The integration of renewable electricity sources

M. J. Grubb

The variable and energy-limited nature of electricity output from many renewables impede their use in small-scale applications. The drawbacks are much less when renewables are connected to integrated power systems. Indeed when capacities are small relative to the total system, renewables can often be more valuable than conventional sources, and very large capacities can in general be accommodated without incurring major operating penalties. Also, the characteristics of different variable and energy-limited renewable sources are usually complementary, and current trends in power system development will further ease their integration. With the possible exception of very large-scale use of photovoltaics, it seems most unlikely that the special characteristics of renewable electricity output will significantly limit their use, provided that their role in power systems is properly managed and reflected in the tariff arrangements for renewable generators.

Keywords: Renewable energy; Integration; Power system economics

The output from most renewable sources of electricity differs from most conventional power sources. Sources such as wind, solar, wave and tidal energy, are usually 'variable': their output follows the natural fluctuations of the weather and tides.[1] Even hydro and biomass electricity differ from conventional thermal plants, in being limited by the amount of energy available rather than the generating capacity installed. As such renewable energy sources receive increasing interest – both in the short term because of the rapid economic advances in wind energy especially, and for the long term because of their potential strategic and environmental importance – questions about the value of such sources when integrated on power systems are attracting growing attention.

It has been widely assumed that the variable nature of many renewables poses a serious obstacle to their deployment, and would necessitate storage which could be costly, The International Energy Agency (IEA) stated that the special characteristics 'present a limitation to expanded utilization of some economic renewable energy technologies.'[2] A generally positive report by the US DoE stated that 'energy storage, or a supplemental source of energy, may have to be provided to make solar energy marketable'.[3] McLarnon and Cairns state that 'energy storage is critical to intermittent energy systems'.[4] Such assertions appear reasonable, but they are assumptions, not conclusions. Serious analysis reveals them to be largely without foundation.

This paper examines the extent to which the special characteristics of renewables affect the value of their output. What penalties do variations and limited predictability impose on the operation of the rest of the system? How much backup capacity is required to maintain a reliable system, and how does this affect the economics? How much benefit might be obtained from greater geographical and source diversity, and how might this compare with the additional transmission requirements? More generally, how would incorporating renewables affect the optimal plant mix and system operation in the longer term, and to what extent might the special characteristics of many renewables constrain their feasible long-term contribution?

These are not new questions, many of them having been examined to some degree in various modelling and other studies, particularly since the substantial efforts undertaken by the US Solar Energy Research Institute at the beginning of the 1980s.[5] This paper examines the key factors which affect the value of variable and other renewable electricity sources on power systems, places this in the context of power systems as they are now evolving, and considers the potential role of various combinations of renewables on such systems.

Before embarking on this, it should be empha-

M.J. Grubb is with the Energy and Environmental Programme, Royal Institute of International Affairs, 10 St James's Square, London SW1Y 4LE, UK.

0301-4215/91/070670-19

sized that, as for many other aspects of renewable sources, few generalizations hold for all renewables; indeed, the characteristics of each are very distinct, and can also vary according to the location and pattern of their deployment. A number of important renewable sources are not significantly variable. Biomass is one obvious example. Large-scale hydropower taps a somewhat variable source (river flow) but with a large inherent storage capacity – usually with inter-seasonal capability, and sometimes enough to smooth across inter-annual variations. Small-scale hydro schemes follow variations in river flow more closely, but are usually still associated with a limited storage capacity. Ocean thermal energy is a genuinely constant source; so, often, is geothermal energy (which is usually considered as a renewable source, although generally it is not because heat is extracted faster than it is replaced).

Some of the technologies for tapping direct solar energy can also smooth out some of the variations. Solar ponds, in which solar-induced temperature differences between layers in salt ponds are used to drive steam turbine cycles, may produce relatively smooth output, with a storage capacity ranging from hours to days. Central 'power towers' in which mirrors focus sunlight on a central boiler, may also give a few hours inertia. The dispersed thermal systems developed by Luz International for California, in which parabolic reflectors heat oil to drive a steam turbine, adopt a different approach; natural gas is used to provide an alternate heat source for the turbine for occasions when peak demand coincides with periods of low solar radiation.[6]

There are, however, important renewables which are inherently variable and which cannot readily have storage or other backup integrated with the design. Outstanding among these are photovoltaics, which arguably offer the greatest long-term potential of any of the renewable sources, and wind energy, which is among the most developed of the major non-hydro renewables. Wave energy and tidal energy, which may also offer important potential on some systems, are also inherently variable.

It is with the economics of such sources when integrated on large power systems that most of this paper is concerned. Before addressing this, it is useful to consider first the scope for and issues raised by other possible applications, and broader issues of power system economics.

Isolated supplies and small systems

Many renewable sources are already used, or under consideration, for applications where the demand is too small to be met by large conventional power stations, and which cannot readily be connected to existing grids.

At the extreme are various mobile applications, such as caravans, and applications which are too small to justify even short extensions from electricity grids. Windmills have been used for centuries to provide mechanical power, and in addition to continuing widespread use for irrigation pumping they are now used for various forms of remote electrical power. Photovoltaics (PVs) tend to be best suited to the smallest modern electrical uses, because the unit costs depend little on the scale of application. Storage is usually required, but for small applications the costs are modest, partly because PVs can generate at least some power every day. In addition to various familiar micro-electronic applications, Hill[7] reports that even in a country such as the UK there are many possibilities: PV is frequently the most cost-effective option for communication repeater stations, cathodic protection of various structures, motorway signs and telephone points, boats and caravans, as well as isolated dwellings: 'it is now cheaper to install a PV lighting unit in a shed at the bottom of the garden rather than pay to have a mains cable'.[8] In developing countries the potential applications are much larger still, and PV can provide invaluable services for mobile or remote refrigeration, lighting, etc.

In addition, there are some homes in most countries which are far from grid supplies. In such applications the cost of the renewable source itself may indeed be a secondary factor; the choice may be driven largely by the competition between the cost of adequate storage against that of the copper lines for connecting to the nearest alternate source of power. Though the applications are small, in total they can be considerable even in countries with developed grid systems; the Californian Pacific Gas and Electric utility has estimated that isolated supplies might total up to 5% of the electricity already supplied through the grid system, and that exploiting these with stand-alone renewable units could yield considerable savings over the costs of continuing to extend the grid.[9]

A different situation is presented by rather larger isolated uses, for example on small islands or isolated villages or farms. In many tropical and subtropical regions, PV may be suitable, but as evening lighting is often a main load, considerable storage may be required. For many island supplies, wind and perhaps shore-based wave machines are promising. Wind is also frequently better suited than PV inland in temperate zones, for example in mountain villages, though combinations with PV can also be of interest.

Currently, such loads are usually met using diesel generators, and the primary interest in renewables is to offset the high costs of running diesel. However, diesel sets are generally cumbersome in operation, with considerable losses incurred in startup, shut down, and part loading (ie running below design capacity), and with many constraints on the rate of change in output and minimum stable output levels. Together with the high variability of output from individual wind turbines, for example, this can result in considerable operating penalties on wind–diesel systems, and the economics can depend heavily upon the development of sophisticated control strategies. In one successful application on Fair Isle, with a single diesel set, some loads are controlled automatically to minimize the need for operation of the diesel set (eg fridges are placed on circuits which can be interrupted for short periods).[10] As compared with the previous diesel-only operation, large savings, together with improved quantity and quality of supply, have been obtained. Other applications make use of small hydro schemes to provide a degree of storage and control, further reducing operation of the diesel set.

On larger diesel systems, the operation and role of renewable sources begins to have more in common with that of large power systems. Some diesel sets are always running, and the system operators need to adjust their scheduling to take account of additional variations imposed by the renewable input. Good control can again yield considerable savings,[11] but the high variability of wind input, for example, combined with the poor operating characteristics of diesel sets means that the renewable contribution may be severely limited if large operating penalties are to be avoided.

Successful applications of renewables for isolated and small-scale supplies can undoubtedly be of great value to those who benefit directly from them, and they offer a market which is very significant for the renewable energy industries. PV, indeed, has largely developed because of such 'niche' markets, and the frontiers of such markets are steadily expanding. But in terms of global electricity supplies, and their economic and environmental impact, such applications are likely to remain marginal compared with the energy provided through large-scale power systems.

One way in which renewable electricity sources could in principle make a large global contribution would be if they could find a way into the transport market. Producing hydrogen from PV in desert areas has been proposed as one of the most promising ways of displacing oil in transport, with long-run costs estimated at $1.70 to $2.40/gallon of gasoline equivalent.[12] An alternative transport application might be to use stand-alone renewable (probably PV) units at car parks, homes, garages or automated roadside filling points, to charge batteries for electric cars or perhaps to generate hydrogen for hydrogen vehicles. This would bear closer analysis as one of the long-term options for moving away from gasoline, but is highly speculative and clearly faces important economic and infrastructural hurdles.

With this exception, renewable electricity sources can only make a major contribution to resolving energy dilemmas if they can compete when integrated into large power systems. The rest of this paper focuses upon the issues this raises.

System operation and the role of different plant types

Electric power systems comprise a wide variety of generating plant types. One key distinguishing feature is the ratio of capital costs to operating costs. For meeting peak loads, plants which are cheap to build but relatively expensive to run are most suitable, because they are not required to run very often. For meeting baseload demand, capital-intensive plants with much lower operating costs are more appropriate. In practice, the great majority of investment in power systems have been associated with plants for baseload operation.

