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Why UK wind power should not exceed 10 GW

Britain's wind power reached 1 GW in June this year, making it the eighth largest national installation in the world. Over the next 5 years a further 6 GW is likely to be built at a cost of £7 billion in the rush to meet the Government's target of 10% renewable energy by 2010. The plan is for wind energy to deliver three-quarters of the target but that, as this paper explains, would actually require 12 GW, meaning the target will not be met. Furthermore, experience in Denmark and Germany shows that the UK will find it impractical to manage much over 10 GW of unpredictable wind power without major new storage schemes or inter-connectors. The paper concludes that while wind power should be exploited as fully as possible, it must not be at the expense of renewing existing firm generating capacity.

In the May 2005 issue of *Civil Engineering* the author explained how the separate west Denmark grid has built and operates a wind carpet constituting 64% of its all-time peak load of 3·7 GW.[1] Germany, Spain and the US may have greater total capacity, and Germany's wind-power installation is the world's largest, at 17 GW, but west Denmark's 2·4 GW is equivalent to 0·88 kW per capita—making it the most wind intensive in the world (Fig. 1). Germany, by comparison, has only 0·21 kW per head.

Denmark copes with this quantity of stochastically intermittent capacity because of fortuitous and previously constructed inter-connections with Norway and Sweden, the generating capacities of which are larger than west Denmark's (27 GW and 25 GW respectively and 100% and 35% respectively, based on hydroelectric plants). To the south lies Germany with a predominantly thermal system of 125 GW and an annual consumption of approximately 550 TWh.[2] By comparison, west Denmark is a small system, with 5 GW of generating capacity (excluding wind power) and a consumption of roughly 20 TWh per year.

In 2004, west Denmark generated roughly 4·8 TWh from its wind capacity, but, as Fig. 2 shows,[3] most wind power in west Denmark coincides with large power flows from the system. In other words, it is exported. Therefore, contrary to popular myth, Denmark does not get 20% of its power from wind energy.

The conclusions are simple: west Denmark is able to support a high degree of wind penetration—24% of consumption—because it is inter-connected with

Fig. 1. Elsam's 160 MW Horns Rev offshore wind farm in west Denmark—part of the world's most intensive wind carpet (Elsam A/S)

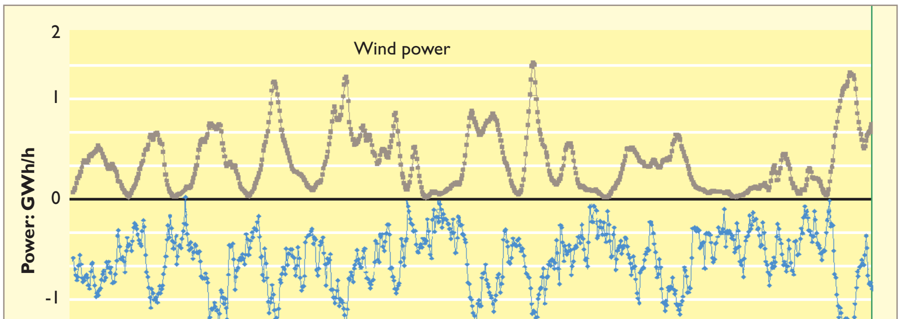


Fig. 2. Wind power and net exchange in west Denmark in January 2004—most wind power is exported from the system (data source: ELTRA[3])

much larger power systems, two of which have a high component of hydropower, the flexibility of which makes it the perfect 'balancing partner' for wind. Indeed, Danish wind is in effect stored, sometimes at a high cost to Denmark, by the curtailment of hydropower.

The UK, through the mechanism of the Renewables Obligation, aims to provide 10% of its supplied electrical energy from renewable resources by 2010, and then 15% by 2015. There is a further aspiration to generate 20% by 2020. The present administration expects most of this, some 75% up to 2010, to come from wind power.[4] After 2010, all incremental growth in renewable energy is foreseen as coming from wind power. This paper will show that, in the author's opinion, the targets and their prospects for implementation are unrealistic.

