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## Why wind power works for Denmark

Denmark generates more wind power per head of population than any other country in the world. Its 5500 wind turbines, including the world's two largest offshore wind farms, generate 16% of national demand. With increasing concerns over fossil fuels, the country is now being closely monitored by energy planners and funders worldwide. However, as this paper reveals, Denmark is exporting most of its wildly fluctuating wind power to larger neighbours while finding other solutions for supply and demand at home. As an 'island' grid based on slow-reacting thermal power stations, Britain may find its comparable wind-power aspirations more difficult to achieve.



Fig. 1. Completed in December 2003, Nysted offshore wind farm in Denmark has 72 turbines with a total capacity of 166 MW, making it the world's largest (copyright: Elsam A/S)

The global oil price rise in the 1970s prompted the Danish Government to switch to imported coal for its thermal power stations and to start a wind energy programme targeted at generating 10% of electricity by 2000. The target was achieved and there are now 5500 wind turbines—including the world's two largest offshore wind farms at Nysted (Fig. 1) and Horns Rev—producing the

energy equivalent of 16% of national demand.

This paper reports on performance data of the west Denmark power grid, to which 80% of the country's wind power is connected. The east Denmark power grid is entirely separate but both grids are heavily interconnected to the national grids of neighbouring countries to the north and south.



Fig. 2. West Denmark's six thermal power stations of 3516 MW are supplemented by a further 1450 MW from combined heat and power plants in most towns and villages

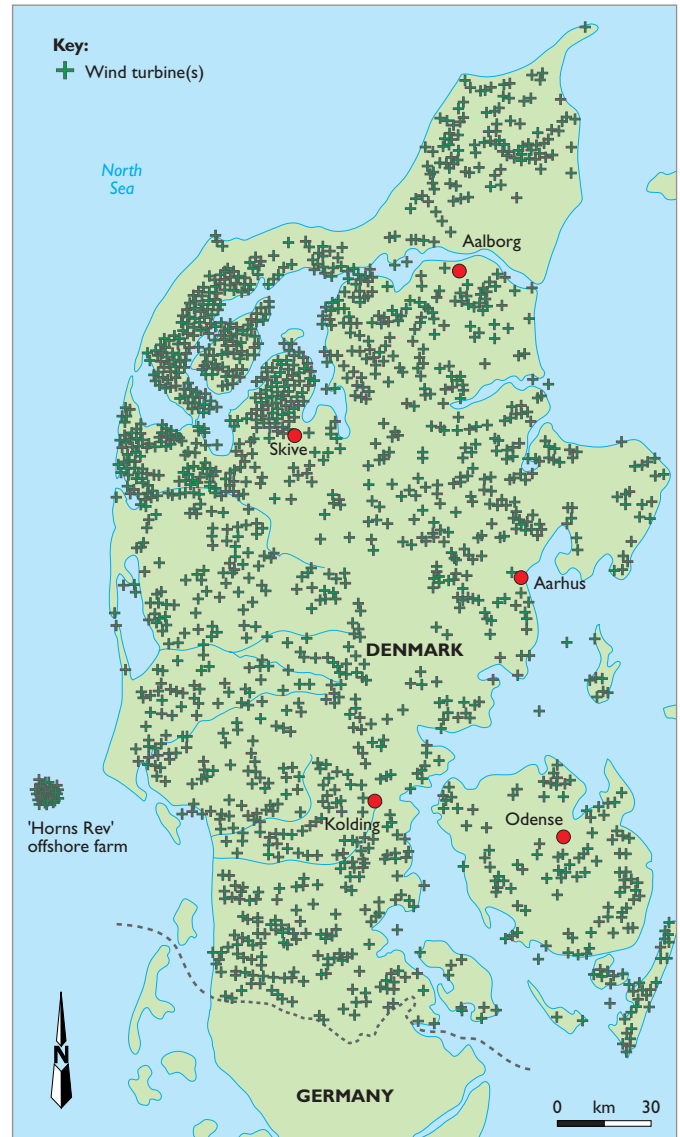


Fig. 3. West Danish wind carpet has an installed capacity of 2374 MW, equivalent to 0.88 kW per person

## A 15-year programme

In 1990 Denmark had six large power stations, all of them designed as combined heat and power plants providing district heating to west Denmark's largest towns (Fig. 2). Five are coal-fired power stations and the sixth is designed for ultra-supercritical steam operation on gas. The coal-fired station near Aalborg has since been extended and this and the gas-fired station are now the most efficient Rankine-cycle plants in the world. The installed

capacity of the main thermal power stations at the end of 2003 was 3.5 GW.