Only one generalization appears to apply to almost all renewable electricity sources, and that is that they are capital intensive, with relatively low operating costs. Even for biomass plantations, the major costs could be associated with establishing the plantation, and investment in the machinery to harvest and utilize the product. Perhaps the only exception is that of waste utilization, where most of the costs may be associated with gathering and sorting the waste, as opposed to leaving it uncollected. With this exception, all renewable sources are best suited for meeting baseload demands.

Most, however, differ from fossil-fuel and nuclear baseload plants in important ways. Such conventional thermal power stations are *capacity limited*, with the output limited by the rated capacity of the plant. These contrast with *energy limited* plants, which are unable to generate permanently at the maximum capacity because the total energy available is limited. Hydropower stations are the classic example; many biomass systems, particularly those based on agricultural wastes or dedicated plantations, would

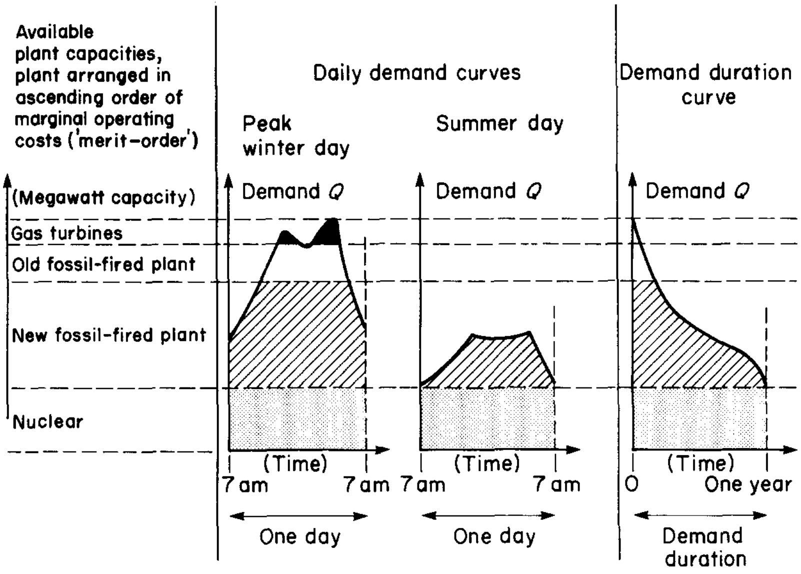

Figure 1. The load duration curve and merit order.

Source: R. Turvey and D. Anderson, *Electricity Economics*, Johns Hopkins, Baltimore, MD, USA, 1977.

also be of this type. Electricity storage is a special case of energy limited plants, in which the energy is derived from conventional baseload power stations at times of low demand. *Variable* power sources, in which the output is determined directly by variations in the energy input, form a third distinct class.

At present, many power stations are composed almost entirely of capacity-limited plants. If the complications introduced by the second-order effects of system dynamics (eg plant startups and shutdowns, operating reserve, etc) are neglected, such plants can be stacked in a simple 'merit order' of operation, in which those with the lowest operating costs are used as much as possible, with those of higher operating costs brought on-line progressively as the capacity of cheaper plants is exceeded. This defines the merit order, which runs from baseload plants through to peaking plants.

The key characteristics of the demand and generating costs can then be usefully represented in terms of the load duration curve (Figure 1), which illustrates the duration for which the load exceeds a given level. With power (load) on one axis and duration on the other, the product, and hence the area under the curve, represents the total energy supplied within the time period under consideration. Going up the y-axis represents steadily declining durations of supply, so that plants can simply be stacked in merit order under the load duration curve to estimate the energy supplied by each, and hence the operating costs.

Energy limited plants introduce significant complications. Although hydro stations may operate more cheaply than any other plant on the system, there is usually not enough energy available for them to be run at full capacity all the time. Operating at a constant but reduced output does not make full use of the capacity, which can be used preferentially to displace more expensive fuels. In fact it is readily apparent that the best use of energy from hydro or other limited energy plants is to operate them at full power whenever the marginal fuel cost on the system exceeds a given level – with that level determined by the amount of energy available. In other words, the greatest value is generally obtained by inserting energy limited plants at a fixed point in the merit order of capacity-constrained plants, such that all the energy available is used at or near the full plant capacity (Figure 2).

Uncertainties in the amount of energy available and in electricity demand over a given period, combined with various aspects of system dynamics (eg the additional value of hydro plants for providing short-term operating reserve – an issue discussed later) complicate this picture, but the principle remains valid. As a result, energy from energy limited plants is more valuable than that from other baseload plants, because of the additional value derived from the flexibility in deciding how the additional capacity is used. Fuller discussions of the management and economics of hydropower are given elsewhere.[13]

As well as hydro, this would apply to biomass-electricity plants. The significance of this factor

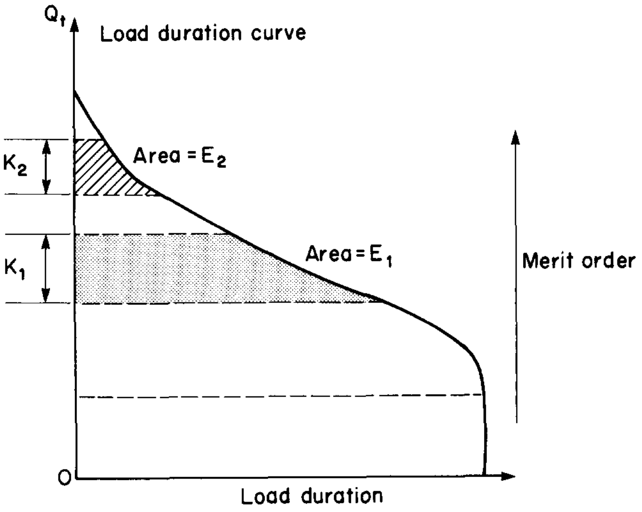

Figure 2. Operating strategy for energy limited plants.

Note: The plants are inserted in the merit order of thermal operation so that all the energy (E_1, E_2) can be delivered at the full plant capacity (K_1, K_2), excepting any spare reserved for system regulation. In this idealized example the second energy limited plant has a high ratio of capacity to energy: it displaces mosly peaking fuels, and makes a relatively large contribution to system reliability.

depends upon the incremental costs of adding extra generating capacity to the energy limited plant relative to those of increasing the total amount of energy available (discussed below in considering different combinations of renewables), the structure of the rest of the system, and the pattern of electricity demand. In general energy limited plants become relatively more valuable for systems which have a wide range of thermal plant generating costs, and a demand which varies widely in the period covered. The same remarks apply to electricity storage plants, which with minor modifications can be considered as energy limited plants with an 'optimal' energy content determined by system conditions (ie, by comparing the cost of using the marginal baseload plant to charge the store (usually overnight) against the value of generation the next day, after allowing for the losses in the conversion process).

Variable power sources form the third distinct class of plants. Almost without exception, their operating costs are lower than those of any thermal plants on the system. Hence, their power would as far as possible be used whenever available, to reduce the fuel-use in fossil-fuel plants: like nuclear power, variable sources would operate at the 'top' of the merit order.

In these conditions they reduce the demand upon thermal units in the system, and indeed it is usually simplest to think of variable sources as a negative load. Since load can vary by nearly a factor of two in its daily cycle, and cannot always be accurately predicted, the variable and perhaps unpredictable nature of such sources does not pose any radically new problems for power system operation. Figure 3, which shows the output which would have been expected from very large capacities of wind and tidal energy alongside the Central Electricity Generating Board (CEGB) demand over the same period, serves to emphasize that source variability needs to be considered in the context of the varying demand which it helps to meet. Dispersed wind varies less rapidly than demand, tidal more rapidly. Figure 4 shows the net effect of subtracting both these series

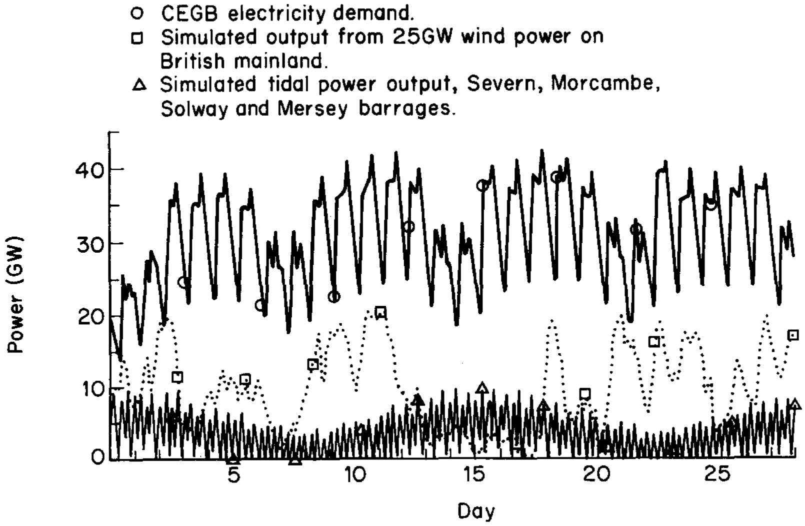

Figure 3. Electricity demand and potential output from wind and tidal sources in Britain (January 1978 data).