UK power system today

Irrespective of where and how the electricity is generated, the UK grid system, as with every other grid system in the world, must balance energy inflows and outflows from second to second. Fig. 3 shows how the typical, daily power demand profile for England and Wales varied during 2002–2003. Minimum summer demand can be less than 20 GW, while peak winter demand is typically 50 GW, and in the UK as a whole this approaches 60 GW. An analysis of the country's 78·5 GW generation capacity supplying this demand is shown in Fig. 4.

The system depends almost entirely on thermal power plants, nuclear and fossil, with a sprinkling of renewables, and supplies demand with high reliability. At its foundation lie the non-cycling base-load nuclear plants, with the balance being provided by conventional steam plants together with the more recently built combined-cycle gas turbine (CCGT) plants (Fig. 5) and the 2 GW French inter-connector built in 1986. The mix at any one time is mostly determined by price signals.

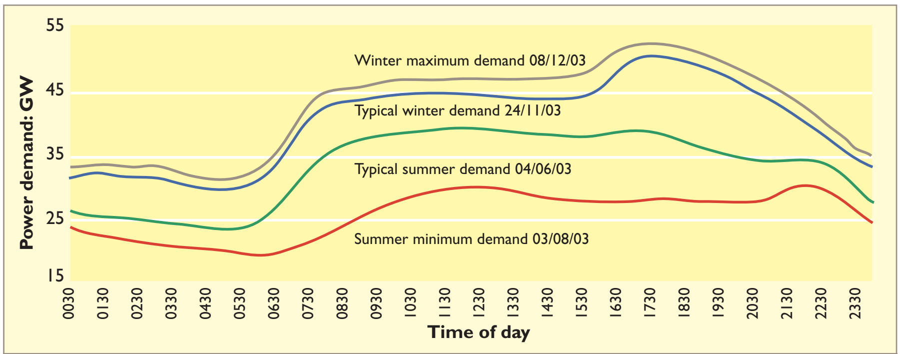
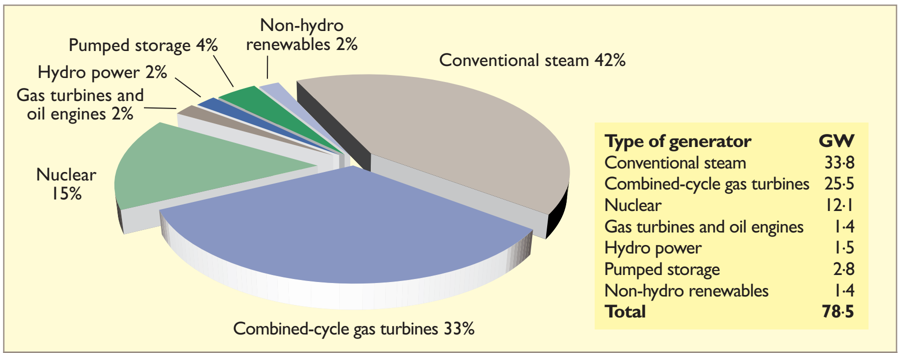


Fig. 3. Typical daily power demand profiles for England Wales during 2003/2004 (source: National Grid Transco)



Type of generator	GW
Conventional steam	33·8
Combined-cycle gas turbines	25·5
Nuclear	12·1
Gas turbines and oil engines	1·4
Hydro power	1·5
Pumped storage	2·8
Non-hydro renewables	1·4
Total	**78·5**

Fig. 4. UK generating capacity in 2003—the country depends almost entirely on thermal plant (source: DTI)

Fig. 5. RWE npower's Didcot B combined-cycle gas turbine power station with Didcot A coal-fired station behind—these two types of power station currently provide around 75% of UK electricity and need to be maintained and renewed (News Cast)

Much of the generating capacity is old and becoming obsolete. A combination of internationally agreed environmental regulations[5–7] and increasing costs will force the closure of most of the steam plants within the next 10 years. By 2020, only one nuclear power plant—the almost 30-year-old Sizewell B—will still be in operation, the oldest of the steam plants will have been working for five decades and the first generation of CCGTs will be approaching their 30th birthday.

