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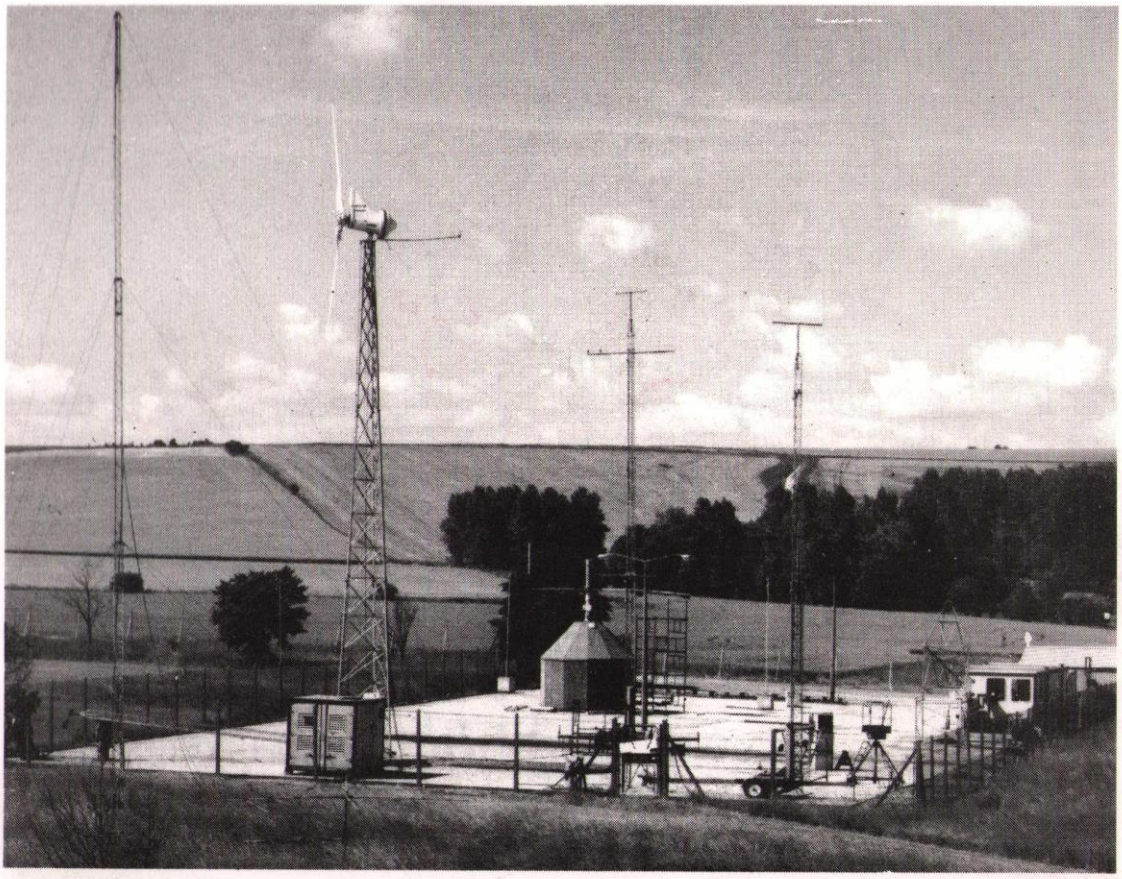
ENERGY RESEARCH UNIT



WIND ENERGY AT RUTHERFORD APPLETON LABORATORY

J H Bass and J T White

December 1987

SCIENCE & ENGINEERING RESEARCH COUNCIL
Rutherford Appleton Laboratory
Chilton
Didcot
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Front cover picture: A panoramic view of the RAL Wind Turbine Test Site (looking South-West).

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INTRODUCTION

Wind energy is now seen as one of the most promising of the renewable energy resources, in particular for electricity generation. Present wind turbine design utilises a combination of the best approaches from modern aerodynamics, materials science and microprocessor control. The utilisation of wind energy, however, is far from new, indeed it is one of the earliest forms of energy exploited by man. Initially, it was used as a means of propulsion for sea going vessels, the first windmills appearing during the 7th century in Persia. By the 14th century it had found uses such as powering sawmills, powering drainage pumps and, its most popular use, for grinding corn. Early in the 19th century small, multi-bladed windpumps were developed in America and Australia and found extensive use on both continents.

The increased mechanisation following the Industrial Revolution led to the development of the steam engine, followed by that of the internal combustion engine. With apparently plentiful reserves of oil, gas and coal available, the price of energy, in real terms, dropped and this meant that wind energy began to lose its importance. Fossil fuels became dominant commodities in the World economy and control of these resources of immense significance.

The sudden and dramatic increase in the price of oil in the early 1970's caused the price of energy to rise substantially, threatening the continuing economic growth of the western world. This shock, together with subsequent price rises, has led to an increased awareness of the finite nature of our fossil fuel reserves and this in turn had led to a re-awakened interest in exploitation of the renewable energy sources, eg. solar, hydro, wind and wave. This interest also derives from concern about the environmental problems associated with some of the conventional sources of generation, eg. acid rain, disposal of nuclear waste etc.

Countries such as USA and Denmark have taken the lead in developing wind energy as a viable alternative. The UK has been slow to recognise the potential of wind energy, but in the last few years several of the UK companies involved in wind energy have secured substantial export orders, and have begun to compete with other countries to harness this cheap and clean renewable resource. The potential of the UK wind resource is itself significant, particularly in the more remote areas of the country, eg. the

Figure 1. A typical scene at RAL Wind Turbine Test Site. In the foreground lies an early version of the Musgrove vertical axis machine and in the background a modern horizontal axis machine.

