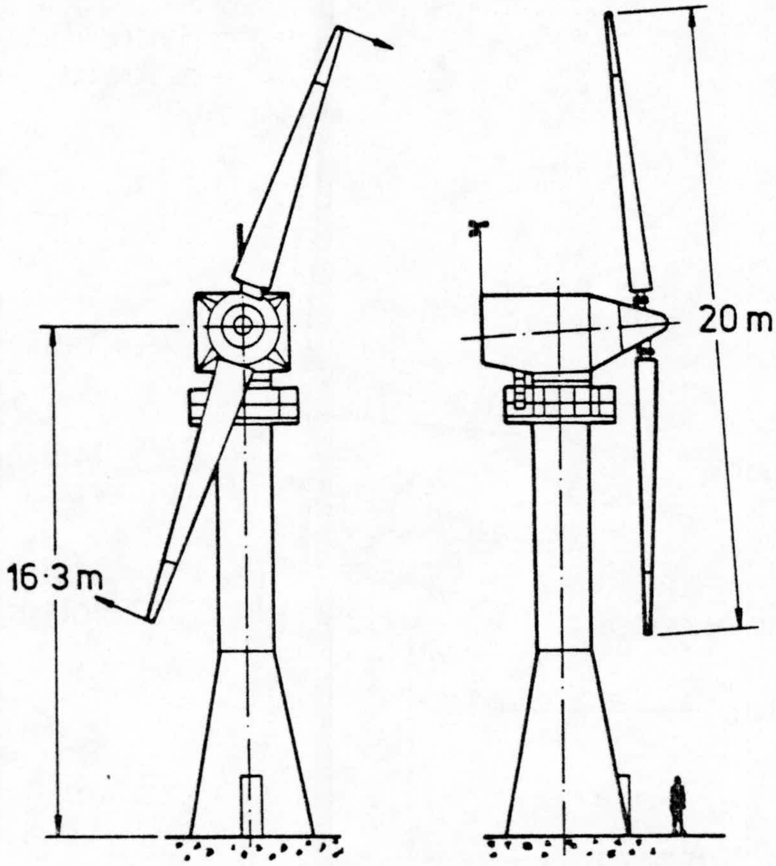
Table 1: Multi-MW rated horizontal axis wind turbines built or planned

Country	Location	Rated Power (MW)	Rated Wind Speed (m/s)	Number of Blades	Diameter (m)	Rotor Position Relative To Tower	Tower Material	Tower Soft/ Stiff	Height To Axis Of Rotation (m)	Power Control System	Status Testing Underway From/Due
Denmark	NIBE A	0.65	13.0	3	40	upwind	concrete	soft	45	VPT	1980
Denmark	NIBE B	0.65	13.0	3	40	upwind	concrete	soft	45	FSPC	1980
USA	Goldendale A	2.5	12.3	2	92	upwind	steel	soft	60	VPT	1981 under test
	Goldendale B	2.5	12.3	2	92	upwind	steel	soft	60	VPT	1981
	Goldendale C	2.5	12.3	2	92	upwind	steel	soft	60	VPT	1981
	Medicine Bow	2.5	12.3	2	92	upwind	steel	soft	60	VPT	1982
	California	2.5	12.3	2	92	upwind	steel	soft	60	VPT	1982
	Medicine Bow WTS-4	4.0	13.7	2	78	downwind	steel	soft	80	FSPC	1982
Sweden	Maglarp WTS-3	3.0	12.5	2	78	downwind	steel	soft	80	FSPC	1982
	Gotland	2.0	12.5	2	75	upwind	concrete	stiff	77	FSPC	1982
West Germany	Hamburg Growian	3.0	12.0	2	100	downwind	steel	soft (guyed)	100	FSPC	1983
UK	Burgar Hill, Orkney	3.0	17.0	2	60	upwind	concrete	stiff	45	VPT	Contract placed. Completion 1985.