So, within 10 – 15 years, it is more or less certain that 44 GW of capacity must be retired; possibly up to 50 GW if the older CCGTs also become obsolete. Yet in conjunction with this, peak demand by 2020 is predicted to rise to at least 70 GW.[8] Thus any new firm generating capacity must not only replace current plant, but also meet a rising demand—and do so in an increasingly competitive international fuel market. Unfortunately, the large increase foreseen in wind power will provide no firm capacity, which will have to come from new-built conventional capacity requiring investments totalling £40–60 billion.

The 2003 White Paper

The present Government's response to this situation, and its design for the reshaping of the national generating capacity, is laid out in the energy White Paper, *Our Energy Future*, which was published in February 2003.[9] The aspirations of this are admirable and can be summarised as favouring four main objectives. These are to

- reduce national carbon dioxide (CO_2) emissions by 60% by 2050
- maintain the security of energy supply
- make energy markets competitive
- ensure that every home is adequately and affordably heated.

It is not the purpose of this paper to question whether these aspirations are or can be consistent, but only to consider the practical consequences of implementing the policies as they appear to be emerging in 2005.

The White Paper foresees the likely disappearance of conventional coal capacity, the run-down of nuclear capacity and a huge expansion both of gas capacity and renewable energy. Wisely, it left options for the future use of nuclear power and 'clean coal', meaning plants that would sequestrate all or most of the emissions of CO_2.

At the time of writing (August 2005), the signs indicate that the administration is shaping economic incentives in such a way that the 2020 system will be overwhelmingly dependent upon gas-fired CCGTs and wind power. While governmental statements confirm that the nuclear option is still open, definite plans have not been published and, although the chancellor has recently made positive remarks for the encouragement of carbon sequestration, nothing precise is yet on the table.[10]

Given the dwindling supplies and escalating costs of gas both in the North Sea and worldwide, there would seem to be a good case on strategic grounds alone for backing development of realistic and practical 'renewable' alternatives to hydrocarbons. This is the case whether or not the development of renewable energy saves CO_2 emissions. Because the only near-commercial, renewable energy source that can be immediately developed on a very large scale is wind energy, it seems reasonable to ask whether wind is the answer to our prayers?

Wind energy and hydrogen

While this paper is primarily about the feasibility of the very large scale use of wind energy in the electricity supply industry, it is worth digressing at this point to see whether wind energy can alleviate future hydrocarbon shortages, particularly transport hydrocarbons, through hydrogen production.[11]

In 2003, the UK consumed 77 Mt of oil, of which about 50 Mt consisted of transport fuels.[12] The energy value of this, at 43 GJ/t, is 2150 PJ. A total of 18 Mt of hydrogen would be required to supply the equivalent energy. Since 48 MWh of electricity are required to make 1 t of hydrogen by electrolysis, to supply the UK's 2003 transport energy with hydrogen would require 864 TWh.

The wind capacity required to produce that quantity of energy would depend on load factor. Load factor, often called capacity factor, is the power actually produced by a generator in a year expressed as a percentage of its theoretical capacity. A 1 MW generator working flat out and continuously (i.e. at a load factor of 100%) for a year would produce 8760 MWh, whereas if it produced only 4380 MWh its load factor would be 50%.

Typical load factors for UK wind farms are in the range 25–35%. To generate 864 TWh at, say, 30% load factor would thus require an installed capacity of 864 000 GWh/8760 h × 100/30 = 329 GW, which is over four times the national current total generating capacity. To produce an installed capacity of 329 GW of wind power would require 110 000 turbines of 3 MW which, if placed at 500 m centres, would occupy an area of 27 000 km^2—rather more than the area of Wales. Clearly wind-sourced hydrogen is not a feasible transport fuel option.

Despite this, strategic and national security reasons justify building as much wind energy as is feasible. After all, each MWh generated by wind will save roughly 150 kg of gas and avoid between 270 kg and 400 kg of CO_2 release (assuming a fuel efficiency for CCGT of 50%). However, because of wind power's stochastic intermittency, there are limits to what is feasible.

Balancing problems

The pattern of electricity used by individuals, households and industry appears to be entirely random, but millions of users have fairly regular habits and their aggregated demand has a 'smoothing' effect on national power demand. Given the long history of energy production and use in UK, patterns of power demand are well understood by the system operators and power suppliers (Fig. 3). The grid operator, armed with the weather forecast, is able predict demand almost minute by minute for any day of the year.