Highlands and Islands of Scotland. This has led the large UK power utilities to investigate the use of wind generated electricity and there are currently several major projects underway.

It is anticipated that the expansion of the UK interest in wind energy will continue, and, as further research and development enables refinement of wind turbine design, that such technology will lose the 'alternative' label and become an accepted part of our energy future.

WIND ENERGY RESEARCH AT RUTHERFORD APPLETON LABORATORY

Rutherford Appleton Laboratory (RAL) is the largest of the four research establishments of the UK's Science and Engineering Research Council (SERC). It employs over 1150 scientists, engineers and craftsmen plus a further 250 support staff and provides research facilities for, and collaborates with, academic staff in UK universities and polytechnics.

The Energy Research Unit (ERU), formerly the Energy Research Group, at Rutherford Appleton Laboratory has been involved in wind energy related research since 1977. Including university personnel on secondment to the site, there are currently some ten scientists and engineers who actively participate in joint projects with UK research groups and run the Wind Turbine Test Site. ERU is able to draw upon the extensive facilities of RAL, such as the engineering workshops and the highly developed computing resources.

In addition to these research activities, ERU carries out a number of coordinating activities for the Central Office of SERC. These include running an 'Energy Research Grants' database and assistance in the running of a bi-annual 'Energy Round Table'. Occasional 'User Meetings' for groups using the RAL facilities are also run by ERU. Individual members of ERU are very active in providing inputs to both the British and European Wind Energy Associations, BWEA and EWEA, and also contribute to the Commission of European Countries' (CEC) and International Energy Agency's (IEA) wind energy programmes.

THE RAL WIND TURBINE TEST SITE

The RAL Wind Turbine Test Site is run by the Energy Research Group for the

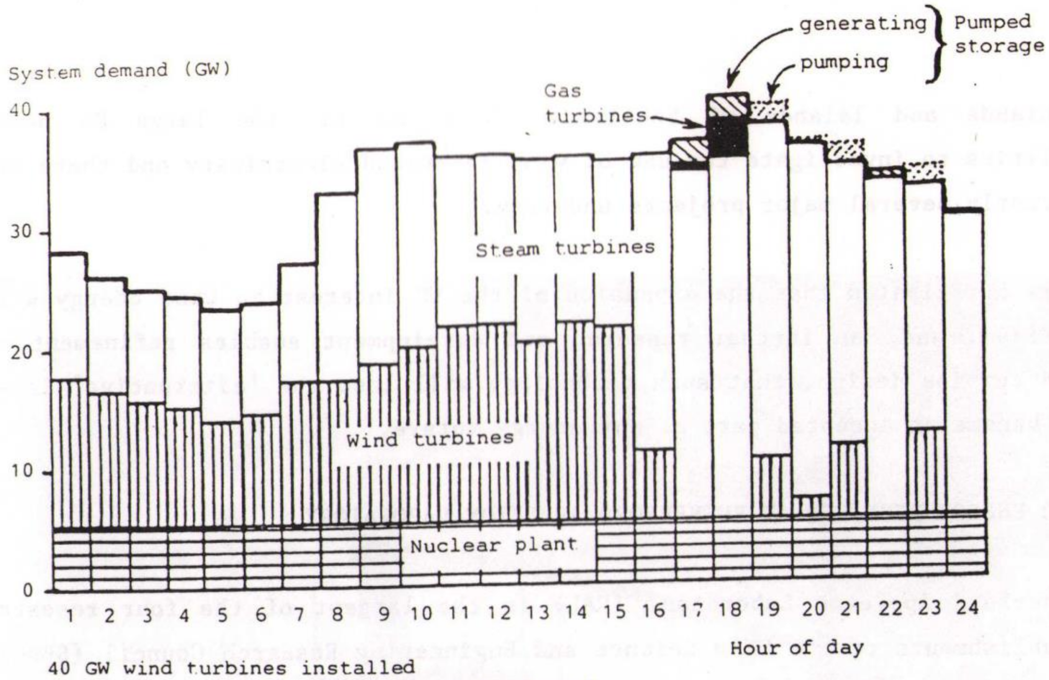

Figure 2. To illustrate the operation of this model, the figure above shows how the system copes on one particular day. After a sustained period of wind generation, at 5pm (1700 hrs) the wind power drops sharply to zero just before the day's peak demand. During the next two hours, from 5-7pm (1700-1900 hrs) the spare capacity of the part-loaded steam plant is insufficient to meet the shortfall in demand and pumped storage plant is therefore brought in, operating at its maximum capacity. This is still not sufficient to satisfy the demand and so gas turbine plant is required. At 7pm the wind power picks up again and the gas turbines are turned off. Available excess steam turbine power is used to replenish the pumped storage plant. By means such as this it is possible to absorb large amounts of fluctuating power output from wind turbine plant.

Figure 3. Locations of the ten meteorology stations considered.
1. Plymouth, 2. Dungeness, 3. Ronaldsway, 4. Bell Rock, 5. Lynemouth, 6. South Shields, 7. Fleetwood, 8. Milford Haven, 9. Scilly, 10. Lizard.
Note the position of the Shetland Islands (see Project No. 2).

Science and Engineering Research Council (SERC). It is operated as a wind energy research centre for UK university groups working in the field. Experimental work is carried out on the site and in addition various computing facilities are made available. The latter include an extensive wind database and also a number of models developed by members of ERG and visiting universities. The experimental equipment on the site includes four wind turbines, ranging in size from 50W to 16kW.