Notes:
1 VPT - Variable Pitch Tips
2 FSPC - Full Span Pitch Control
3 Soft tower has natural frequency less than blade passing frequency
4 Stiff tower has natural frequency higher than blade passing frequency

Table 2: Estimates of resource and energy costs

Location	Resource TWh/y	Estimated Cost Range, p/kWh	
Onshore	20-50	Capital (wind turbine)	1.6 -3.8
		Capital (transmission)	0.3 -0.3
		Maintenance	0.03-0.2
		Total	1.93-4.3
Offshore	140-200	Capital (wind turbine)	2.3 -5.5
		Capital (transmission)	0.7 -0.8
		Maintenance	0.1 -0.7
		Total	3.1 -7.0

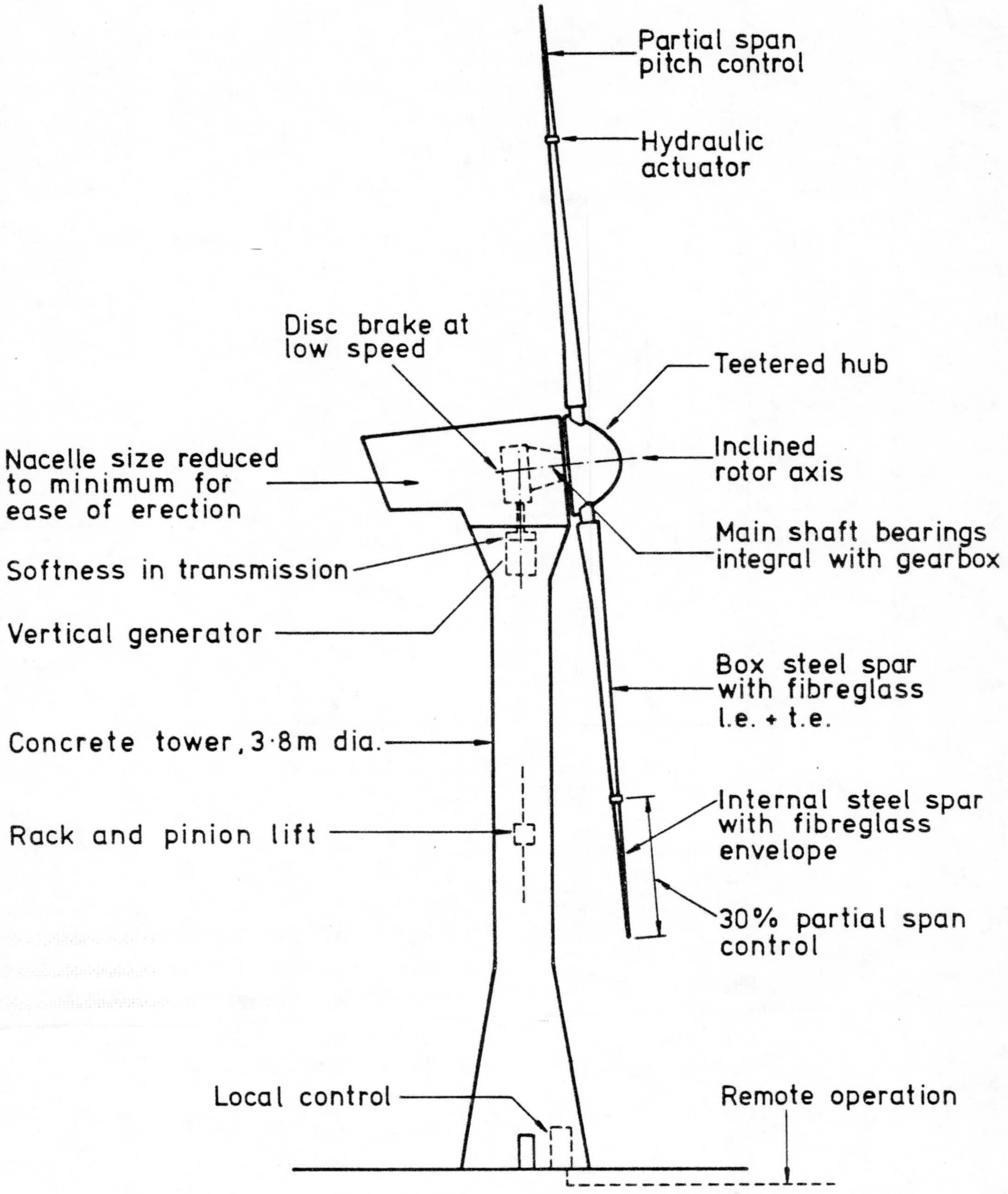


ORKNEY 20 m W.T.G.