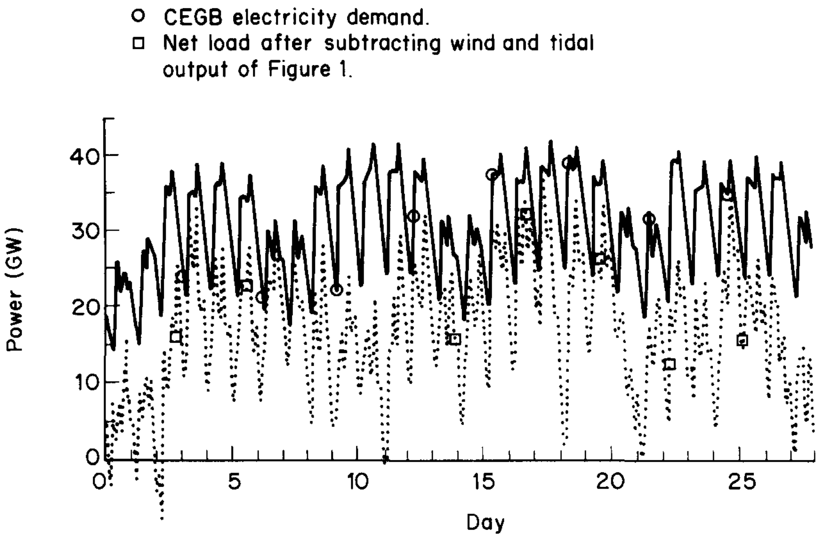

Figure 4. Residual demand to be met by thermal system after including wind and tidal sources in Britain (January 1978 data).

from the demand, leaving a much reduced net load to be met by the thermal plants.

The important question is: how do these variations affect the economic value of variable sources? To address this it is useful to start by disposing of two myths: first, that variable sources are best suited to small-scale or isolated electricity supply; and, second, that electricity storage is needed to exploit them to any substantial degree.

From a technical viewpoint, variable sources are far better suited to large power systems than to localized supplies. On small systems, just one or a few units, clustered on one site, may generate a substantial fraction of the total energy. The output may then be very variable, sometimes fluctuating widely within a few minutes. As noted above, the rest of the system might well amount to just a few diesel stations, which then may have to alter their output rapidly to follow the changes, with individual units repeatedly shut down and restarted, wasting fuel and increasing maintenance requirements.

By contrast, a large system can often take advantage of natural diversity in variable sources. Significant capacities of wind energy, for example, would involve many wind turbines, spread out between different sites, and this would smooth the overall output greatly. The variability is reduced, predictability increased, and overall distribution becomes much more favourable with far fewer occasions of near zero or peak output. Appendix 1 discusses how these effects may be roughly quantified, and illustrates this with examples of wind energy in Britain. Diversity would not of course remove diurnal variations in PV output, but it would still help to smooth more rapid weather-related variations.

Furthermore, there is much more natural reserve on large systems, with many thermal generating units connected at any one time. Such systems will mostly also have some units – hydropower or gas turbines – which can respond very rapidly to changing conditions. So all round, the problems of integrating variable sources are much reduced when the are connected to large power systems.

Bulk storage becomes far less important for much the same reasons. Since the fluctuations of variable sources combine with those of the electricity demand, storage can only usefully be considered in relation to the whole of the power system. Storage is valuable if it can often be charged using cheap energy (eg at times of low demand or high output from variable baseload sources) and discharged to save expensive fuel (eg at times of high demand and low output from the variable sources). But if variable sources are well diversified on a large system, they may not greatly increase the frequency of such opportunities unless the capacities are very high. Except in such cases, additional storage is unlikely to be very important; backup may be required, but as discussed in the next section there are many other options for providing this.

This is just as well. Large-scale electricity storage – usually in the form of water pumped up and down a mountain – is expensive, and about 20% of the energy may be lost in passing through the store, due to inefficiencies in charging/pumping and generating. On small systems the high cost of alternative fuels (and hence potential savings) may make such costs and losses justifiable. On large power systems, with much lower generating costs, renewable sources would be virtually ruled out if extensive storage really were an essential component. Of course, increasing capacities of variable sources may increase the value of storage, and vice versa, but storage is in no sense a central element. Since it greatly complicates the analysis and behaviour of the power system and this obscures the main issues, most of this paper will make the conservative assumption that storage is too expensive to be of relevance in assessing the large-scale integration of variable sources.

This poses an immediate question to many observers. If variable sources are not combined with storage, they cannot be relied upon to generate power at times of high demand, when it is most needed. Other backup is apparently required. Doesn't this itself impose a serious penalty?

The capacity question

Some renewable sources can reliably produce power at times of peak electricity demand. In addition to energy limited plants, which can be scheduled to generate maximum power at such times, the classic example is that of solar electricity on systems which have peak demand driven by air conditioning loads, which are greatest when the sun is bright. In a few areas, the strongest winds are driven by local, solar-induced thermal gradients and happen to coincide with a solar-driven peak demand. When such strong and dependable correlations occur, it is clearly very convenient, and adds somewhat to the real value of the source to the system. But such correlations can rarely be relied upon. As noted above, the Luz thermal systems achieve the same result by use of a cheap gas backup; but such opportunities are again limited.

In most cases variable sources are not necessarily available for demand peaks. In some temperate countries (eg the UK) there has been some debate over correlations between wind and electricity demand. There certainly can be some correlation – winds increase the thermal loss from buildings, for example – but there are many other factors. High demand can also coincide with periods of very cold, clear calms. Surprisingly, it is still not possible to be sure of the overall relationship at peak demands: statistical evidence from 10 year's data in Britain is still ambiguous.[14] Though there is a substantial seasonal correlation, wind energy *in winter* in Britain is very weakly correlated with demand. Other sources, such as wave and tidal energy, also have low correlation with peak demand during the peak season.

Nevertheless, such sources can save thermal capacity. Since no generating station is completely reliable, there is always a finite risk of not having enough capacity available. To keep this risk low, a large margin of plant capacity over maximum expected demand, typically 20–30% excess capacity, must be maintained. Variable sources may be available at the critical moment when demand is high and many other units have failed, so they reduce the overall risk of failure and allow the thermal plant margin to be reduced. In fact it can be shown that when the capacity of any independent source is small relative to the rest of the system (low system penetration), its 'capacity value' is independent of its actual reliability, and equals that of a completely reliable plant generating the same average power at times when the system could be at risk. One proof of this result is given in Appendix 2.

As the capacity of any variable source rises, it becomes progressively less valuable for saving thermal capacity, because there are times with little or no output however large the capacity. The savings, however, can in total be considerable. Figure 5 shows the approximate savings in thermal capacity which dispersed wind energy in England and Wales might allow as the wind capacity rises. Wind energy contributes as much as other sources, relative to the mean power, for the first few thousand MW, but falls off thereafter. At maximum, about 5.5GW of thermal capacity might be saved (about 10% of the total thermal capacity). This still implies a margin of thermal plant capacity over peak demand, but the degree of excess would be reduced to 10–15%.

The relatively high capacity value reflects in part the benefits of the large diversity available, which makes periods without any wind at all in winter quite rare; results for the Netherlands show a proportionately somewhat smaller capacity credit (differing methodologies and wind turbine and resource characteristics may also contribute).[15]

Suitable combinations of renewable sources may yield greater thermal capacity savings. When two variable sources vary independently, their capacity contribution may also be largely independent, and additive. A still greater effect is obtained if different variable sources are directly complementary, for example, solar and wind energy are frequently, because strong winds tend to be associated with overcast conditions. In thermally-driven wind regimes, the strongest winds may also occur towards or after sunset. Indeed in some areas of California it

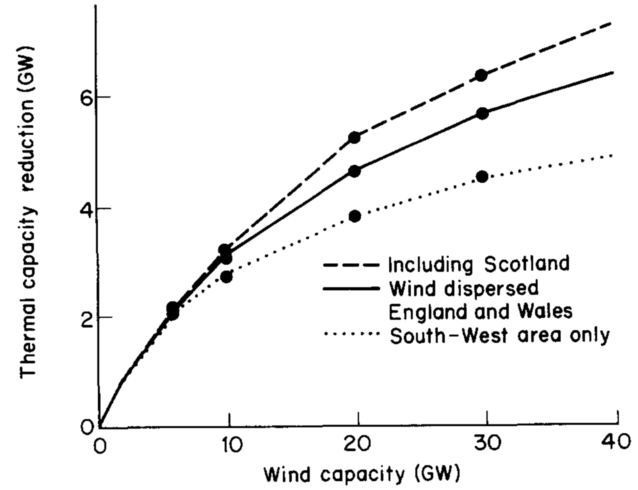

Figure 5. Thermal capacity displacement with increasing system penetration, illustrative estimate of wind energy in Britain.

has been realized that winds pick up as the sun is going down, and that the combination of wind and solar provides a fairly reliable input across the period of high demand, which spans from the early afternoon to early evening.

However, despite the concern and interest which such issues and opportunities raise, capacity credit is usually of much less economic importance to the system than many assume. The value of capacity credit itself is the marginal cost of ensuring that the available capacity is sufficient to meet demand in peak periods. Some systems may already have substantial capacities of old, inefficient plants on the system, and keeping them serviceable for peak demands instead of retiring them may be a cheap way of ensuring adequate capacity. Many industrial users, especially, have their own backup capacity, which could provide cheap emergency capacity if it could be tapped. This might be a special example of ways in which more sophisticated load management of various forms, could also help to reduce the costs associated with peak demands.

Even without such options, the marginal costs of adding 'firm capacity' for meeting peak loads is modest. Industrial gas turbines can provide capacity at one-third to one-fifth the cost of most baseload plants. Such units can be expensive to run (though with the advent of modern gas turbine cycles this is less true than it used to be), but by definition peaking plants are only used occasionally so matter little. Even if there were no capacity credit for variable sources, building gas turbines for backup would generally add less than 20% to the estimated complete capital costs of wind energy.[16] The incremental costs of adding capacity to limited energy plants – increasing the rating of hydro turbines, or the capacity of generating sets for advanced biomass systems for example – may be even less.