The Test Site itself occupies approximately 3000 square metres and has the important advantage that it is secure. At present buildings occupy about 110 square metres although all except the main Control Room can be considered temporary. The site has been intentionally kept clear of buildings in the prevailing wind direction, ie. W/SW.

Two 18m. meteorological towers are used in support of projects at the site. The wind regime of the site is now monitored constantly and the results made available to site users. In addition facilities have been developed for the transfer of data from various data loggers, data recorders and microcomputers onto the RAL mainframe computer. These data can then be accessed directly by universities via the Joint Academic Network (JANET) or SERCNET.

Several projects are currently in progress, ranging from those concerning local or small-scale use of wind energy to those involving national, large-scale exploitation of the wind resource. Some examples of recent and ongoing projects are presented below.

1. WIND ENERGY INTEGRATION INTO THE UK ELECTRICITY GRID

Participants: ERU.
Energy Group of the University of Reading.

Project Aims: To assess the operational and economic impact of the large scale use of wind generated electricity in the UK National Grid.

The Approach: The analysis is based on a computer time-step simulation model of the entire UK electricity grid. This model is based on a detailed knowledge of conventional generating plant and operating practices of the CEGB (see figure 2).

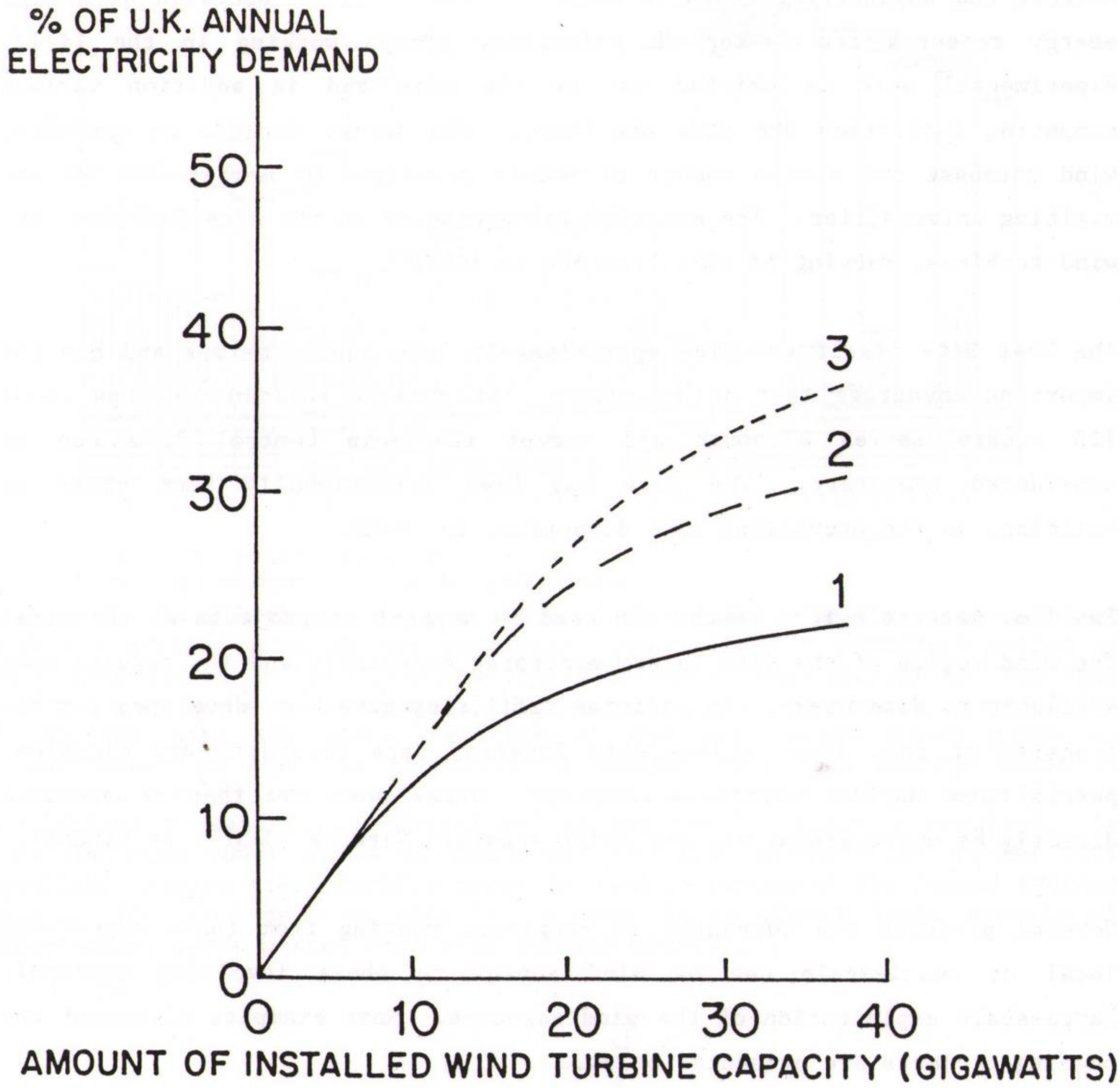

Figure 4. This graph shows the effect on the fraction of the annual UK electricity demand that can be satisfied by wind power when the same capacity of wind plant is:

1. Installed at one site only. (————————)
2. Spread equally between three sites. (— — — — — —)
3. Spread equally between ten sites. (- - - - - - - -)

We see that a much greater contribution from the wind can be accepted if the wind turbine plant is more widely dispersed. For example, 20GW of plant could satisfy 19% of the annual electricity demand if concentrated at one site or 25% if distributed over ten sites.