Specification

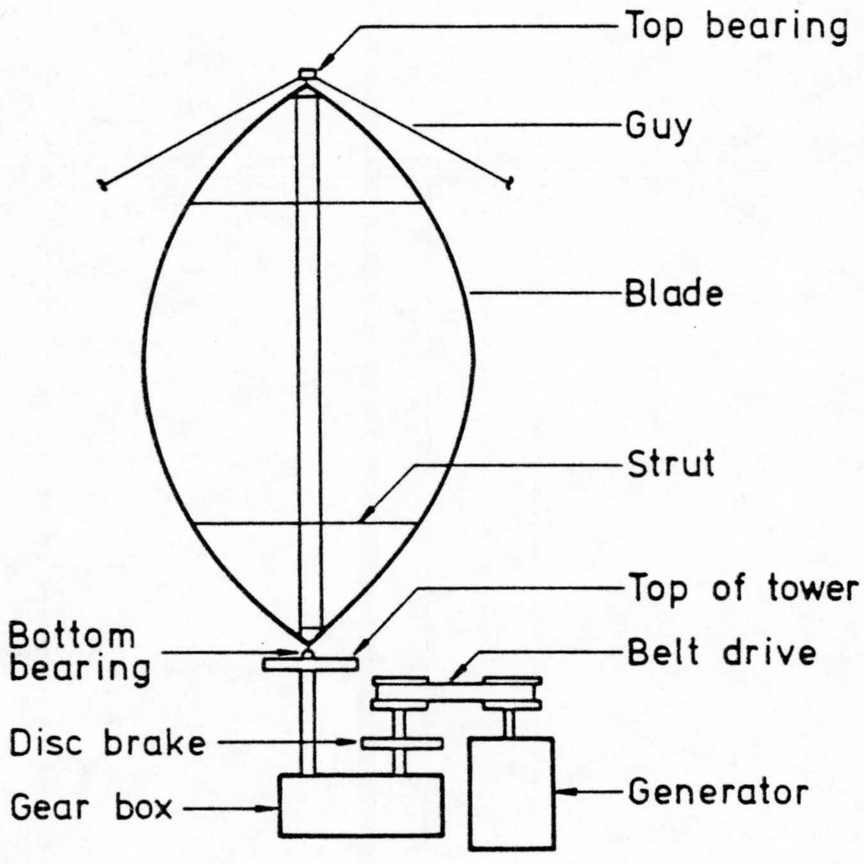
Diameter	20 m
Rated power	250 kW
Rated wind speed	17 m/sec
Rotational speed	44-88 rpm
Blades	Fixed pitch NACA 44xx series
Control	Variable pitch tips
Transmission	2 stage shaft mounted
Generator	Synchronous 440 v. 3 phase
Orientation	Servo drive
Tower	1·82 m dia. steel
Controller	Microprocessor
Annual energy	700,000 kWh at 10 m/sec site