During the past 15 years there was also an intensive construction programme to upgrade the district heating plants in most Danish towns and villages to combined heat and power. The total capacity of these 'de-centralised' power units in 2004 was 1450 MW. They are mostly based on natural gas engines, though a significant number are bio-fuelled. Many industrial combined heat and power plants and factories also supply heat to the district heating system.

During the 1990s, there was a crash-building programme for wind power, totalling 2374 MW<sup>1</sup> at the end of 2003 (Fig. 3). Although more wind power overall has been installed in the US and Germany, the 'wind intensity' of western Denmark is still unmatched. It is equivalent to 0.88 kW of installed capacity per person in western Denmark compared with 0.18 kW per person in Germany and 0.01 kW per person in the UK (at the end of 2003).

Furthermore, Denmark boasts one of the world's most developed wind energy man-



Fig. 4. Horns Rev wind farm has 80 turbines generating 160 MW (copyright: Elsam A/S)

contribution its wind turbine manufacturers are already making to the UK's wind energy portfolio—make its experience with wind energy highly relevant.

The term 'wind carpet' was coined in Denmark and is frequently used to describe the way many wind farms join together to form what is effectively a large, virtual power station. Individual wind farms, in different parts of the country, will be observed giving very different outputs at the same time from winds that may be strong in one area but weak, and from a different direction, in another. However, from time to time, a cyclone covers the whole of west Denmark.

West Denmark covers the same latitudes as Sunderland to the Moray Firth and is comparable in size to Scotland. Critically, it would appear that the wind regime in Denmark is broadly similar to that in the UK—though it is unarguable that there are better wind locations in the Britain, particularly in the north and west (Fig. 5). It is therefore worth evaluating the experience of the Danish experiment with wind energy in some detail. Indeed, Danish experience is highly relevant to the UK at this very early stage in the development of a large national wind carpet.

### Load factor is just 20%

Load factor (or capacity factor) has been averaging about 20% in west Denmark (Fig. 6). For those not familiar with the term 'load factor', if a 1 MW wind generator is working at 100% load factor, it would produce 1 MW per h, 24 h per day, 365 days per year, giving a total of 8760 MWh per year. If it produces half this annual amount—4380 MWh—its load factor would be 50%, and so on.

In the UK the onshore load factor has dropped to around 25%. As time goes by and the development of wind power at the best wind sites gives way to less favourable ones, the specific output at each new site in the UK is likely to decline further.

Furthermore, wind generators are not exempt from breakdown and, like any other rotating plant, need regular servicing. Breakdown outages and even routine service outages can be extended, especially if these are offshore. In

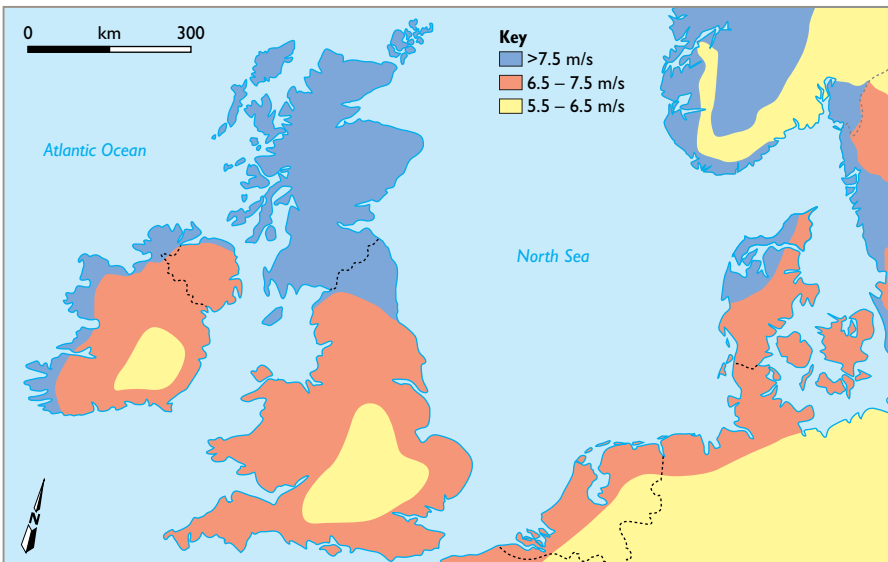


Fig. 5. Britain and Denmark have similar wind regimes (source: European Wind Atlas<sup>2</sup>)

manufacturing industries and, as mentioned above, the world's two largest offshore wind farms (Fig. 4). West Denmark's production from wind generators during 2003 was 4.36 TWh out of a total of nearly 27 TWh, with local consumption at just over 20 TWh—a record amount.