Some of the major findings of the modelling work were:

(i) Annual savings in the CEGB's fuel budget of £800 million (1981 prices) could be realisable with the addition of around 20GW of installed wind turbine capacity.

(ii) Approximately 20% of the annual CEGB electricity demand could be supplied by wind power without any major difficulties.

(iii) There were useful savings to be made by re-optimising the plant mix when installing wind plant. In particular, expensive base-load plant, such as coal and oil fired steam turbine plant, could be replaced with cheaper, fast response peaking plant, such as gas turbines. This could increase the total annual savings to the CEGB to about £1,200 million (again, 1981 prices).

(iv) The geographical dispersion of installed wind generating capacity could provide a smoothing effect and enable a greater amount of the available wind energy to be used (see figures 3 and 4). Wind data from ten meteorological stations around the UK were obtained and the effect of distributing the same total installed capacity of wind plant equally between these sites assessed.

(v) Better techniques for forecasting wind speed would improve predictions of available wind power and enable even greater use of this energy source to be made.

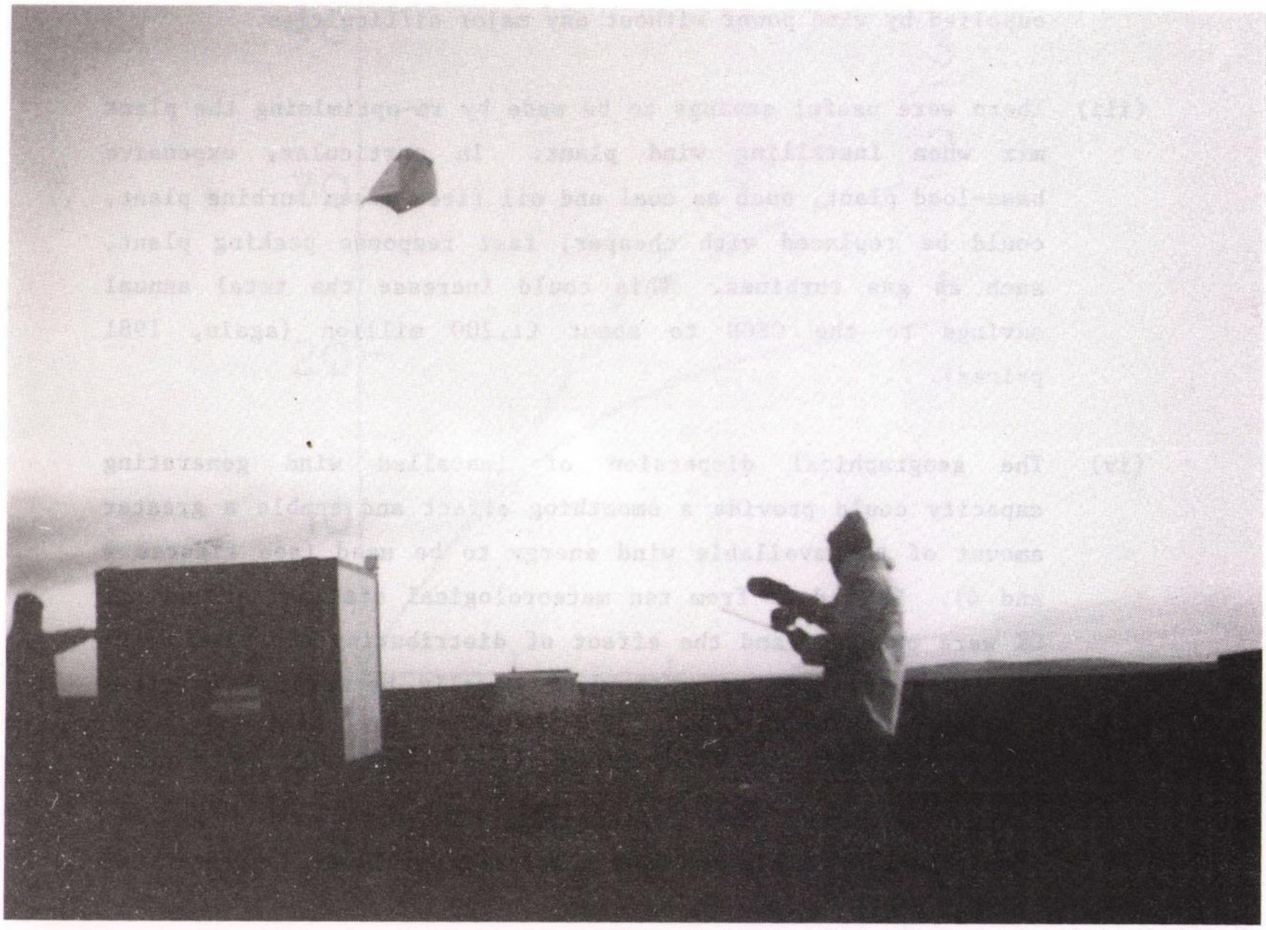

Figure 5. RAL personnel collecting wind data on the Hill of Susetter, Shetland.

2. MESO-SCALE WIND INTEGRATION BASED ON THE SHETLAND GRID

Participants: ERU.
North of Scotland Hydro Electric Board.
Energy Studies Unit of the University of Strathclyde.

Project Aims: To assess the potential for large scale power generation on the Shetland Islands using wind turbines. There are three separate components to the work:

(a) Assessment of wind resource. The long term potential of two hill top sites is being evaluated by monitoring the wind regime of each and relating them to simultaneous measurements from two local Meteorological Office Stations, at Lerwick and Sumburgh (see figures 5,6 and 7).

(b) Assessment of the fossil fuel savings that a wind energy input would make and identification of any changes in the operating strategy of the existing 60 MW of diesel generating plant that might be required.