FIGURE 1



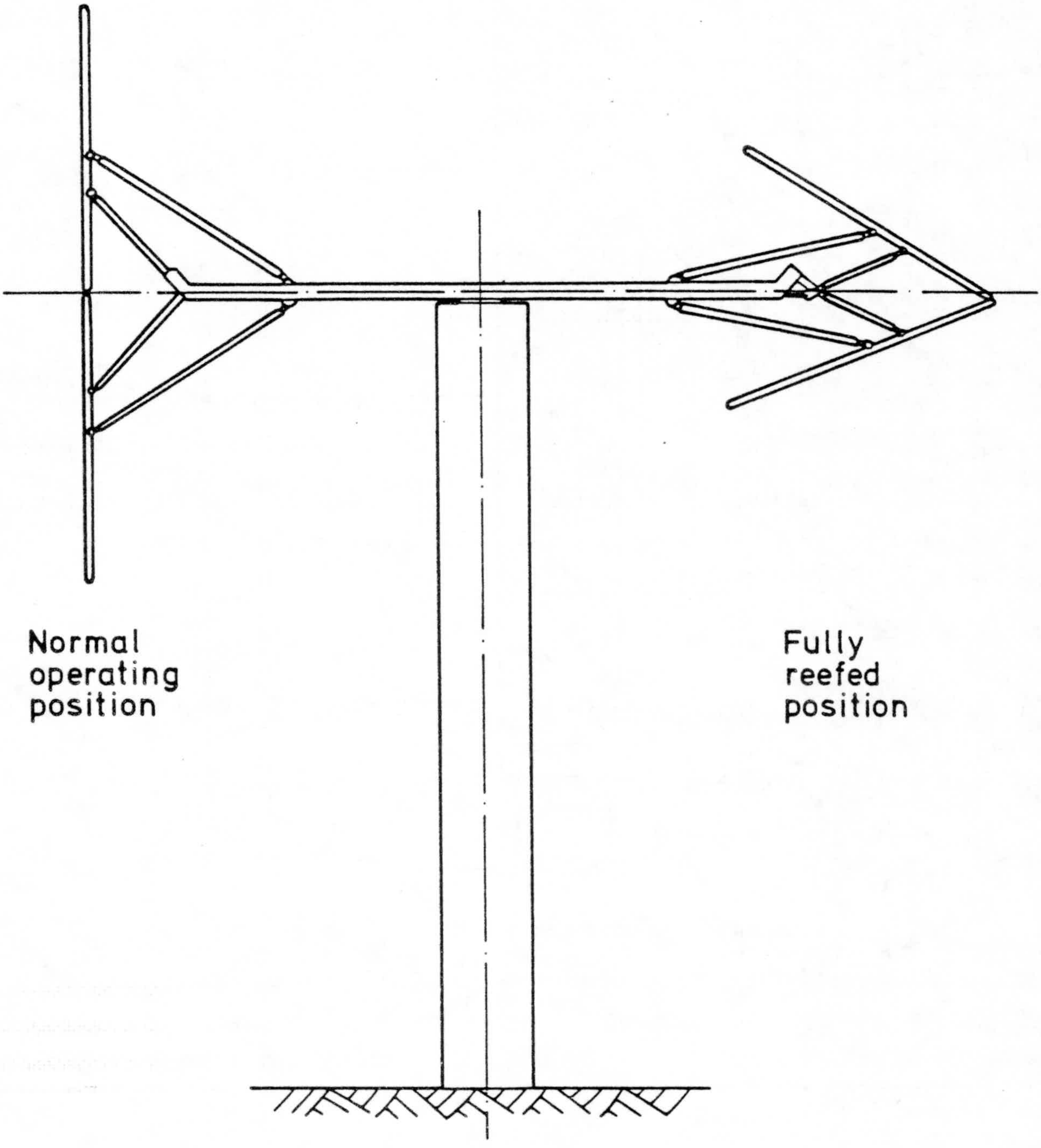
60m WIND TURBINE GENERATOR SCHEMATIC

FIGURE 2



Schematic Darrieus wind turbine.
Courtesy British Wind Energy Association.