The marginal cost of increasing capacity, thus, need not be high and the real long-run value of capacity credit alone is correspondingly low; while it would be an exaggeration to describe capacity concerns as a non-issue their economic importance has certainly been greatly exaggerated. Variable sources are valuable primarily because of their fuel savings and – like all other baseload plants – cannot be justified primarily in terms of capacity needs.

This is a rather theoretical viewpoint and simplifies the interaction between capital and operating costs over time. In practice, the complex and interdependent statistical nature of capacity issues, and the range of options which need to be considered for long-run optimization, is hard to reflect in simplified pricing policies, particularly when utilities buy power produced independently. Utilities generally do not perform detailed statistical analysis and optimization of system reliability, incorporating all the long-run options, in estimating 'capacity payments'. The short-run value of being able to ensure a reliable system is very high, and few utilities attempt to evaluate directly the real capacity contributions from individual variable sources deployed in different regions. Frequently, an inflated capacity value is assigned to producers which can guarantee power at times of peak demand, and none at all is given to sources which fall below a certain threshold of reliability. Such simplifications discriminate against indepedently-managed variable sources.

At higher penetrations variable sources may not save capacity, but they can still reduce capital expenditures in other, perhaps more important ways. By reducing the time for which many thermal plants would operate, they make capital intensive plants (such as nuclear power) less attractive relative to those with low capital cost but higher fuel costs (such as gas turbines). Hence, the optimal plant mix for planning would alter towards lower capital expenditure on other plants. Since changing the thermal capacity mix alters the operating costs, these issues become inseparable from the broader questions of fuel savings. To these we now turn, before returning to a broader overview of the economics of variable power sources at high system penetrations.

Fuel saving: determining factors

The 'ideal' fuel savings from a variable source are those which would be obtained by considering only

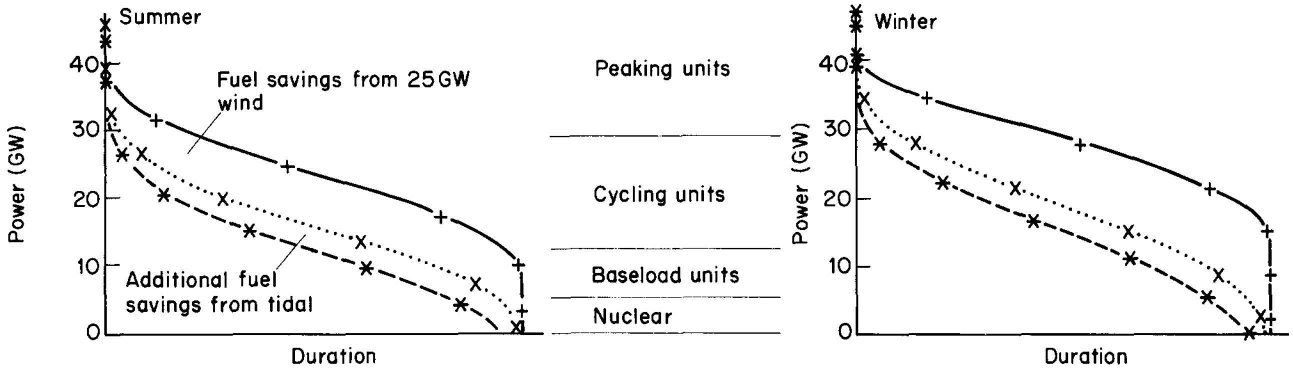

Figure 6. Load duration curve illustration of ideal fuel savings.
Key: + Original load (1971–78 CEGB data).
× Net load after subtracting output of wind capacity used for Figure 1.
* Net load after subtracting output of wind and tidal capacity used for Figure 1.

the reduced operating time required of thermal units after subtracting the variable input from the original demand. The actual fuel savings may differ from the ideal savings due to various operating considerations, as discussed later.

The ideal fuel savings can be estimated from the simple load duration curve representation of the merit order operation of the thermal power system, as illustrated in Figure 1. At low penetrations, the variable input simply 'shaves the edge' off the duration curve. It can then be seen – and proved mathematically[17] – that the fuel savings are not affected by short-term variability and equal that from a perfectly reliable source with the same seasonal pattern of energy output. The extent to which this holds at high penetrations depends upon the detailed characteristics of the output, demand, and thermal plant profile, but again the duration curve gives a useful representation. To illustrate characteristics at very high penetrations, Figure 6 shows the load duration curve corresponding to electricity demand in England and Wales over 1971–78 (a period of relatively constant total demand), and the 'net' load duration curves after subtracting the output from a notional 25GW of wind energy, and from several large tidal schemes as used for Figure 3. The difference between the original curve and the net curves illustrates the ideal fuel savings. Their extent is readily apparent; the available wind energy amounts to around 30% of the total demand and tidal adds another 13% or so.

In this illustration, the peak of the duration curve is not much lower, for there are occasions when demand is high and there is little wind or tidal input. But such occasions are rare so the peak is much sharper and the use of peaking fuels is greatly reduced. At the opposite extreme, the duration curve does go into negative values, reflecting times when the available wind plus tidal power exceeds demand; power would then have to be shed from the wind turbines or tidal schemes. But although the total capacity of variable sources in this illustration greatly exceeds the minimum demand, such occasions are so rare as to be economically almost irrelevant. More significant in this illustration would be the reduced value of savings when the variable input competed with nuclear operation. Nevertheless, if the ideal fuel savings are the only issue to be considered, clearly very large capacities can be usefully accommodated.

There are, however, many complexities to be considered. Operating penalties can be usefully divided into three main components:

- *cycling losses,* due to the increased start-up and shut-down of thermal plants, and other short-term changes in their output;
- *reserve costs,* arising from the need to ensure that the system can respond adequately to unpredicted changes; and,
- *discarded energy,* when the available variable input exceeds the amount which can be safely absorbed while maintaining adequate reserve and dynamic control of the system.

Modern thermal power stations are complex high-precision machines, designed for continuous operation at their rated capacity. It can take many hours, and cost a great deal, to start them up – perhaps £50 000 to start a modern, 1 000 MW coal station from cold, if estimates of associated wear and tear are included.[18] Any power source which greatly increased the need for plant starts would rapidly make itself uneconomic.

However, as emphasized above, variations need

Table 1. Variability coefficients of demand and variable power sources.

Series	Variability coefficient (MW/day/MW mean power)
Electricity demand	0.5
Wind energy (in one major region)	1.8
Wind energy (dispersed over England and Wales)	1.3
Tidal energy (single ebb-generation scheme)[a]	6.3
Wave energy (1 site data – South Uist)[b]	0.8
Solar energy[c]	3.0

Notes: Values estimated from hourly data, except wave (six-hourly data) and solar (estimated on basis of load factor, assuming single daily cycle). [a]Variability of tidal energy might be greatly reduced if several complementary schemes could be combined. [b]Reflects large scheme, with relatively low capacity rating. [c]Solar and load variations tend to be closely related, so that simple comparisons assuming rough independence may be invalid.

to be considered in the context of continually varying demand. As illustrated in Figure 3, dispersed wind energy may vary less rapidly than demand itself. Relative to the mean power, solar energy may vary somewhat more rapidly, and tidal energy more so. In general, cycling costs may be roughly proportional to the 'average variability' of the load on thermal plants in a given period – which is the average rate of change (eg in MW/hour) in the load (in either direction). A rough estimate of the potential impacts can be gained by noting that when variations in the source and demand occur roughly independently, the total resulting variation in the net load to be met by thermal plants is approximately a 'sum-of-squares' addition of the components – in a simplified form:[19]

$$\begin{aligned}&(\text{total variability of load on thermal units})^2\\&= (\text{total variability of electricity demand})^2\\&+ (\text{total variability of variable source})^2\end{aligned}$$

This has several implications. The marginal impact of fluctuations in variable sources at low penetrations is zero – they are lost as noise among demand fluctuations. More generally, the impact can be gauged by comparing the average variability of demand and different variable sources. Table 1 shows the variability coefficient (average variability relative to the mean power) for a number of variable sources in the UK. Dispersed wind energy in England and Wales, for example, has an average variability of around 1.3 GW/day per GW of wind capacity, compared with mean load variation of up to 15 GW/day. Clearly, very large amounts indeed would have to be installed before fluctuations from wind energy became comparable with those already met in the daily demand cycle.

Tidal power appears to be the only source which is likely to incur substantial start-up penalties when deployed on large systems. For the UK's Severn Barrage, which could supply 5–6% of demand with an average 5.5GW cycle every 12.5 hours, this simplified statistical treatment suggests penalties of around 7% of the 'ideal' fuels savings, which accords well with more detailed simulation model estimates of 6–10% performed for government studies of the scheme.[20] Because the diurnal variation of solar energy often parallels that of load, such simplified approaches cannot be used; indeed, solar energy may reduce cycling penalties.

A related concern is that variable sources could increase the maximum rate of change in output required of thermal units. This is primarily an issue of ensuring sufficiently sophisticated system control and the economic penalties involved are likely to be negligible.[21]

The problems arising from the possible unpredictability of variable sources are usually considered to be more significant. In general, 'operating reserve' must be provided to protect the system against such uncertainties. Reserve assessment is complicated because there are many different timescales over which reserve is required, and many different sources of it.[22] They divide into *inherent* reserve, which exist simply because of the nature of the system, and *active* reserve, which must be provided, at a certain cost.