In a system supplied by conventional power plant, called up upon demand, the grid operator can minimise the need to purchase so-called 'balancing power'. The amount of balancing needed is the small difference between instantaneous demand and scheduled production.

Wind power poses an entirely new challenge to the grid operator. Unlike any previously experienced power capacity, it cannot be 'called upon' at any time. It is available only when the wind blows. How much wind power is available depends entirely on how much wind is blowing. The challenge to the operator is to anticipate the amount and timing of wind power entering the system.

The output of the modern wind turbine is very sensitive to wind speed, as is shown in Fig. 6. Consequently, the 'holy grail' of wind energy forecasting is to achieve a next-day forecast accuracy of +/–1 m/s. In fact, the best on offer today is about 1·5 m/s. In Fig. 6 we can see that, applied to a single turbine, this level of accuracy is only good enough to predict a single turbine's output within a range of 26% to 69% around the 'middle' operating range of 46% at 9 m/s. Of course, if the predicted wind speed is over 16 m/s or under 5 m/s, the predicted output (100% or close to zero) is not so sensitive to variations in wind speed.

Some degree of 'smoothing' occurs when a large capacity of wind power is distributed over a wide area, but even so, in west Denmark, where the best wind forecasting has been employed for the last four years, it can be shown that a difference of just 1 m/s between the forecast wind power and the actual wind power corresponds to 14% of the wind capacity in operation. In the UK, 14% of, say, a 10 GW wind carpet (1·4 GW) is typically the size of two or three modern CCGTs.

At present, with wind power's low level of penetration into the UK power grid, physical balancing requirements are small and every GWh generated by wind probably displaces a GWh from a fossil fuel plant. In this sense, and at this level of market penetration, wind power is fulfilling the Government's aims of cutting CO_2 emissions and diversifying energy sources, although rather expensively.

When the penetration of wind power increases, its stochastic intermittency will become a challenge for the grid operator. This is also affected by where the wind power is generated.

Transmission losses

Figure 7 shows the locations of the UK's 109 operational wind farms in July 2005.[13] There are currently 1316 turbines with a total capacity of 1·1 GW. The

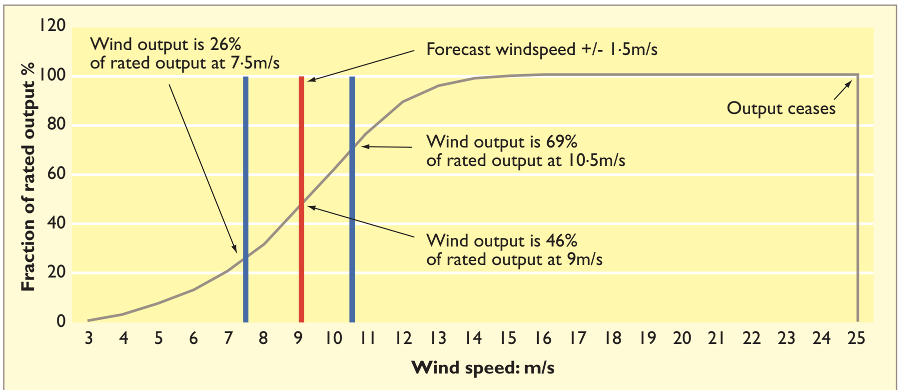


Fig. 6. Power curve of a typical modern wind turbine, showing potentially significant effects of wind-speed forecast accuracy of +/–1·5 m/s on output

Fig. 7. Location of operational UK wind turbines—most are in the north or west of Britain, remote from the main centres of demand

wind generators are paid at the station boundary and do not suffer a significant financial penalty for the fact that around 10–15% of the power they generate is lost during transmission

Fig. 8. E.ON UK's 31 MW Bowbeat Hill wind farm near Peebles is typical of Scotland's fast-growing wind carpet (News Cast)