### Highly relevant to the UK

On the face of it, west Denmark has already nearly achieved the 20% renewable energy goal to which the UK aspires for 2020. Its proximity and shared latitudes with the UK—as well as the large

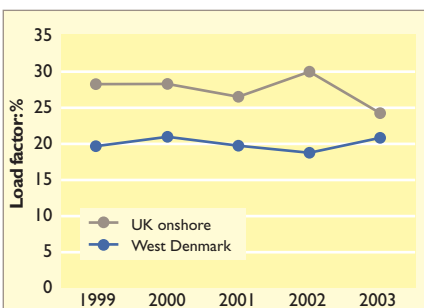


Fig. 6. Load factors are now relatively steady in west Denmark but declining in the UK (sources: ELTRA and [www.dti.gov.uk/energy/inform/dukes](http://www.dti.gov.uk/energy/inform/dukes))

Denmark there is a very large and healthy service sector devoted solely to the maintenance and repair of wind turbines. Maintenance and repair of an ageing wind-carpet probably accounts for some of the long-term decline in Danish load factor.

It is axiomatic that a high load factor will result in high output. A lower load factor necessitates a larger installed capacity just to deliver the volume of energy required. If the Danish load factor is a reasonable guide to that which will be reached in the UK, the projections of the capacity needed to deliver the 60 to 70 TWh in 2020 foreseen by the UK's energy planners will be large.

In Fig. 7, it can be seen that if 70 TWh are needed to fulfil the UK Government's renewable energy targets, this can be supplied from 25 GW if the load factor is 35%—but 41 GW would be needed to supply the same amount if the load factor were to be as low as the wind farms of west Denmark. Each GW of wind generation costs roughly £1 billion—this is the average cost of equal amounts of offshore and onshore wind capacity—so the financial penalty for not getting the load factor right is enormous. To these costs must be added the infrastructural costs of delivering the power to load centres and the accompanying costs of standby power and load balancing.

### A highly variable supply

From an installed capacity in west Denmark of 2374 MW there were nine occasions during 2003 when the wind carpet output exceeded 2000 MW (Fig. 8). Furthermore, there were many events during 2003 when the whole carpet was delivering an output of over 75% of its installed capacity. When this happens, it behaves as a single power station, responsive only to nationwide weather conditions, not demand.

Sometimes the Danish wind carpet produces maximum output when there is little demand. On other occasions it delivers no energy when demand is high. There were 54 days in 2002, for example, when wind supplied less than 1% of demand (Fig. 9). On one of those days (16 August 2002) the wind power system steering requirements exceeded

wind output and the wind carpet consumed more power than it could produce. In other words, the wind carpet became a net energy consumer. There was also a whole week in February 2003 when virtually no wind power was generated in west Denmark.

In view of the Danish experience, it is probably imprudent to believe the UK can expect firm capacity from its wind carpet, despite its larger size and more westerly geography. If the wind does not blow, no power can be generated—and high-pressure systems can be very large and persistent. Paradoxically, if the wind blows too much, there is also no power generated. A modern wind turbine needs a wind speed of around 4 m/s before it can begin generating but it must feather its blades at around 25 m/s to prevent mechanical damage (Fig. 10).

Figure 11 illustrates how the country-wide wind carpet, consisting of the modern wind machines on which the UK's renew-

ables hopes are founded, actually behaves. Output increases more or less linearly between a wind speed of 5 m/s and 13 m/s. Above this speed, output levels off and, at 20 m/s (45 mph, force 8), stalls altogether for many machines in the system. Most modern turbines are designed to operate above this speed with a 20% lower

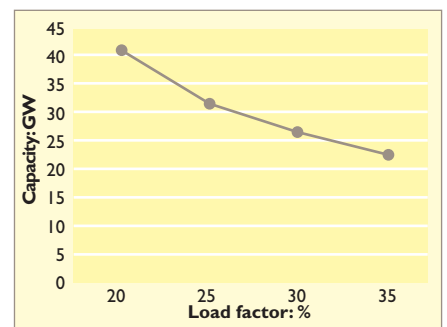


Fig. 7. Installed wind farm capacity needed to deliver the UK Government's 2020 target of 70 TWh increases dramatically as load factor decreases