Sources of inherent reserve include: the inertia in the rotating turbines and boiler units; pumped storage and hydro units, which can change their output, and often start-up, very rapidly; gas turbines, which can start up from cold within 5 to 15 minutes; and the running of thermal units above design capacity, which is quite feasible, but increases losses and stresses. Load management and voltage reductions are further options, of increasing severity. Sources of active reserve include: spinning reserve (the spare capacity on thermal units which are running at reduced output); and pre-scheduled or 'banked' plant, ie plant kept on hot standby just in case they are required. Providing such active reserve can incur significant holding costs, in terms of wasted fuel and the reduced efficiency of part load operation for many thermal units. However, in total there is such a wide variety of reserve options that modern power systems rarely fail completely, unless the network itself is severely disrupted.

Two fundamental points govern the impact of unpredictable variable sources on reserve requirements and costs. First, since the variable sources are connected to an integrated system, *operating reserve should be allocated to the system as a whole, not to back up any particular source*. Second, excepting protection against sudden losses (such as the failure of a major plant or single infeed), the costs of *providing* active reserve must be traded off against those of having to *use* one of the various forms of 'inherent' reserve, when the actual prediction error exceeds the active reserve held for that timescale.

In other words, beyond a minimum security level determined by the need for very short-term protection against loss of the largest single infeed to the system, active reserve levels are based on an economic trade-off, not an absolute security requirement – and reserve costs are determined primarily by the average[23] errors involved in predicting the demand upon the thermal part of the system. When errors in predicting the output from variable sources occur independently of those in predicting demand, which is usually a good approximation, the combined error is again a sum-of-squares addition:[24]

$$(\text{average error in predicting net load on thermal units})^2$$
$$= (\text{average error in predicting electricity demand})^2$$
$$+ (\text{average error in predicting variable input})^2$$

Thus again, for small capacities of variable sources, the prediction errors are lost among load fluctuations, with no associated penalty, and models which optimize system reserve levels confirm this.[25] Nevertheless, since demand is fairly predictable, forecasting errors could come to dominate reserve requirements at capacities above 5–10% or so of the thermal capacity if prediction is poor. However, as long as all the energy could be safely absorbed, the economic impact would still be modest, with reserve penalties alone rarely exceeding 5% of the fuel savings.[26]

As the capacity of variable sources increases on a system, various cost penalties may rise other than those considered earlier. Prominent among these is the fact that there might be occasions when the available power cannot be used. This is not simply a matter of the available energy exceeding demand; it would occur well before this stage was reached, because power systems would need to keep a minimum level of thermal plant generating to maintain adequate operating reserve and system control capabilities.

This need not in itself pose any fundamental problems for the integration of variable sources. It is always possible to 'discard' energy by shutting down some of the variable generators, for example by furling the blades on wind turbines. It does, however, result in an economic penalty which becomes increasingly important as the capacity rises further. The 'minimum thermal level' would be determined by many factors, including the predictability of load and variable sources, and the part-load level of the thermal plants. In this context, it is important to note that the ability to part load baseload plants (even nuclear) would be very important at high penetrations of variable sources, a sensitivity brought out by modelling studies.[27]

Such analysis presents a very encouraging picture of the value of variable sources. At small penetrations, their energy is usually as valuable as that from conventional power sources with the same seasonal pattern of output. For applications in which the seasonal variation follows that of demand, the value may thus be greater than that of conventional sources – though this must be compared against the ability to schedule maintenance on conventional sources to follow seasonable load variations, and to maximize availability during peak demand periods. With increasing capacities, the marginal value falls – as capacity credits decline, as the variations and prediction errors become significant in relation to those of the demand, and as occasions when the energy cannot safely be accepted become significant. But overall, it appears that large capacities can be accommodated without major losses.

By way of illustration, the results of modelling studies which attempted to optimize system operation, with the current thermal generating structure but incorporating large capacities of dispersed wind energy in Britain are illustrated in Figure 7.[28] These suggest that over a third of the energy might be obtained from wind energy before the marginal value of the fuel savings declines by over 25%. A study using the same model which also attempted long-term optimization of the plant mix suggested that even higher wind capacities could be economic under some circumstances, resources allowing.[29]

Clearly, such capacities could not be considered for many decades, if ever; the principal conclusion from such results is that system constraints are

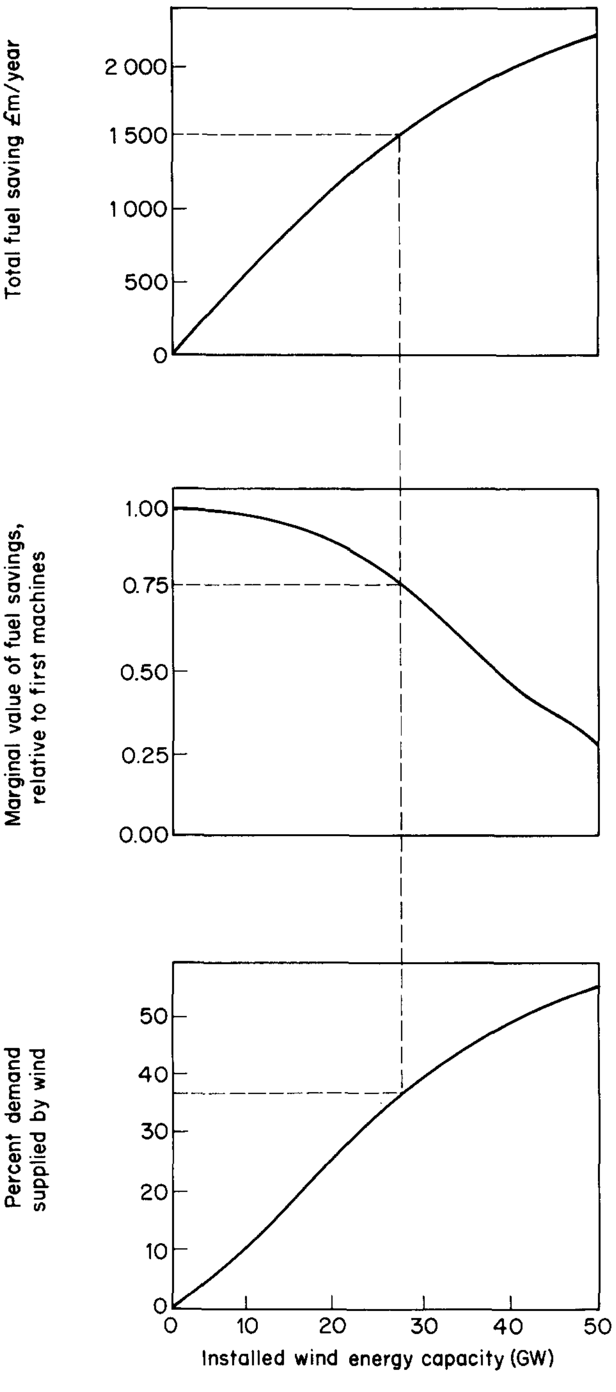

Figure 7. Measures of wind energy fuel savings at increasing penetrations into large power system including operational penalties (thermal capacity is 60GW).

unlikely to be the factor which limits the role of wind energy, at least. Other renewables, and the possible gains from combining them, are considered below.

There are still a range of results and differing views concerning the value of variable sources at high-system penetrations. A broad review and critique of modelling studies has been given elsewhere.[30]

It should also be stressed that results discussed here assume the system operation to be fully integrated, with the various components well coordinated. This may require control procedures to be adapted, and institutionally may not be easy to achieve. For example, Sola and Sioshansi[31] report that variable power has been a 'logistical headache' for the Pacific Gas and Electric utility becaue the input 'does not necessarily match the utility's system requirements.' One reason for this is that the Californian windfarms are all owned by independent power producers, selling output to the grid. The utility has little information on when to expect power and no control over it. Even so, it is not clear that the current experience constitutes any kind of significant economic penalty or security risk to the whole system, but more of an inconvenience for operators, who need to adapt traditional control procedures to the new conditions. There is, however, no doubt that if much more wind energy is deployed in California, the utility will have to have more information and control over night-time power production, and the experience could provide useful experience of the practical issues involved in integrating variable sources.

Interfacing, transmission, and interconnection

The discussion has not so far addressed issues of local connection and transmission. Because most renewable sources generate in much smaller units than conventional power stations, they would be connected at lower voltages (Table 2). To the extent that the power could be used directly on the local low-voltage system, this would reduce transformer and transmission losses as compared with conventional stations, but set against this, voltage fluctuations and other transient phenomena could be propagated throughout the low-voltage network. The engineering requirements for maintaining adequate local quality of supply, fault recovery, etc, is a

Table 2. Connection voltages for given power levels (UK standard voltages).

Power level (MW)	Voltage (kV)
100–700	132
10–50	33
0.5–20	11
0.3–1.0	0.415

Source: 'Integration of renewable energy sources in electrical power systems', *Watt Committee Report on Renewable Energy Sources*, Watt Committee, London, UK, 1990.

subject in itself, and particularly if variable sources use induction generators this will often require additional investment, for example in local capacitors and relays.[32] While these issues are crucial in engineering terms, adequate protection generally adds on a per cent or two to the capital costs of a source like wind energy, and together with the local transmission connection and interface itself is usually considered as part of the overall installation package.

Different transmission and transient stability issues would be raised by very high capacities of variable sources. A strong integrated transmission system would be required to take full advantage of diversity in renewable sources and to allow stable operation with just a few thermal stations connected for providing bulk operating reserve. Such bulk transmission costs are not generally allocated to particular plants, and would depend heavily on the particular circumstances and power flows in question, but obviously in principle they should be accounted for.