(c) Assessment of any changes in the quality of the electrical supply, ie. voltage and frequency stability, that might result from the presence of wind turbines connected to the island's electricity grid.

The motivation for the project is financial. Diesel generation of electricity on remote islands, like Shetland, can be very expensive and in an effort to reduce their costs the NoSHEB have chosen to investigate the potential of the local wind resource.

At each of the two hill top sites, Scroo Hill and the Hill of Susetter, a guyed 45m mast has been erected. Each mast is instrumented with anemometers, wind vanes and thermometers so that wind speed, direction and ambient temperature can be measured.

This information is automatically recorded for subsequent analysis and assessment of the wind resource. A computer simulation model of the Shetland Island electricity supply system is used to predict the impact of this wind input on the operation of the power station. A further computer model examines the electrical transient problems.

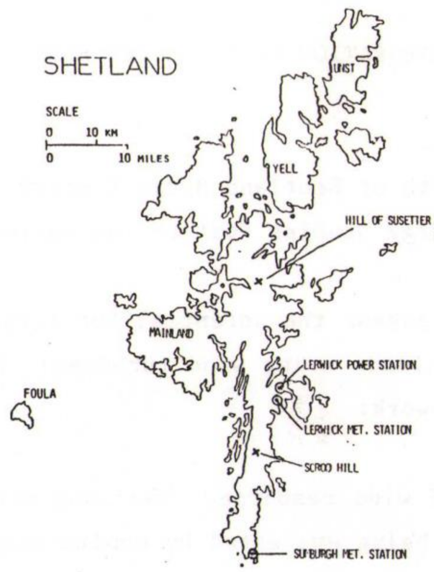

Figure 6. The location of the two meteorological masts and the two Meteorological Office Stations.

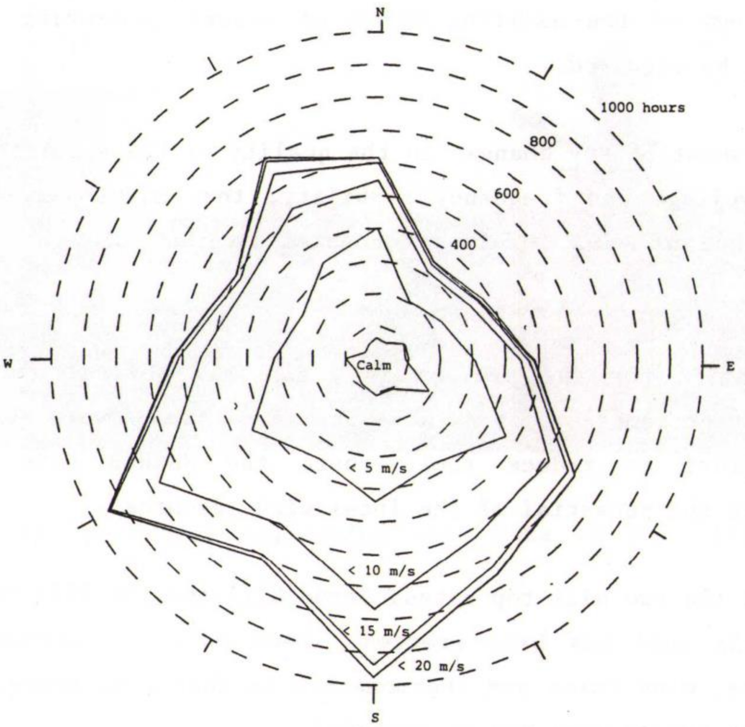

Figure 7. A wind rose chart for Scroo Hill between 1st December 1984 and 2nd December 1985. The chart represents the frequency distribution of wind speed and direction at 35m. Such graphs are useful in determining the suitability of a site for wind turbine generators, and on the basis of the data obtained from the two sites, the NoSHEB has decided to install a 750 kW wind turbine on the Hill of Susetter.

3. AUTONOMOUS WIND/DIESEL SYSTEMS

Participants: ERU.
Imperial College of Science & Technology.
Leicester University.
Hawker Siddeley Power Plant Ltd.
John Laing & Sons Co. Ltd.

Project Aims: A large potential demand for electricity exists in areas isolated from grid supply. Diesel generation in these usually remote areas, although common, is very expensive due to the high cost of both purchasing diesel fuel and then having it delivered to the site. 'Wind/diesel' systems, with the wind turbine viewed primarily as a fuel saver, can be very attractive in such circumstances.

The Approach: To gain operating experience with and to identify some of the likely problem areas, a wind/diesel system consisting of a 7 kW HSPP diesel generator and a 16 kW Northwind wind turbine has been installed at the RAL Test Site.

The simplest control strategy for such a system is to run the wind turbine and diesel generator in parallel. The wind turbine supplies as much of the consumers load as possible and any residual load, which it cannot meet, is then supplied by the diesel generator. The diesel set runs continuously to provide continuity of supply and control of voltage and frequency. This strategy has drawbacks, however, such as:

(i) Low wind energy utilisation.
(ii) Prolonged low load running of the diesel set. This can increase wear and lead to a reduction of its working lifetime.
(iii) Fuel savings are relatively small.

To make large reductions in fuel consumption it is desirable to shut down the diesel generator during those periods when the wind power available is sufficient to meet the demand on its own. The drawbacks of this 'intermittent diesel' strategy are chiefly:

(i) High numbers of start/stop cycles of the diesel generator because of the variability of wind turbine power and consumer load.

(ii) Poor quality of supply, in terms of voltage and frequency stability.