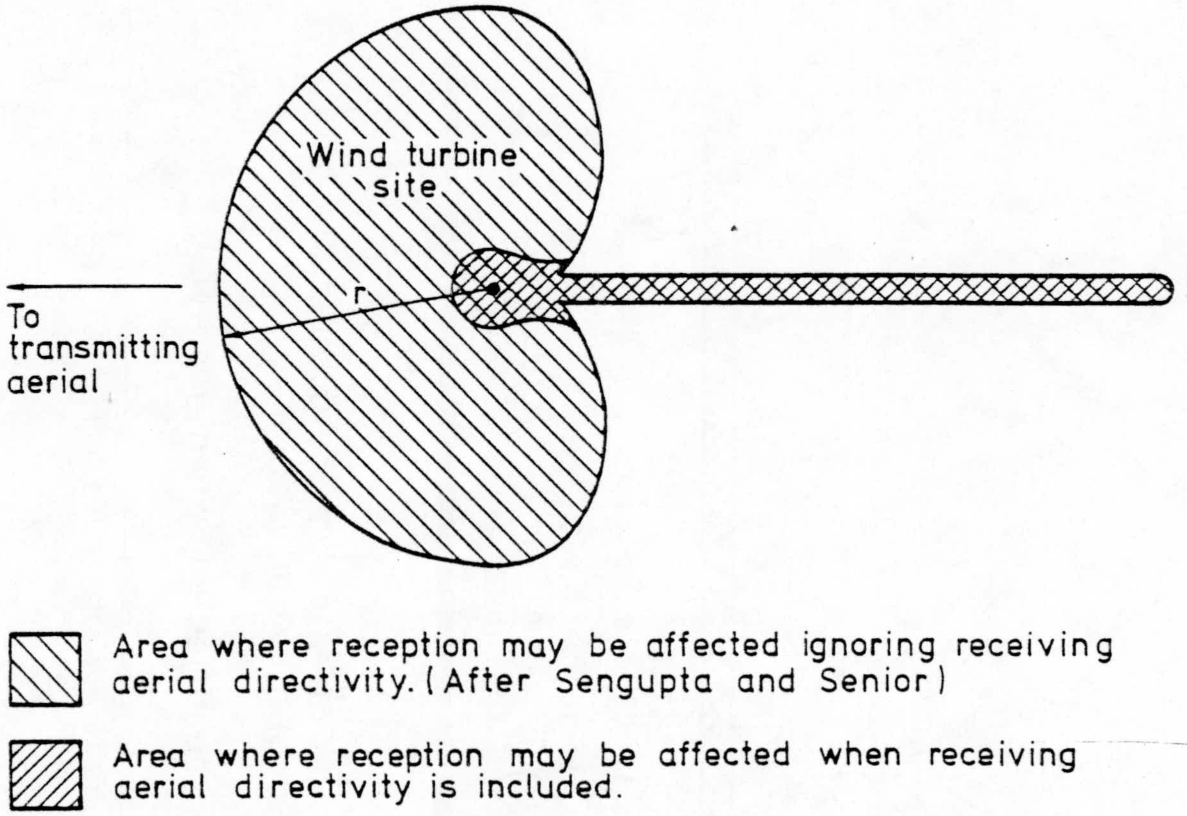
FIGURE 3



The 150 kw vertical axis wind generator of the Musgrove design.
Courtesy Sir Robert McAlpine & Sons.

FIGURE 4

FIGURE 5: Interference Zone Around a Wind Turbine



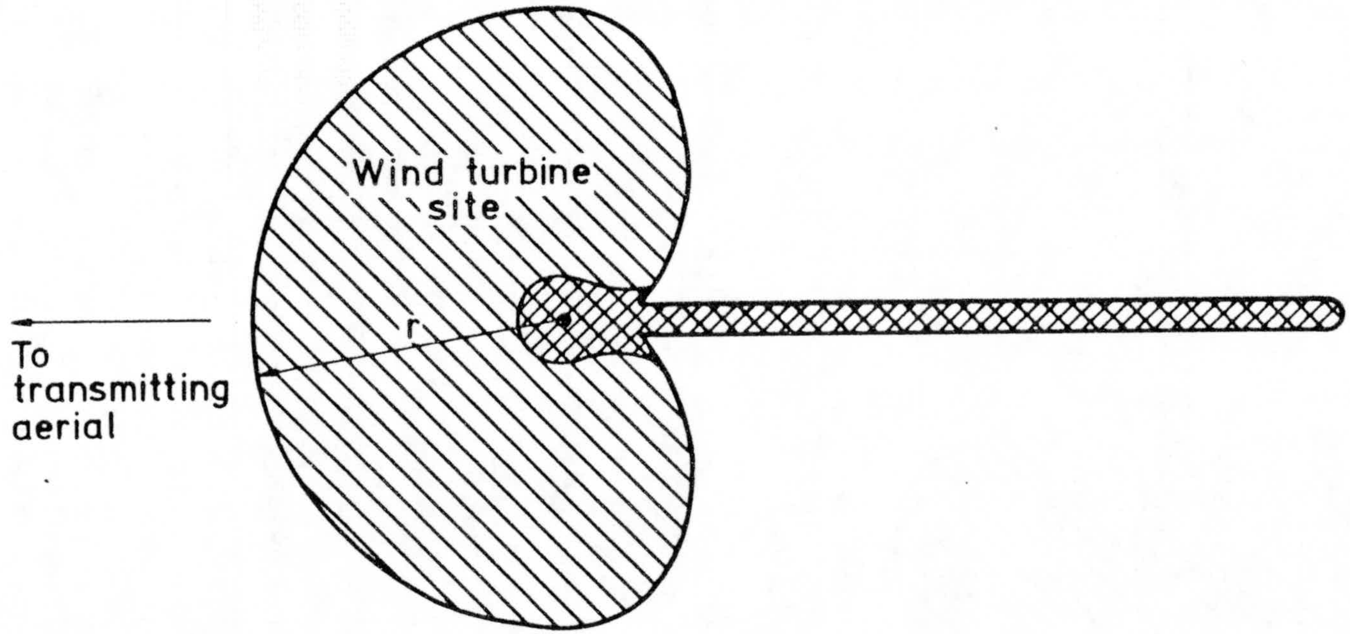
The numerical values of r in the diagram may be derived from the following formula:

$$r = \frac{C \eta A}{\lambda m_o} \text{ metres} \qquad (1)$$

where η is the reflection efficiency
λ is wavelength of radiation (metres)
A is projected area of blade (metres^2)
C is a constant
m_o is the modulation index for unacceptable interference.

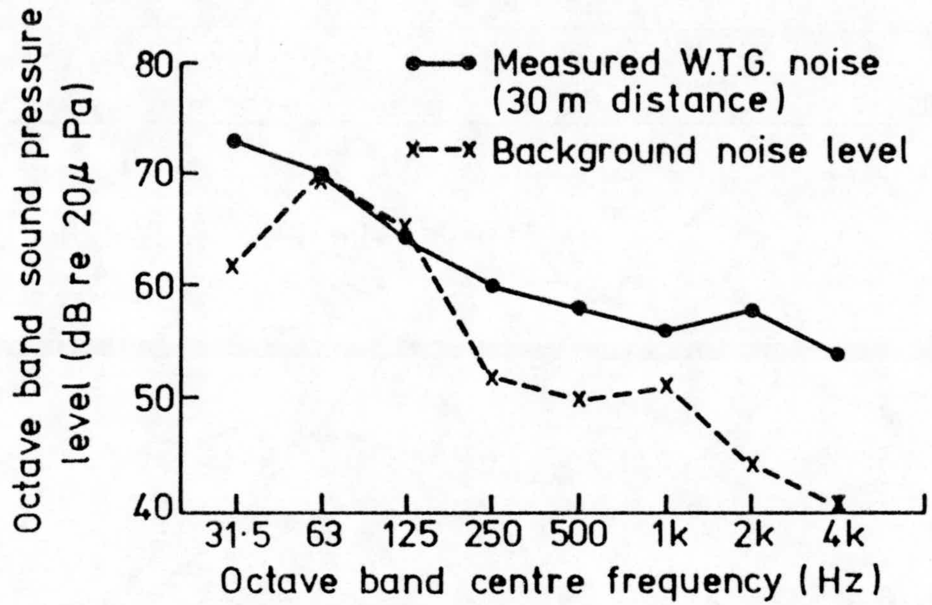
Typical values for η are 0.7 for a metallic blade or 0.3 for a fibre-glass one [Sengupta and Senior, 19] for UHF TV signals in the UK the value of λ varies from 0.64 m to 0.35 m, while the value of C depends on the transmitter-receiver-wind turbine geometry. Broadly speaking, C ranges from a value of 2 when the wind turbine and receiver are within the line-of-sight of the transmitter, to 5 when they are beyond the radio horizon. The modulation index, m_o, is an empirical constant with a value of $\sim$ 0.15.

The above description assumes a flat earth with no buildings or other obstructions. If there is good line-of-sight between the transmitter and wind turbine, and receiver and wind turbine, but not between receiver and transmitter, interference is more likely and the effects will be spread over a larger area. This is more likely to occur for hill-top sites than for sites in lowland Britain.