Analysis is complicated by innumerable factors. The need for new transmission capacity will depend upon how a new source and line affects the contingency analysis for the system (ie protection against line and plant failure). The costs depend upon whether existing lines can be upgraded, or new lines are required. Traded off against the costs are the benefits arising from reduced losses in lines of greater capacity, and greater flexibility in operating other plant. There can be further complications in relation to variable sources: experience in California, for example, has demonstrated the significance of the wind in cooling transmission lines, so that the effective carrying capacity increases along with the wind power output.

Thorough analysis of transmission issues for general planning applications is probably impossible, but rough estimates can be made. Even in the USA, with relatively low demand density in some regions because of low population density, transmission is typically valued at no more than 10% of generation assets;[33] estimates of the grid assets in England and Wales suggest similar or lower proportions for this (much denser) system. A crude analysis for wind energy suggested that the costs and losses of ensuring adequate transmission would be minor in relation to the benefits of greater wind diversity (including Scotland).[34]

For sources which are much more concentrated in relation to the system, such conclusions may not apply. One such case is probably the Severn Barrage, for which analysis suggests significant grid reinforcement costs. Also, more serious transmission costs and losses would be incurred for tapping renewable sources which are remote from the main demand centres.

The penalties of distance for transmitting electricity increase faster than for fossil energy transport. Large transfers over more than a few hundred kilometres begin to involve considerable costs and (more importantly) dissipative losses, though these are not necessarily prohibitive; there have been serious proposals, for example, for tapping offshore wave energy and Icelandic geothermal electricity via subsea cables to the UK. But bulk transmission over much more than a thousand kilometres appears most unpromising. For these reasons, many have suggested that very long distance transport would involve conversion to hydrogen which would then be pumped through pipes, as discussed in a companion paper by Winter in this series.[35]

Such cases excepted, this discussion suggests that despite the range of possible effects at higher-system penetrations, in most cases the major system constraint on the power which can be usefully accepted from variable sources will be the provision of adequate bulk spinning reserve. This conclusion is reinforced by the inevitably increasing use of automated generation, load and voltage stability controls. If this is correct, assessing the overall value of variable sources becomes amenable to generation modelling analysis up to very high penetrations, suggesting that modelling results such as those summarized earlier, for all their simplifications, do capture the key economic issues.

Combining different renewable sources

As the capacity of any given source increases, its marginal value declines, primarily because successive increments of capacity are correlated with those already on the system. How might different combinations of renewable sources affect the situation?

When sources are directly complementary, there are potential large benefits. Examples of wind and solar energy have been noted earlier with reference to capacity credits; thermally-driven winds may be strongest after sunset, so that the combination usefully covers periods of high demand. In many temperate regions, there may be more general seasonal and short-term complementarity.

Even for sources which are not directly complementary, simple statistical independence makes different variable sources more valuable than just more of the same. An illustration of this was given by studies of wind and tidal sources on the British supply system.[36] One feature which emerged from the investigations was that, when the thermal system was allowed to reach a long-term optimal mix with tidal power, the marginal value of wind energy at low to intermediate penetrations was increased. This initially surprising result occurs because the system adapts to incorporate the tidal power by increasing the ratio of peaking plant to baseload, both because of the changes in the load duration profile and because of the more flexible operational characteristics of the peaking plant. The marginal fuel cost on the system is therefore increased, and it is this which initially determines the value of wind energy. The value of the seasonal match between wind and load is also enhanced by the presence of a source (tidal) which does not vary with the seasons.

In these circumstances the marginal fuel savings from wind decline more rapidly with penetration than in the absence of tidal power. But losses only become serious when the probability of having excess power becomes significant, so that energy needs frequently to be discarded. The fact that wind and tidal are uncorrelated means that this does not occur until high penetrations are reached. The study concluded[37] that 'an integrated British supply system could, if it were considered desirable, absorb at least half of its energy from wind and tidal power combined without significant [operational] difficulties'. Such results reflect the very diverse system (four tidal sites, with unconstrained power flow between England, Wales and Scotland and wind resources in each), but assumed no storage. The transmission requirements would be substantial, though as indicated above, not necessarily prohibitive. Generalization to other systems and other mixes of variable sources is difficult, but it serves to emphasize the fact that very large inputs from variable sources can in principle be accommodated without major losses, without any reliance on storage.

Further possibilities are offered by combining variable sources with energy limited plants, which are usually also renewable and which complement variable sources very effectively. The energy can be used selectively when most required. If the generating capacity can be increased at relatively low cost, it allows greater flexibility in dispatching the energy, reserving it for times with relatively low variable output and high demand. The potential role may be judged schematically from Figure 2, by noting that variable sources will tend to make the demand curve steeper (as in Figure 6), so that a higher energy limited plant capacity can be used profitably to displace similar amounts of peaking fuels, while also contributing more to system reliability.

There are various limits on this. For hydro stations, the ability to increase generating capacity may be distinctly limited by the engineering constraints (eg the physical space available in the dam and/or cavitation on the turbine blades at high flow rates), and by the ecological consequences of greater variation in downstream flow rates. For biomass plants, such problems would not arise, but the incremental costs of increasing generating capacity, and perhaps the storage capacity for dry biomass (which is a relatively bulky fuel), may be rather higher. As yet it is not possible to judge how large the scope will be and, as with many issues surrounding renewable sources, it would vary considerably according to system and resource conditions. But the potential synergisms between different renewable sources are clearly much too important to ignore, and they may often make the combined potential larger than the sum of parts considered in isolation.

Long-term trends and capabilities of supply systems

How might likely long-term developments in power systems affect the integration of variable sources? One of the most significant factors has been identified as the operational flexibility of thermal baseload plants, and in particular the ability to part-load them to provide operating reserve. Most large baseload units, nuclear and thermal, can be run stably down to at least 50% capacity. Below this, a range of problems emerge. To date, there has been little incentive to part-load new baseload plants to any greater degree, because they are intended to run at full capacity; but when it has been required, it has generally proved possible to operate plants down to 30–40% of capacity,[38] and studies suggest that lower levels still could be achieved, at relatively low cost, with suitable modification in design.[39] Minor modifications can also improve responses in terms of the rate of change of output, frequency response etc, but the inertia and sensitivity of highly-tuned steam turbine systems inevitably sets limits on such flexibility.

The current trend towards smaller generating units based on gas turbine technology raises further opportunities. Gas turbines are operationally more flexible and less capital intensive that traditional baseload plants. Both features are favourable to the integration of variable sources. The performance of combined-cycle plants is still partly constrained by that of the steam turbine cycle. But advanced steam-injected gas turbines, based on aero-derivative engines rather than industrial turbines, may offer comparable efficiencies with still greater operational flexibility, including good part-load performance, high load-following capabilities, and even considerable ability to boost power above the design rating with minor penalties in efficiency.[40] As well as being used for natural gas, such technology is probably also the most promising way of exploiting biomass, and perhaps even coal, using gasifiers. The characteristics, combined with the low capital costs, again increase the ease of absorbing high-variable inputs.

The same is probably true for small-scale systems. Steam-injected gas turbines are not only more flexible operationally, they are also practical on much smaller scales than steam turbines, perhaps down to sizes of under 10MW. One intriguing possibility concerns applications on island and other small-scale systems. Such areas at present frequently run on diesel, and the difficulties of integrating variable sources on such systems have been noted. Given the range of fuels which can be used to drive such plants, combinations of gas turbine technology with variable sources could emerge to be a mainstay of decentralized supplies in the future.

Development will not only be confined to the hardware of supply technologies. There is little doubt that for relatively little expenditure, the predictability of most variable sources could be greatly increased, partly through judicious use of existing weather-related data, and partly by developing dedicated monitoring stations (for example, of windspeed patterns a few tens to hundreds of kilometres from major generation areas) and predictive models. Prediction capabilities would develop alongside any major deployments of variable sources; in reality, unpredictability seems unlikely to be a serious issue.

The discussion has also noted the value of having adequate diversity of the variable source(s). The natural diversity available increases greatly between systems and countries. The existing trend towards greater system interconnection will thus further ease the integration of renewable sources. Spread over Europe, for example, wind energy would be quite a reliable source, and the extent of additional control offered by integrated use of Alpine and Norwegian hydro capacities would add further flexibility.

Finally, whatever kind of system is considered, the growing role of microprocessor controls is likely to be important in both automated generating controls and, more importantly, the short-term management of controllable loads. Industrial load management is already an important feature in many utilities, but the potential of modern technology for increasing the degree to which loads could if desired respond to changing system generating conditions, with benefits to both consumer and producer, has barely been tapped. Development of such techniques is a trend which will again aid the accommodation of variable soures on any scale.

Conclusions

The potential applications of renewable electricity sources are many and varied. The ubiquitous nature of many renewables means that renewable energy is frequently available for small and isolated applications where transporting and using fossil fuels is expensive. In such cases, the penalties and difficulties imposed by the variability of many renewables may be very significant, though they may still be more than offset by the high value of utilizing locally-available resources, even if storage is required to exploit them effectively.

It has been widely asserted that the application of renewable sources on larger power systems will be severely constrained unless cheap storage can be developed. This assertion is without foundation. The discussions in this paper emphasize two main contrary conclusions.