A conceptually simple solution to these problems of frequent start/stops and poor quality of supply is the introduction of a storage medium into the system. Its primary role is to reduce diesel start/stop cycling to an acceptable level. However, because it also has the effect of 'buffering' excess wind energy until it is needed, it also facilitates greater continuity and a better quality of supply.

Most forms of energy storage are very expensive and this means that in practical and cost effective systems only limited amounts of storage will be viable. In the particular application of a wind/diesel system, any storage medium or device must be capable of tolerating both frequent and rapid changes in the direction and magnitude of the energy flow, without undue wear or a reduction of their working lifetimes. A variety of candidate storage media are potentially suitable and some of these are currently being investigated. At RAL the proven technology of flywheel storage is now being exploited.

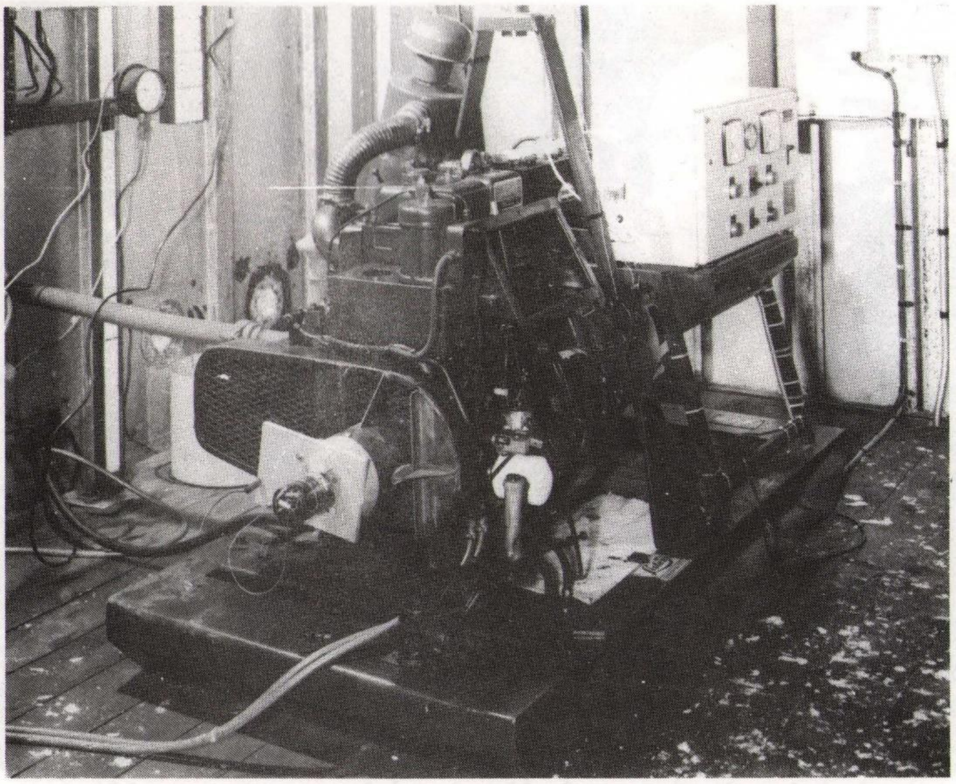

Figure 8. The Nova II 7 kW diesel generator at RAL.

Figure 9. The Northwind MP9 16 kW wind turbine generator at RAL.

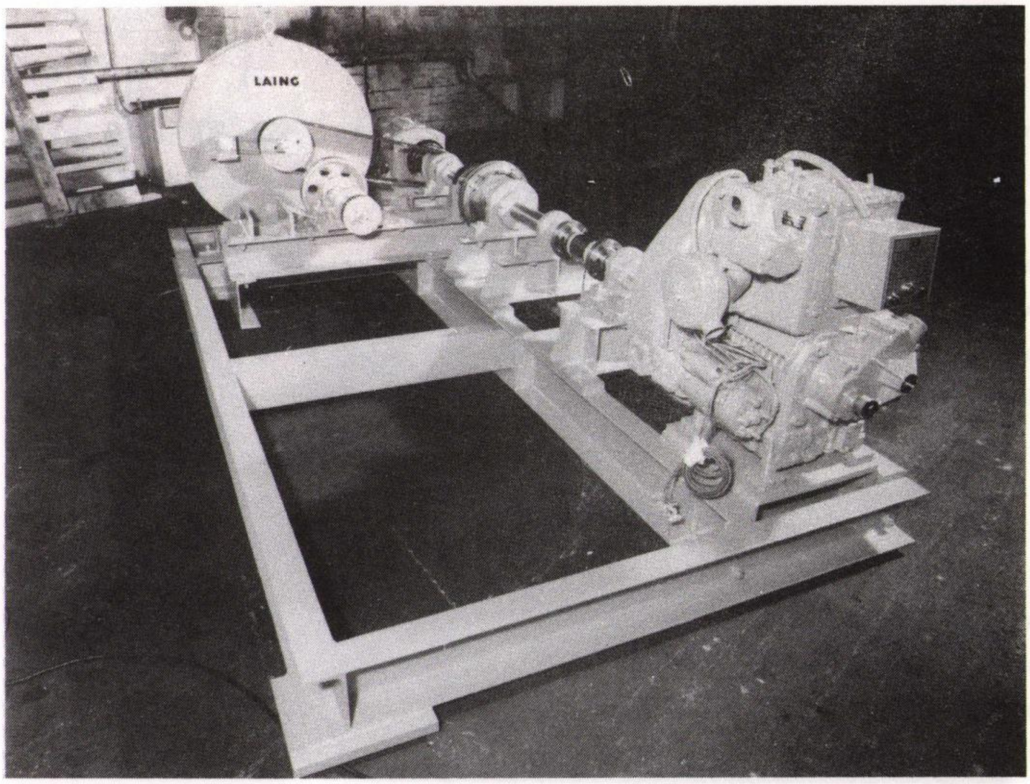

Figure 10. A view of the diesel/flywheel rig under test at RAL. Flywheels are a relatively cheap and simple form of storage where energy is stored as rotational kinetic energy in a large rotating mass. These can 'smooth out' the fluctuations in the output from a wind turbine and allow the more rapid starting up of diesel sets following lulls in the wind.