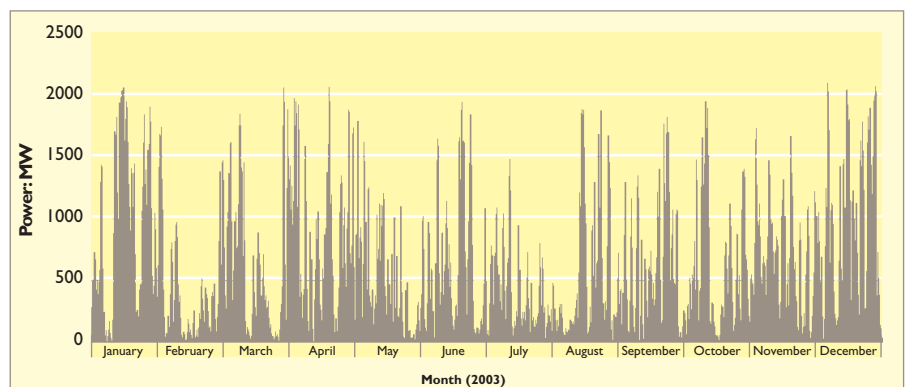


Fig. 8. Wind power production in west Denmark exceeded 2000 MW nine times during 2003

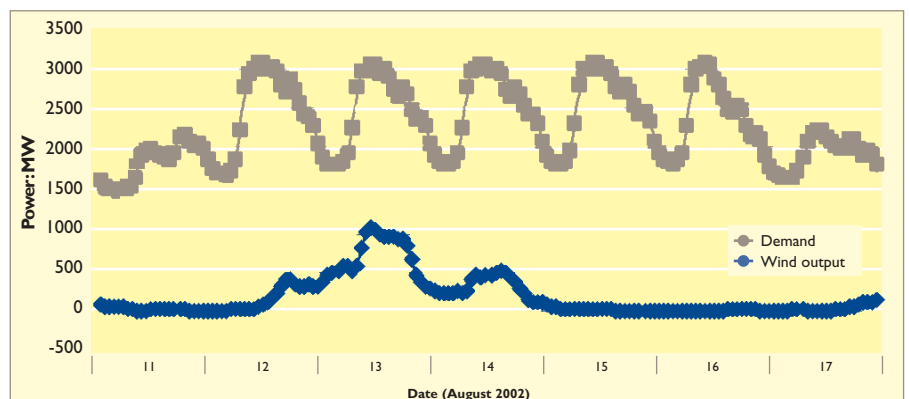


Fig. 9. Wind power during the week of 11–17 August 2002 fell a long way short of overall demand





Fig. 10. The Vestas V80 2 MW turbines at Horns Rev need 4 m/s wind speed before they can begin generating but must feather their blades at around 25 m/s to prevent mechanical damage (copyright: Elsam A/S)

output and even these are turned off completely when the wind speed exceeds 25 m/s (56 mph, force 9–10).

### How the Danish grid is balanced

In every power grid, load and demand are balanced dynamically as there is effectively no storage in the transmission and distribution system. This is not to be confused with energy storage systems (e.g. pumped or compressed air storage), which buy low-cost power in times of excess generation and deliver it very much as any other generator in times of higher demand.

As mentioned above, the west and east Danish grids have strong interconnections with neighbouring countries but are not linked to each other. West Denmark is tied into the much bigger grids of its neighbours Sweden, Norway and Germany with a total interconnector capacity of 2400 MW (Fig. 12). This is equivalent to two-thirds of the region's peak winter demand and, interestingly, about the same as its current wind capacity.

As shown in Fig. 13, west Denmark makes full use of its interconnections for balancing wind power as there is a strong correlation between wind output and net power outflows. However, the interconnectors were built primarily to link Norway and Sweden to Germany and, without their prior existence, it may not have been viable for west Denmark to build wind capacity on the scale it has.