First, when the capacity of a renewable source is small relative to the total capacity of thermal plants – as is currently the case for all renewable sources except (occasionally) hydro – source variability is essentially irrelevant, and the value of renewable energy can indeed be greater than that from conventional thermal sources. This is true for energy limited plants of hydro and biomass because of the greater flexibility in using the available generating capacity, and for variable sources it can be true either due to positive correlations with peak demand (as with solar energy on systems with solar-driven demand peaks) or due to more general seasonal correlations with demand (as for wind and wave energy in temperate zones). In general there is no case for penalizing renewable energy relative to conventional sources at the capacities currently employed or likely over the next couple of decades in most areas.

The marginal value declines as capacities increase, but relatively slowly. In many cases, contributions of perhaps 20% of the demand could be obtained from one type of variable source with only a modest reduction in the value of the energy, and contributions of 30–40% would seem to be feasible before the penalties become severe, even neglecting storage and possible power exchanges with other systems. Various existing trends in power systems will further ease their integration, and by using combinations of different variable sources, storage, and trade between neighbouring systems, there seems nothing technically to prevent large systems developing over periods of decades to accommodate well over half of their power from variable sources.

Given the nature of other constraints, it therefore seems highly unlikely that the use of most renewable sources on large power systems will ever be seriously inhibited by bulk systems limitations. The main possible exception to this conclusion could be the use of PV, where the output can vary quite rapidly and the benefits of resource diversity are least, because the variations are strongly correlated even across entire continents. System constraints on PV could be especially important in densely populated tropical countries which have severely limited biomass resources (due partly to various competing uses), few other renewable resources, and limited access to hydro or gas resources which might ease the integration of such a variable source. Yet even for this, it may be several decades before capacities sufficient to pose serious operational difficulties can be deployed, and other options for easing integration may arise. With this partial *caveat*, it is hard to escape the conclusion that concerns over the integration of renewable sources have been grossly exaggerated. Of all the problems faced by renewable energy, system integration and the supposed penalties of variability seem among the least significant.

---

[1] Various terms have been applied to sources with fluctuating output, including 'non-dispatchable' and 'intermittent' technologies. 'Variable' is chosen here as the most generally descriptive and distinctive, since some such sources can be dispatched to a limited extent (and thermal sources differ substantially in their practical flexibility) and, taken literally, most sources are 'intermittent' by virtue of mechanical failure if nothing else.

[2] International Energy Agency, *Renewable Sources of Energy*, IEA/OECD, Paris, 1987.

[3] US Department of Energy, *The Potential of Renewable Energy*, SERI/TP-260-3674, Solar Energy Research Institute/DoE, CO, USA, March 1990.

[4] F.R. McLarnon and E.J. Cairns, 'Energy storage', *Annual Review of Energy*, Vol 14, pp 241–71.

[5] T. Flaim, T. Considine, T. Wintholderm and M. Edesses, *Economic Assessments of Intermittent Grid-connected Solar Technologies: A Review of Methods*, Solar Energy Research Institute, Golden, CO, USA, 1981; S. Hock and T. Flaim, 'Wind energy systems for electric utilities: a synthesis of value studies', 3rd annual meeting of the American Solar Energy Society, Minneapolis, MN, USA, 1983.

[6] Since in the area of application (California) these occasions are relatively infrequent, and the dominant capital costs associated with the steam turbine are an integral part of the solar process, the incremental costs of using gas to provide reliable power in this way are small.

[7] R. Hill, 'Review of photovoltaics', in M. Grubb, ed, *Emerging Energy Technologies: Policy Implications and Impacts*, Dartmouth/Gower, Aldershot, UK, forthcoming 1991.

[8] *Ibid.*

[9] J. Ianucci, private communication.

[10] W.M. Somerville, 'Applied wind generation in small isolated electricity systems', in M.B. Anderson and S.J.R. Powles, eds, *Wind Energy Conversion 1986*, MEP Ltd, London, UK, 1986.

[11] N.H. Lipman *et al*, *An Overview of Wind/Diesel R&D Activities*, Rutherford Appleton Laboratory, Oxford, UK, 1989.

[12] J.M. Ogden and R.H. Williams, *Solar Hydrogen – Moving Beyond Fossil Fuels*, World Resources Institute, Washington, USA, 1989, p 63.

[13] See, for example, T.S. Dillon, R.W. Martin and D. Sjelvgren, 'Stochastic optimisation and modelling of large hydrothermal systems for long term regulation', *Electrical Power and Energy Systems*, Vol 2, No 1, January 1980, pp 2–20.

[14] H. Cook, J. Palutikoff, T. Davies, 'The effect of geographical dispersion on the variability of wind energy'; and M.J. Grubb, 'On capacity credits and wind-load correlations in Britain', 10th BWEA Wind Energy Conference, London, UK, March 1988.

[15] J.P. Coelingh, B. van der Ree and A.J. van Wijk, 'The hourly variability in energy production of 1000MW wind power in the Netherlands', Proceedings European Wind Energy Conference, Glasgow, UK, 1989.

[16] The optimal 'backup' capacity would roughly equal the man output in peak load conditions; for wind energy, this is usually 20–40% of the installed capacity.

[17] M.J. Grubb, 'The value of variable sources on power systems', IEE Proceedings C, Vol 138, No 2, March 1991, pp 149–165.

[18] Watt Committee Report in *Renewable Energy Sources*, 'The integration of renewable energy sources in electrical power systems', Watt Committee, London, UK, 1990.

[19] The full derivation is given in M.J. Grubb, 'The integration and analysis of intermittent sources on electricity systems', PhD Thesis, University of Cambridge, 1986, to be published in amended form as a book. A summary derivation and examples are given in Grubb, *op cit*, Ref 17.

[20] *Ibid.*

[21] M.J. Grubb, 'The economic value of wind energy at high power system penetrations: an analysis of models, sensitivities and assumptions', *Wind Engineering*, Vol 12, No 1, 1988, (Section VII).

[22] For a fuller description of reserve options see, *ibid.*

[23] Strictly, the 'average' prediction error in this context is the root of mean square (*RMS*) error in prediction.

[24] Grubb, *op cit*, Ref 17.

[25] See, for example, E. Bossanyi, 'Use of a grid simulation model for long-term analysis of wind energy integration', *Wind Engineering*, Vol 7, No 4, 1983, and associated references.

[26] Grubb, *op cit*, Ref 17.

[27] *Ibid.*

[28] *Ibid.*

[29] M.J. Grubb, 'The potential for wind energy in Britain', *Energy Policy*, Vol 12, No 1, December 1988, pp 595–607.

[30] Grubb, *op cit*, Ref 21.

[31] S.J. Sola and F.P. Sioshansi, 'The role of the US electric utility industry in the commercialization of renewable energy technologies for power generation', *Annual Review of Energy*, Vol 15, 1990, pp 99–119.

[32] G.E. Gardner, 'The supply interface', Proceedings BWEA-Department of Energy Workshop on electrical generation aspects of wind turbine operation, ETSU-N103, Energy Technology Support Unit, Harwell, UK, 1987.

[33] S. Linke and R.E. Schuler, 'Electrical energy transmission technology: the key to bulk power supply policies', *Annual Review of Energy*, Vol 13, 1988, pp 23–45.

[34] Grubb, *op cit*, Ref 19.

[35] Carl-Jochen Winter, 'Solar hydrogen energy trade, *Energy Policy*, Vol 19, No 5, June 1991, pp 494–502.

[36] M.J. Grubb, 'The integrated analysis of intermittent sources on power systems: methods and application', Proceedings IEE Energy Options Conference, Reading, UK, 1987, (Conference Proceedings No 276, IEE, London, 1987).

[37] *Ibid.*

[38] In coping with its over-capacity of nuclear plants, Electricité de France (EdF) developed control facilities to further improve and extend low-load operation, A. Gautier, 'Enhancing PWR flexibility: the reactor advanced manoeuvrability package (RAMP)',

Framatome newsletter, September/October 1984; EdF part-loaded PWR reactors to below 40% of capacity on more than 250 occasions in 1985 (EdF performance statistics 1985). A detailed survey of fossil-fuel plants in the USA found part-load limits varying down to around 30–45%, F.H. Fenton, 'Survey of cyclic load capabilities of fossil–steam generation units', IEEE Transactions PAS-101, No 6, June 1982.

[39] A discussant to Fenton, *ibid*, states that 'many of the existing limitations can be overcome by careful and judicious upgrading and modification of existing equipment, along with the employment of operating procedures designed to improve cycling performance.' The difficulties and costs involved would depend very much on initial plant design.

[40] R.H. Williams and E.D. Larson, 'Expanding roles for gas turbines in power generation', in T.B. Johansson, B. Bodlund and R.H. Williams, eds, *Electricity – Efficient End-Use and New Generation Technologies, and Their Planning Implications*, Lund Univeristy Press, Sweden, 1989.

Appendix 1

The impact of geographical diversity

Exploiting the diversity available between different sites can greatly increase the reliability and predictability of variable sources, and reduce the variations in power output. This Appendix give some quantitative examples, focusing on wind energy.

Wind energy from any one machine would be very variable. A typical wind turbine in temperate zones might be idle for perhaps a third of the time, and could be operating at maximum power for up to another third. At intermediate levels the power output would often fluctuated greatly, even within minutes. The economics of windpower integration depend heavily on having such variations smoothed out between sites.

Some of the potential benefits of diversity within Britain are illustrated in Figure 8, which shows the probability of obtaining different levels of total wind power output (relative to the installed capacity) if wind turbines were sited at many different locations around Britain. In summer, the chance of obtaining maximum power (when some wind energy might have to be discarded) is very small indeed, but there is a 25% chance of output being below 10% of the installed capacity. In winter, such low outputs would occur for only about 10% of the time (or less, if variable-speed turbines capturing more energy from low wind speeds were used), and the chance of obtaining output within 10% of maximum is still barely one in 20. Most of the time, the output would be at intermediate levels.