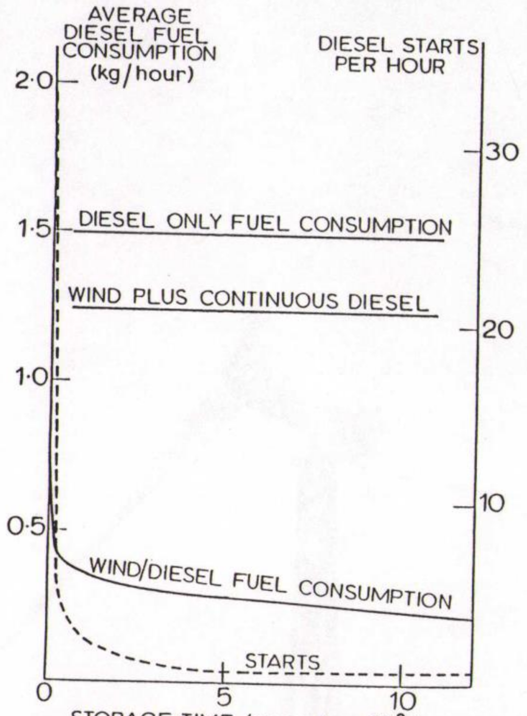

Figure 11. The calculated effects of increasing amounts of storage on both diesel fuel savings and start/stop cycling. The initial rapid decrease in the rate of fuel consumption and the frequency of diesel starts for relatively small amounts of storage, ie. 100-200 seconds, illustrates the dramatic improvements that can be obtained. Here storage time is defined as the ratio of the amount of storage in the system to the average level of consumer demand.

4. WIND CLIMATOLOGY STUDY

Participants: Climatic Research Unit of the University of East Anglia
ERU.

Project Aims: To investigate the wind climate of the British Isles with a view to assessment of the wind resource and the potential for electricity generation. In particular to investigate the long term variations in the wind resource that occur as a result of climatic change, and so enable more reliable estimates of available wind power to be made.

The Approach: Historical wind data has been obtained from a network of carefully chosen Met. Office Stations around the UK. After allowing for the effects of local terrain, it is hoped that it will be possible to build up a picture of 'national' changes in the wind characteristics over the last few years. This information will enable much better estimates to be made of the annual energy output of a wind turbine at a given site.

5. OPTIMISATION OF SMALL WIND TURBINE GENERATORS

Participants: Energy Group of the University of Reading.
Marlec Engineering Co. Ltd.
ERU.

Project Aims: In many parts of the world there is a need for small, low cost wind turbines to charge batteries and power a wide variety of small-scale applications, eg lighting, radio telephones etc. Marlec Engineering, who have already designed and now market a highly successful 50 W machine, have recently designed a larger, 250 W machine and are interested in optimising its generator and rotor design, with a view to improving both energy yield and working lifetime.

The Approach: The 250 W prototype machine is to be installed and erected at the RAL Test Site. The aerodynamic performance of the rotor will be examined to indicate the 'best' design for the blades. In particular researchers will be investigating the effects of changing the blades' profile, pitch, twist, taper and solidity. On the electrical side, the generator will be bench tested over the full range of rotor speeds to determine its characteristics. Using this data it will be possible to identify any modifications that need be made in order to optimally match the performance of the generator to the rotor.

6. THE IMPERIAL COLLEGE WIND TURBINE

Participants: Imperial College of Science and Technology.

Project Aims: A prototype wind turbine incorporating a number of novel features has been designed and built at Imperial College. The aim has been to develop a versatile research tool that will allow the impact of these various features to be assessed.

The Approach: The wind turbine is a downwind, horizontal axis type machine featuring active pitch control to provide control of the rotor's speed. It has novel features on both the mechanical and the electrical side. The rotor incorporates 'free coning' blades which are individually balanced and mounted on separate universal joints. This enables the blades to 'shed' gusts in the wind and reduces the aerodynamic loading due to turbulence. It is hoped that this will improve their fatigue life. On the electrical side, the machine is able to operate in a variable speed mode by virtue of a specially designed, single phase induction generator. In addition, a dedicated 16 bit microprocessor controller is used to 'optimise' the energy output of the machine.

The turbine, which has a hub-height of 9m, has had two sets of blades designed for it. Initially it is to be fitted with 3.6m diameter blades, giving a rating of 1.5 kW, and after testing these will be changed for larger 8m blades, giving a rating of 7 kW.

Figure 12. The 5 kW vertical axis machine at RAL.