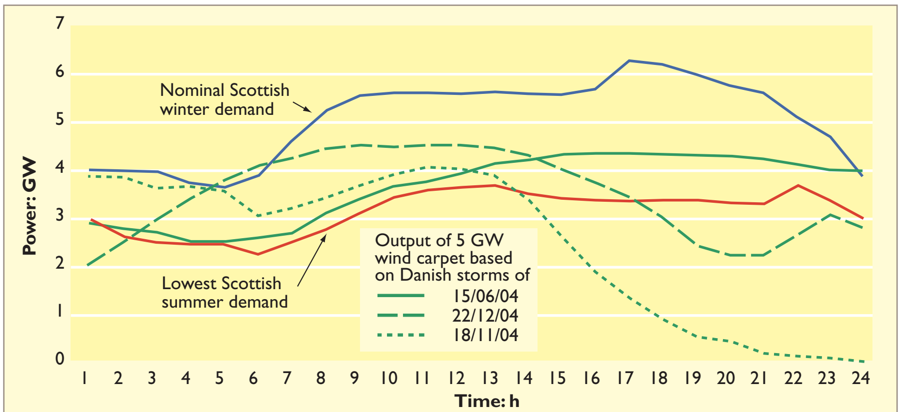


Fig. 9. Typical maximum and minimum daily power demand in Scotland compared with likely outputs of 5 GW installed wind power based on performance of Danish wind carpet during three storms in 2004—wind power would equal or exceed demand at various times of the day, making it very difficult to manage

majority have been erected in the north and west of Britain and this trend continues. Of the additional 10·7 GW being built or planned, 6·8 GW is in Scotland (Fig. 8). This is unsurprising, since most of the wind resources of the British Isles are concentrated in the north-west.

Unfortunately, the centre of load is many hundreds of kilometres away, somewhere between Birmingham and London. However, wind generators are paid at the station boundary and do not suffer a significant financial penalty for the fact that around 10–15% of the power they generate is lost during transmission. Further action has recently been taken by the Government to ensure that remote location is no obstacle.[14] Consequently, a large part of the planned onshore wind capacity will probably be built in Scotland.

Scotland's electrical inter-connection is currently limited to 0·5 GW with Northern Ireland and 2·2 GW with England. Obviously, these links will have to be upgraded and high-voltage transmission lines built throughout the Highlands and Islands. At the time of writing, the planning and budgeting procedures for getting Scottish wind power to consumers in England do not appear to be adequate.

The case of Scotland

How much wind power can Scotland take without grid instability? Fig. 9 shows how demand on the Scottish power system varies during a normal summer holiday or weekend and during a normal working winter day. Overlaid on this chart is the contemporaneous wind output of the west Danish wind capacity of 2·4 GW for three typical, stormy days, extrapolated to represent a 5 GW Scottish wind carpet. This is arbitrarily but not unreasonably assumed to have a similar behaviour profile to that in Denmark and gives a similar per capita 'wind penetration' of 0·8 kW.

During all three storms, wind output would have equalled or exceeded Scottish demand at some time during the day. The situation would be particularly challenging on a summer day when output would exceed demand for most of the period. Furthermore, the 18 November 2004 storm shows wind output falling from 4 GW to 0·5 GW in just 6 h during a time when demand is rising.

It is clear that 5 GW, just two-thirds of what is already operating and planned, will be unmanageable unless turbines are shut down. Such ‘wind curtailment’ is already widely used by German utilities, which have great difficulty coping with a level of wind penetration that is only 0·2 kW per capita.[15] Curtailment of output, as a policy, is a curious solution when wind power is already three to four times more expensive than conventionally produced energy. Furthermore, when its output is curtailed, no thermal MWh are displaced, so its value is further eroded.

Although the words ‘wind curtailment’ appear in unofficial remarks about the UK’s energy planning, no official acknowledgement is made that in the absence of very expensive technical solutions, such as storage or the construction of large inter-connectors, it is the all-but inevitable solution. Furthermore, it is unclear who is to carry the cost.

Capacity in England and Wales

It appears that only a small part of the total 7·3 GW wind power currently proposed for Scotland can ever be connected. How much can actually be accommodated will depend on the willingness of the politicians and the public to make very large investments in grid upgrades and, possibly, power storage, but these issues are not currently at the forefront of debate, and there are no mechanisms in place to pay off these investments.

Scotland might be able to absorb around 2–3 GW of wind so, to meet the Government’s wind power targets the balance must therefore be built in England and Wales.