Furthermore, the success of the interconnections has much to do with the extent to which both Sweden and Norway generate hydropower—which can supply 50% and nearly 100% of

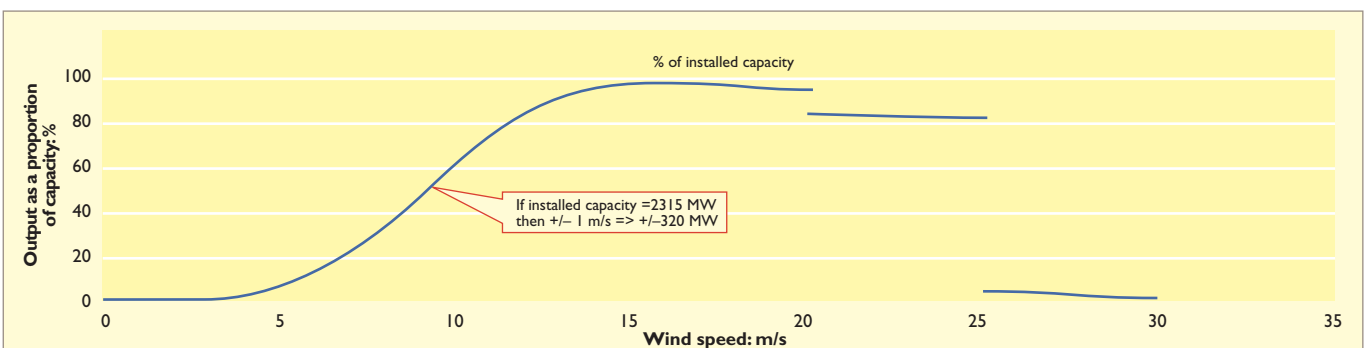


Fig. 11. How power output in west Denmark increases, decreases and finally shuts down with increasing wind speed (source: ELTRA)

their respective needs from water turbines. Hydropower output can be adjusted very rapidly as the highly variable wind power flows through the interconnectors.

It is also relevant that all three neighbouring systems, including Germany's, are many times bigger than west Denmark's and can act as a power sink to stabilise west Denmark's much smaller grid. Even in 2000, when wind capacity was 1000 MW less, the Danish balancing solution was mainly handled across the interconnectors.

The extent of the balancing challenge can be seen in Fig. 14. This shows the changes in wind carpet output each hour during 2002, expressed as a percentage of the total carpet capacity, which was then 2310 MW. In a conventional grid, thermal power stations must balance these flows by ramping up and down or by some other means. There is little doubt that this chart will be representative of the manner in which a UK wind carpet will perform.

Norway and Sweden, with their mainly hydro-supplied grids, are generally able to accommodate power surges from west Denmark. Hydro is a good match for wind power and both these countries are well placed to accommodate a large pene-

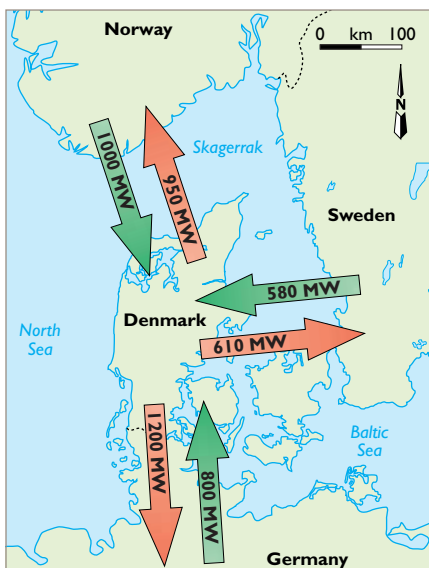


Fig. 12. West Denmark has a total interconnector capacity of 2400 MW with its neighbours Germany, Norway and Sweden—about the same as its installed wind power capacity

tration of wind capacity in future. In contrast, an 'island' system depending mostly on thermal generating capacity will have to accommodate power swings by ramping thermal capacity up and down, sometimes very quickly.

### Problems with forecasting

Although the climate of the British Isles is notoriously fickle, Denmark also experiences difficulties with weather forecasting. Fig. 15 shows a bad but unfortunately

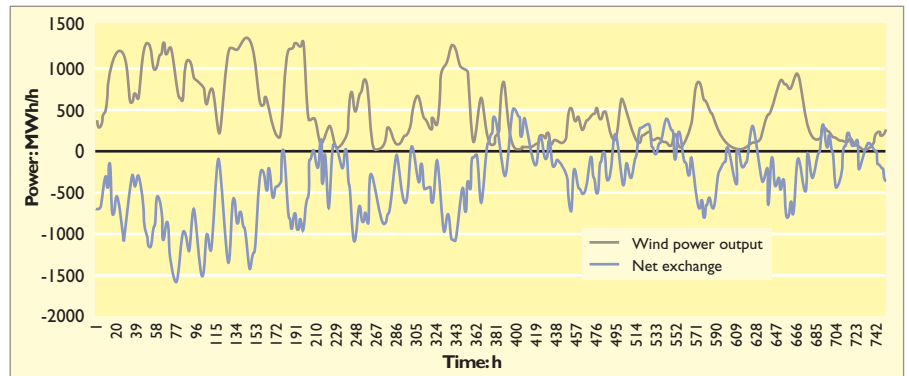


Fig. 13. West Denmark's wind power output compared to net power outflow to neighbouring countries in December 2003—the amounts are closely in balance