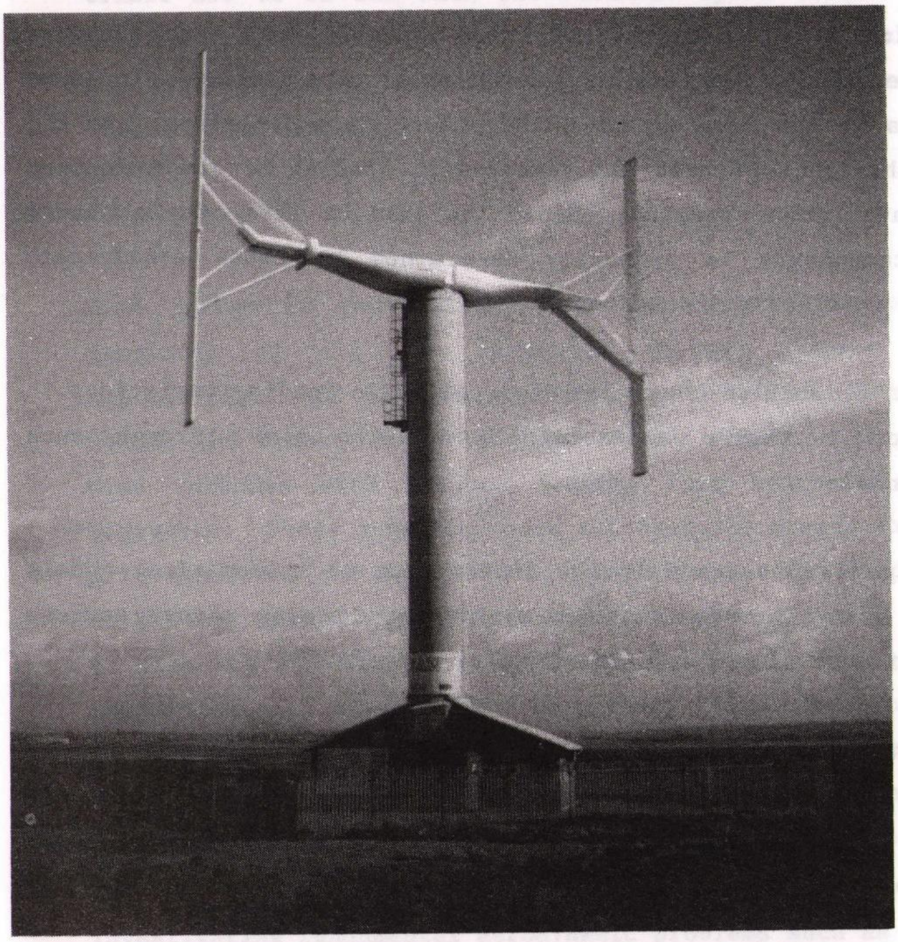

Figure 13. VAWT Ltd's 130 kW machine at Carmarthen Bay.

7. THE RAL 5 kW VARIABLE GEOMETRY, VERTICAL AXIS WIND TURBINE

A prototype 5 kW vertical axis type wind turbine was constructed at RAL during 1977. Designed by Dr Peter Musgrove of the University of Reading and supported by the SERC, such wind turbines have now become known as the 'Musgrove' type. The design has stimulated much industrial interest and a 130 kW version has now been constructed and installed at Carmarthen Bay, South Wales. Built by Vertical Axis Wind Turbines Ltd, the 25m tall, 25m diameter research machine can generate in wind speeds of up to 30 m/s.

RAL's 5 kW machine is still maintained and has become a valuable research facility. Two examples of projects that make use of this facility are shown below.

1. UNSTEADY AERODYNAMIC RESPONSE OF VAWTS.

Participants: Cranfield Institute of Technology.

Project Aims: In their normal operation vertical axis wind turbines are subjected to a variety of aerodynamic conditions. In some circumstances it has been observed that there is a departure from the predicted behaviour and that the aerodynamic loading of the structure is much greater than expected. Since the fatigue life of the blades and other components is primarily determined by these aerodynamic forces there is clearly a need to:

(i) Obtain a detailed knowledge of aerodynamic loading variations.
(ii) Develop a better understanding of air flow through such turbines.

Such knowledge is necessary in the development of mathematical models used in the design process of such machines. It also allows assessments of their useful working lifetimes to be made.

The Approach: These aerodynamic effects have been investigated by constructing special carbon composite blades sections that are extensively instrumented with pressure transducers. These have been subjected to tests in both wind tunnels and mounted on the vertical axis machine at RAL. It is hoped that, by analysis of the data obtained, areas where current aerodynamic theory is inadequate can be identified.

2. ELECTRICAL MACHINES: THE VARIABLE SPEED DRIVE.

Participants: Leicester University

Project Aims: To research methods that allow the variable speed operation of an electrical generator when connected to a 'fixed' frequency grid system. In particular to develop a machine that will allow the variable speed operation of a wind turbine. Advantages include:

(i) Greater operational flexibility.

(ii) Increased Energy Capture.

The Approach: A variable speed drive has been developed in the Engineering Department of Leicester University. To investigate appropriate control strategies for the device a series of proving trials are to be run with the variable speed drive connected to the vertical axis machine at RAL. Ultimately it is hoped to incorporate the variable speed drive into the autonomous wind/diesel/flywheel rig discussed in Example 3 earlier.

8. CONCLUSIONS

Wind energy is increasingly becoming regarded as one of the most promising of all the renewable energy sources for commercial exploitation. UK manufactures such as the Wind Energy Group, James Howden and Company and VAWT Limited now supply a range of commercial wind turbines with outputs ranging from hundreds of kilowatts to Megawatts. These have been used successfully around the world for both grid connected and stand-alone applications. The Energy Research Unit at RAL has made a significant contribution to research and developments in wind energy; concentrating on small and medium scale wind systems, meteorological wind site surveying, wind turbine control and aerodynamics. These activities have involved close collaboration with both universities and UK industry. It is anticipated that our work will continue to develop with new projects planned on applications of power electronics to energy storage and advanced techniques for investigating fundamental aerodynamic problems such as anomolous stall.

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