The Government intends that renewable power will deliver 39 TWh by 2010 and 58 TWh per year by 2015. It is widely assumed that 75% of the 2010 target will be wind and all the additional renewable capacity between 2010 and 2015 is assumed to be wind. But how much wind capacity needs to be built in order to deliver 29·25 TWh in 2010 and 48·25 TWh in 2015?

The answer depends upon the load factor of the installed capacity (Fig. 10). In turn, this will require some idea of where most of the plant will be installed. The onshore wind developers are voting with their pocket books and choosing higher load factor locations in Northern Ireland, Scotland and Wales.

The Department of Trade and Industry’s digest of United Kingdom energy statistics (DUKES) in 2004[16] reported a load factor of 24·1% for onshore wind in 2003. The Office of Gas and Electricity Markets’ (Ofgem) reports[17] show that, notwithstanding the very high load factor of some UK wind farms, the national average achieved in the UK during the last two Ofgem periods is a similar value (see Table 1).

With Scotland clearly unable to accept much more than 2–3 GW, it is probably valid to assume that the overall land-based load factor will be no more than 24%, and that the average load factors for offshore wind farms, taking into account low wind areas like the Wash and the Thames estuary, will be little better than 30% in the long run. If half is built onshore and half built offshore, the overall load factor will be around 27%.

The Government’s 2010 renewable energy target can therefore be met by building 12·4 GW of wind capacity and the 2015 target can be met by building 20·4 GW of wind capacity. Is this manageable? The British Wind Energy Association (BWEA) claims that just 4 GW of onshore and 4 GW of offshore wind can meet the Government’s targets for 2010, implying an average load factor of 42%. It does not help that the 2010 targets themselves have just increased. However, the BWEA consistently insists that wind turbine load factors are much higher than the evidence suggests.

Figure 11 addresses the question by performing extrapolations and overlays similar to those carried out for Scotland. The same Danish storms are extrapolated to 12·4 GW and 20·4 GW of installed wind capacity and compared to a typical lowest-demand summer day, which is when the balancing problems will be most acute. It is clear that 12·4 GW of wind, if ever built, will impose severe strains on the England and Wales system. It is equivalent to 0·25 kW per capita, well above the level at which the German system (0·2 kW per inhabitant) is already under severe difficulties. If the wind capacity was 20·4 GW, it would be an impossible situation to manage. It therefore appears that the England and Wales system will begin to run into balancing problems as it approaches 10 GW of wind power.

First and foremost, wind forecasting is unable to offer any degree of accuracy better than 1·5 m/s, equivalent to +/–21% of installed wind capacity. Often, it is worse. Large amounts of thermal capacity must thus be in a constant state of ‘hot’ reserve to provide balancing power, upwards or

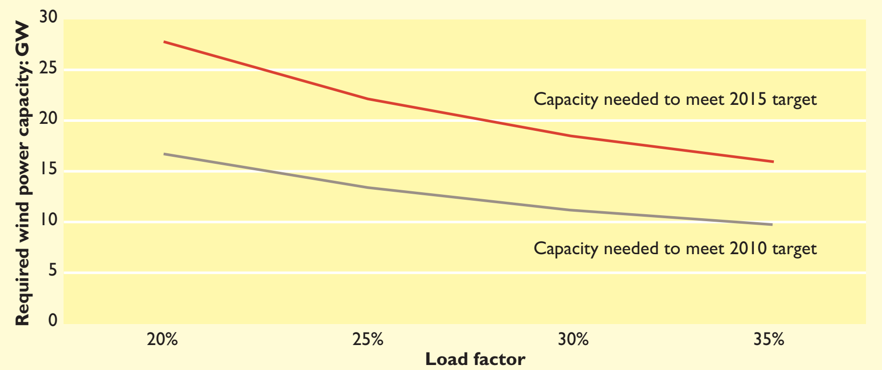


Fig. 10. Wind energy capacity required to deliver UK’s 2010 and 2015 renewable energy targets of 29·25 TWh and 48·25 TWh vary considerably with load factor

Table 1. National average wind farm load factors achieved in the UK during the last two Office of Gas and Electricity Markets (Ofgem) periods