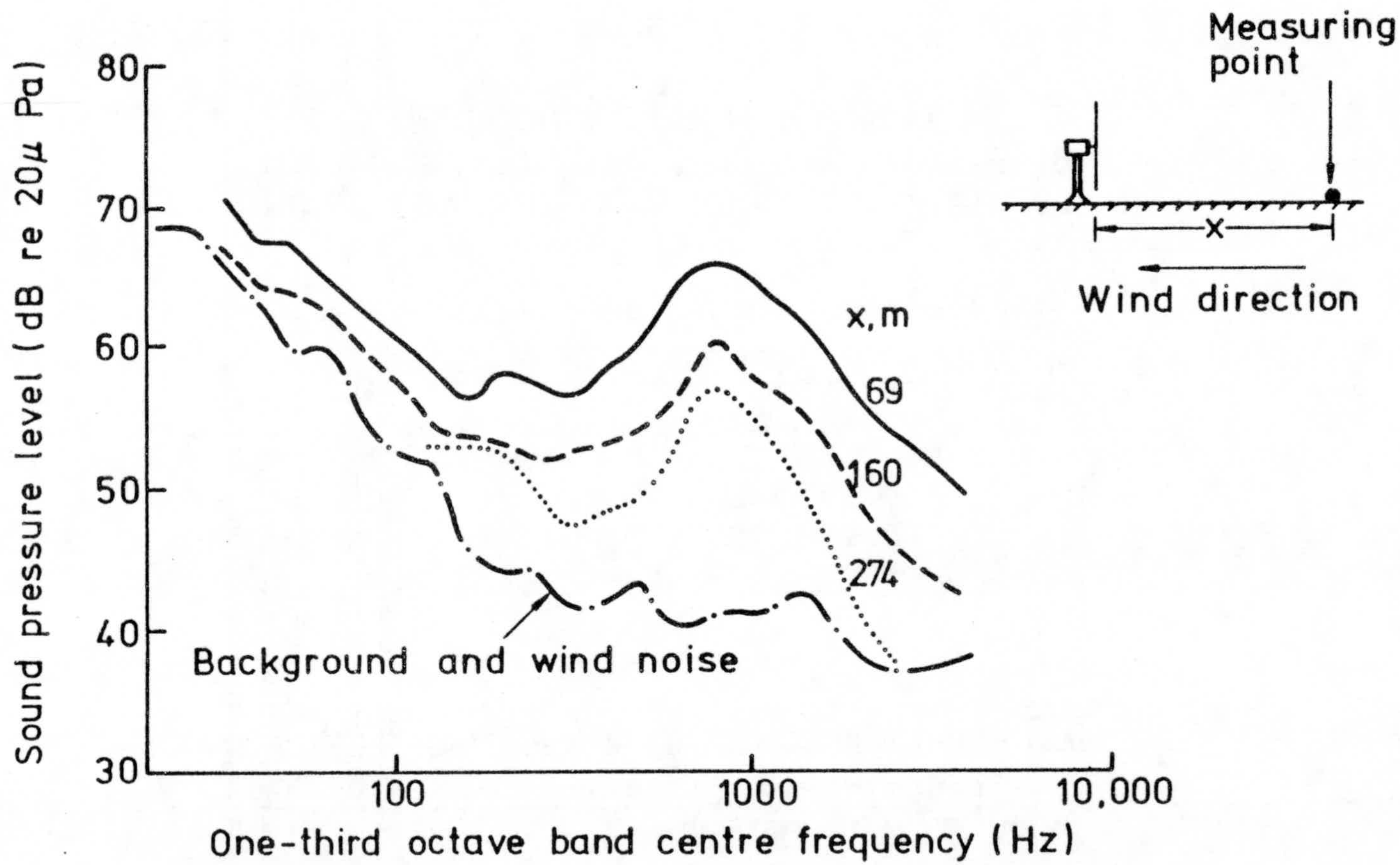
Area where reception may be affected ignoring receiving aerial directivity. (After Sengupta and Senior)

Area where reception may be affected when receiving aerial directivity is included.



NOISE LEVEL OF LAWSON - TANCRED WIND TURBINE GENERATOR (AFTER CHRISTIE, 1981, REPRODUCED FROM MANNING)

FIGURE 6 .