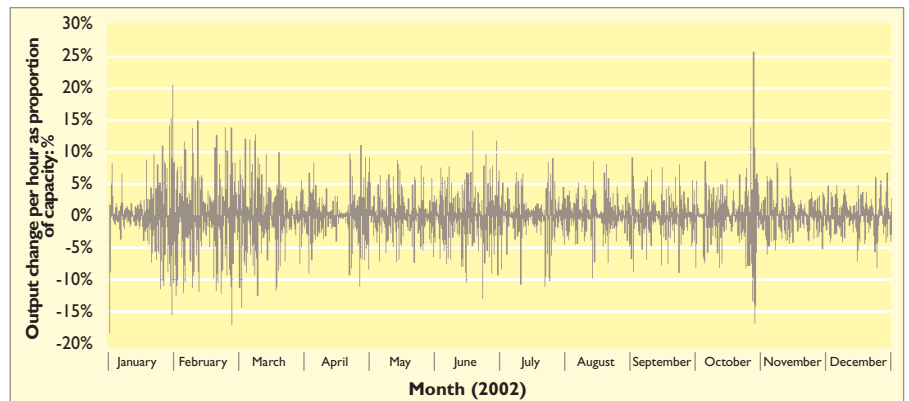


Fig. 14. Hourly changes in west Danish wind output power in 2002 as a percentage of overall wind capacity. In the absence of interconnectors, thermal power stations would need to be ramped up and down to match this

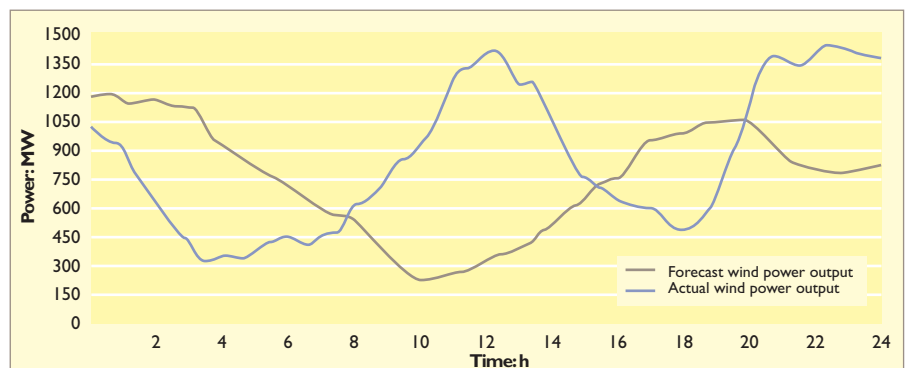


Fig. 15. Forecast versus actual wind power output in west Denmark on 27 October 2002 (source: Jyllands Posten)

common day for Danish wind forecasts.

Wind forecasting to the requirements of the transmission system operator is a major challenge as even the best mean average wind speed can only be predicted to within 1 m/s. As indicated in Fig. 11, for west Denmark wind power this equates to +/- 320 MW or 12% of wind capacity.

West Denmark's transmission system operator, ELTRA, is making significant investments to improve the accuracy of wind forecasting and it is possible that during the next 10 to 15 years more accurate weather predictions will make surprise events somewhat rarer. However, it is unlikely they can be ruled out altogether or that their probability can be reduced to an insignificant level.

## Conclusions

Denmark has the most intense wind carpet in the world, with a total of

3000 MW installed by the end of 2003—equivalent to 0.88 kW of wind energy per person in west Denmark. The average annual load factor for the wind turbine carpet in west Denmark is measured at approximately 20%. There are considerable and often rapid output variations throughout the day and throughout the year. Accurate forecasting of wind speeds is still difficult and output rarely matches demand, sometimes dropping below zero as stalled wind turbines still require power for their steering systems.

The variations, which are inherent in any wind energy system, can be readily accommodated in west Denmark because there are very strong electrical connections to the much larger grid systems of Norway, Sweden and Germany that can absorb these variations, particularly due to their reliance on rapid-reacting hydropower. Countries such as the UK, which operate an 'island' grid, will find it

difficult to do this with slower-reacting thermal power stations and may thus have to limit their reliance on wind power.

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