Load factor in UK	England	Scotland	Wales
First ROC period, April 2002–March 2003	24·0%	25·5%	23·4%
Second ROC period, April 2003–March 2004	23·8%	25·6%	23·9%

ROC, renewables obligation certificate

downwards. The UK Government is advised that this can be supplied by gas turbines, but this would not be economic with the CCGTs that are likely to supply most future power. CCGTs lose thermal efficiency when turned down and frequent cycling shortens plant life. Open-cycle, aero-derived, gas turbines have a peak efficiency of about 40% (compared to CCGT efficiencies of 55–60%) but the average efficiency will be much lower at part load. As soon as such plant needs to be used to balance wind loads on a large scale, the CO_2-saving advantages of large-scale wind power diminish further.

Nevertheless, in view of the looming fuel-supply crisis, it is wise to build as much wind capacity as will not negatively affect the system as a whole. This should be built to save fuel as well as CO_2 emissions. Due to better load factors and reduced environmental impact, as much as possible of this capacity should be built offshore, where plant can be built on a larger scale and therefore be connected to the grid more easily. A further factor favouring offshore sites is that the identified areas are so much closer to the urban centres of demand (Fig. 12).

Fuel and CO_2 savings—at a cost

The total CO_2 savings achieved by a 10 GW wind power capacity will be in the region of 9–11 Mt/y. This is roughly 1·5–2·0% of the UK's 2004 emissions (550 Mt) and 0·046% of global emissions. Global CO_2 emissions were about 24 000 Mt in 2003 and are increasing at about 2% per year, mainly from India and China.[18] This is a very modest saving, but would cost the UK consumer more than £10 billion (including transmission and distribution expenses).

The National Audit Office has recently pointed out that the cost of CO_2 savings achieved by wind are up to 20 times more expensive than the early 2005 value of displaced CO_2 in the EU Emissions Trading System.[19] These remarks are consistent with the advice of the Irish grid board, ESB, and the German energy authority, DENA: wind power is a very costly emissions-reduction method.

However, 10 GW of wind energy will also deliver a small but significant fraction of all energy, thus saving fuel, most of which will need to be sourced from distant countries. A wind carpet of this size, predominantly offshore, might generate roughly 22 TWh, thus saving the UK 3·3 Mt of gas a year. This is significant, but only a small fraction of the electrical energy needed to support the country. Gas consumption in 2003 was 86 Mt[20] and, under current government policies enunciated in the energy White Paper, may increase to anything up to 130 Mt by 2020.

Contribution to secure capacity

Evidence from both Denmark and Germany shows that even a very large wind system contributes no firm capacity to a power system. No matter how large a British wind carpet is, if the wind does not blow or blows too strongly, little or no power will be produced. Furthermore, power output can fall off, sometimes sharply, if wind speeds are high.

On 8 January 2005 in west Denmark, the weather forecast predicted winds strong enough to supply roughly two-thirds of west Danish demand (Fig. 13). During the morning the actual wind output was already more than anticipated. By midday, the storm unexpectedly increased and the turbines did what they are designed to do and closed down to avoid mechanical damage. The same storm had a similar effect in northern Germany, which also unexpectedly lost over 2500 MW during this period. Together,

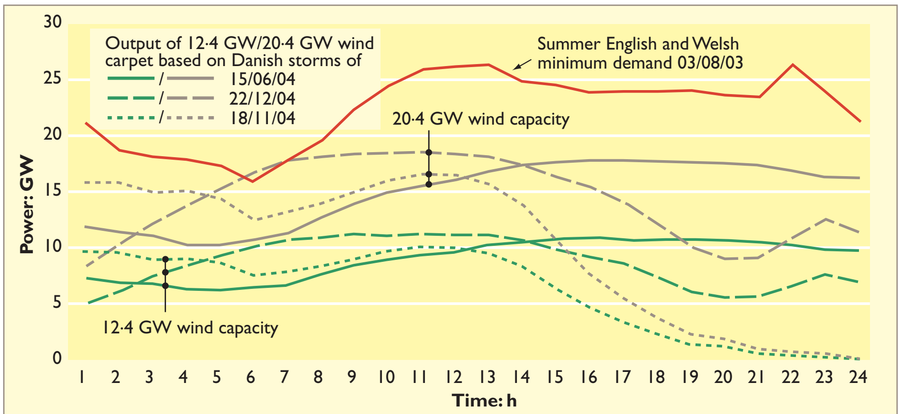


Fig. 11. Summer power demand in England and Wales compared with likely outputs of government targets of 12·4 GW and 20·4 GW installed wind power based on performance of Danish wind carpet during 2004 storms—in the absence of large storage systems or international inter-connectors, wind farms will need to be shut down extensively to balance the grid