MOD-2 WIND TURBINE GENERATOR NOISE SPECTRA AT GROUND LEVEL UPWIND OF THE ROTOR AT VARIOUS DISTANCES (AFTER HUBBARD ET AL)

FIGURE 7

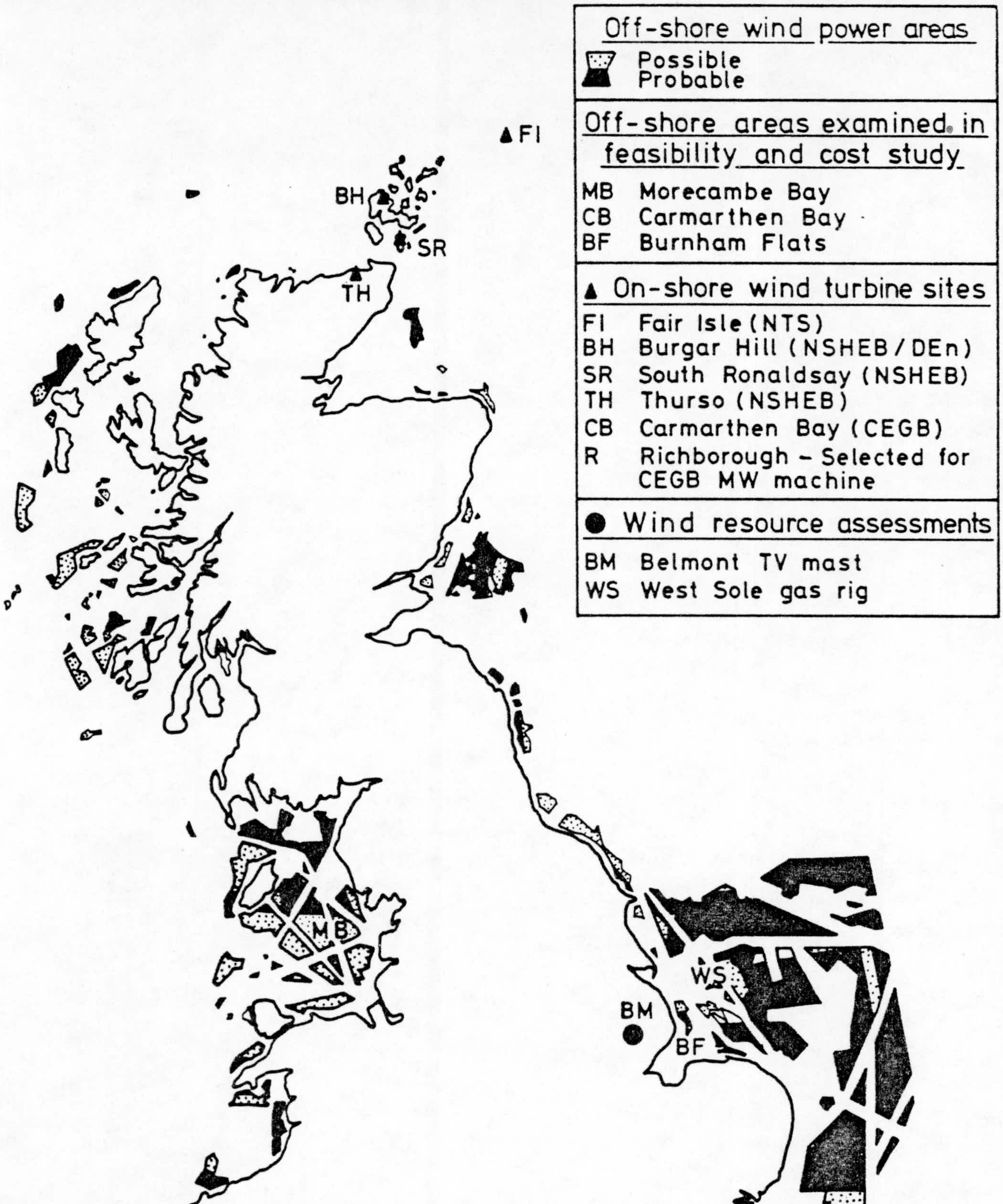

Off-shore wind power areas
Possible
Probable
Off-shore areas examined in feasibility and cost study
MB Morecambe Bay
CB Carmarthen Bay
BF Burnham Flats
On-shore wind turbine sites
FI Fair Isle (NTS)
BH Burgar Hill (NSHEB/DEn)
SR South Ronaldsay (NSHEB)
TH Thurso (NSHEB)
CB Carmarthen Bay (CEGB)
R Richborough - Selected for CEGB MW machine
Wind resource assessments
BM Belmont TV mast
WS West Sole gas rig
FI
BH
SR
TH
MB
WS
BM
BF
CB
CB
R

FIGURE 8