The effects of diversity on wind fluctuations are just as important. This can be analysed using a 'diversity factor' $D(t)$, which expresses the average variation in output from a group of wind turbines relative to the variations in one machine. This is defined by:

$$\frac{\text{Variation of total output}}{\text{total capacity}}$$

$$= \frac{\text{variation in single machine x } D(t)}{\text{machine capacity}}$$

The diversity factor for an array of machines can be found if the 'coherence length' $L(t)$ of fluctuations – a measure of the maximum distance over which fluctuations occur simultaneously – is known. For a square array of N machines spaced a distance d apart, it is given by:

$$D(t) = \tanh(d/2L(t))/(SQRT(N))$$

where $\tanh(x)$ is the hyperbolic tangent $= (e^{x}-e^{-x})/(e^{x}+e^{-x})$.

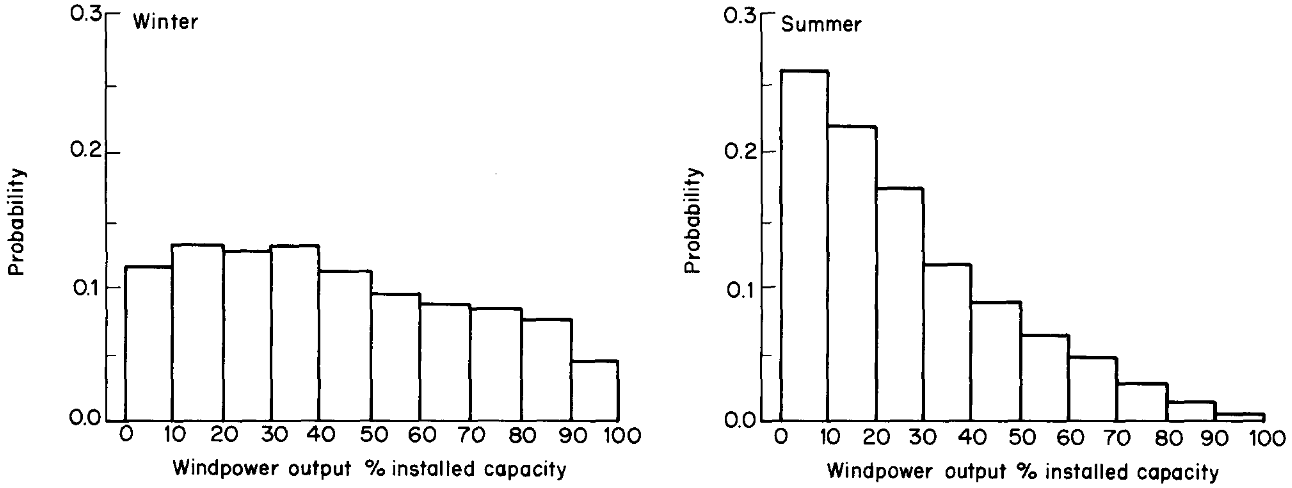

Figure 8. Distribution of output from nationally-distributed wind energy in Britain.

Farmer[41] cites some typical estimates of coherence length associated with various timescales; in practice, *L(t)* is approximately equal to the windspeed times the timescale *t* involved. For 'microscale' variations, within tens of seconds, *L(t)* will be less even than the spacing between machines *d*. The equation then approximates to *D(t)* = *SQRT(N)* – physically, this corresponds to the fact that the fluctuations between the machines are independent. So even if 5 000 wind turbines of 2MW capacity each were deployed in the long term, and the average microscale power fluctuation from each machine was 15% of the capacity, the total variation would be 10 000MW × (15% × 2MW)/2MW × *SQRT* (5 000), = 20MW. Such fluctuations – about 0.5% of the total wind capacity – would be negligible on large power systems.

When the timescale stretches to 10 minute fluctuations (a timescale of particular interest, since it takes about 10 minutes to start up gas turbines for emergency supply), random fluctuations would only be independent between machines spaced more than about 5–10km apart. In such cases the equations can be applied just as well to evaluate the effects of diversity between clusters of machines. If, for example, the same 5 000 turbines were arranged in 50 separate clusters of 100 machines (many perhaps offshore) the *RMS* random fluctuations on timescales of 10 minutes to half an hour would be around 150MW – significant, but still small compared with demand variations on most systems which span such an area (eg compared with the 10–15GW diurnal demand cycle in Britain).

This applies to random fluctuations. The effect of storm fronts moving across wind or solar arrays could produce wider correlation. For this, explicit analysis of real data at many sites, together with a detailed stability analysis of the system taking into account the various emergency reserve options available, would be required to conduct a credible 'worst case' analysis. A study of 10 years' data in the Netherlands,[42] a relatively small region compared with the diversity available on many other systems, concluded that on no occasion would the output have declined by more than 40% of the installed wind capacity within an hour, and 'an hourly decrease in wind power output of 30–40% of the installed capacity might occur four times in 10 years.'

Similar conclusions are likely to apply to weather-driven variations in other sources, for example, cloud-induced variations in solar output. Diurnal solar variations, of course, cannot be much reduced by diversity, though the rate of change in the morning and evening may be significantly moderated by a longitudinal spread of several hundred kilometres. Diversity would smooth wave power variations to a degree depending heavily on the locations and orientations relative to the primary wave regime and coast. For tidal energy, although the driving force is primarily lunar, local topography determines the relative timing of tides, so that different sites in the same region can complement each other; the timing and form of output can also vary according to the system design and control.

[41] E.D. Farmer *et al*, 'Economic and operational implications of a complex of wind generators on a power system', IEE Proceedings A, Vol 127, June 1980.

[42] J.P. Coelingh *et al*, *op cit*, Ref 15.

Appendix 2

Capacity credit from variable power sources

How can variable sources contribute to the reliability of a system when they cannot be relied upon to produce power at times of peak demand? The key logic has been given in the text and it applies equally to all generating plants – none are completely reliable, but a reliable system can be built from them because of the risk of many independent inputs failing simultaneously is so small. Statistically, it emerges that providing a new source fails independently of other units on the system, its contribution to improving system reliability at the margin does not depend on its own reliability – all that matters is the mean energy available at times of system risk. Until their capacity rises above the level of general statistical variation on the system, variable sources thus contribute as much as conventional plants.

This result can be proved in a number of ways. Rockingham proved the result for normally-distributed outputs, and Swift-Hook has given a general proof via binomial expansions.[43] For the less mathematically-minded, a graphical illustration is also possible. Running short of capacity can occur due to any one of thousands of possible combinations of high demand and high plant outage. Figure 9 illustrates the density of failure states *S(x)* which result in capacity shortfall of *x*. The total probability of failure is proportional to the area under this line, and the number of potential failures states which will be prevented by adding a new source can be represented as illustrated in Figure 9.

If the capacity of the new sources is small enough, *S(x)* will be more or less constant over the range of possible plant output, and the contribution to system reliability will be *S(0)* times the totals source energy output in the period considered – the standard result. The conventional plant capacity can be reduced by an equivalent amount while maintaining the original

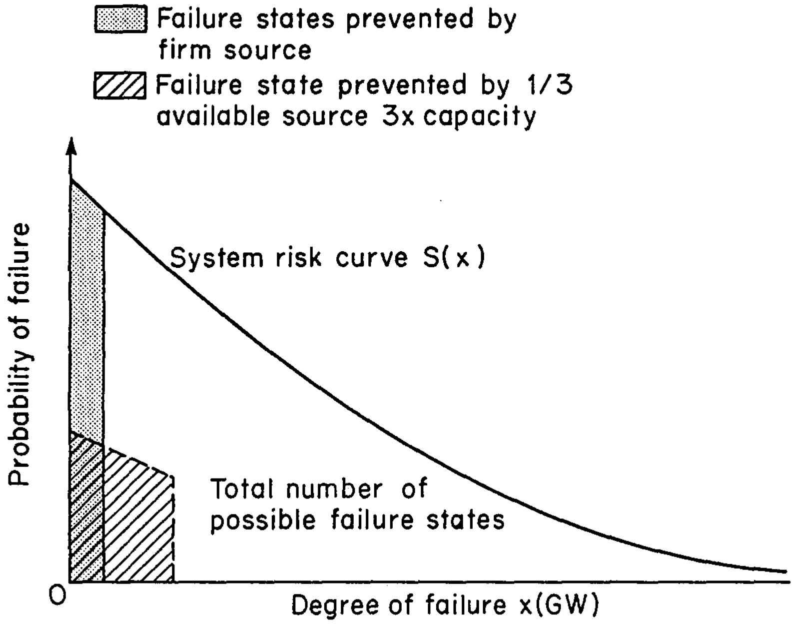

Figure 9. Capacity value of variable source at low system penetration.

level of reliability. This treatment also shows why, and in principle how, the capacity credit will decrease with increasing plant capacity and variability: increasing capacities of a given variable source extend the area of the block to the right, but not upwards, and the reliability contribution from adding more of the same soon declines towards zero if there are significant periods with no output anywhere.

---

[43] A.P. Rockingham and R.H. Taylor, 'System economic theory for WECS', Proceedings 2nd BWEA Wind Energy Conference, Cranfield, UK; D.T. Swift-Hook, 'Firm power from the wind', Procedings 9th BWEA Wind Energy conference, Edinburgh, UK, 1987.