Fig. 12. RWE npower's 60 MW North Hoyle wind farm in Liverpool Bay—offshore farms can be larger in scale, making them easier to connect to the grid, as well as being closer to urban centres of demand (News Cast)

west Denmark and northern Germany lost 4800 MW of capacity in 4 h.

Fortunately, Denmark's northern neighbours, also hit by the storm but having very little wind capacity, had been importing most of the Danish wind power and were able to compensate for the loss of wind energy and supply some of the Danish shortfall. Most of the shortfall was met by imports, thus keeping the systems in all these countries stable.

The high concentration of wind power in western and northern parts of the UK will lead to similar events, which might just be manageable at a level of 10 GW overall, with a southern offshore component. However, it could not be at 20 GW of wind capacity, at which level protection against such an event would be technically difficult and probably uneconomic.

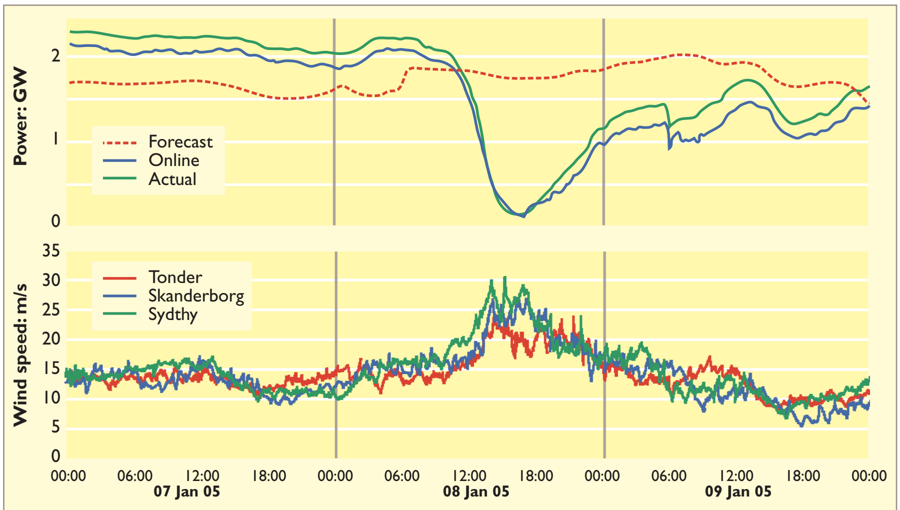


Fig. 13. Danish wind turbines had to shut down on 8 January this year as wind speeds were higher than predicted (data source: ELTRA)

Conclusions

In view of the pending energy crisis, substantial challenges lie ahead in every sphere of industrial, domestic and commercial activity and we are forced to conclude that the UK needs as diverse an energy supply as possible.

The Government is advised that the UK's system can accept anything up to 26 GW of wind power. For all the reasons explained in this paper, this advice cannot be regarded as sound. Ample evidence from relatively large wind systems in Denmark and Germany exists to prove that 10 GW (+/–25%) will be the probable safe upper limit of all wind capacity.

Wind power's contribution at 10 GW, albeit small and costly, can be significant. However, its construction will do nothing to offset the inevitable loss of firm generating capacity. Between 40 and 50 GW of diversely energised, new generating capacity, costing £40–50 billion, must be planned, financed, engineered, procured, built and commissioned between now and 2020.

At the time of writing (and considering that almost nothing of substance besides yet another couple of GW of CCGT are being considered), this is a significant challenge. The successful realisation of the nation's infrastructure redevelopment requires much greater involvement from the engineering profession than has been the case in the period before and since the 2003 energy White Paper.

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