Wind power in Denmark

By Dr V.C. Mason (November 2008) ©

About a fifth of the electricity produced annually in Denmark is generated by wind. Of this, just over a half can be used directly within national borders over the year. The rest must be exported (often at much reduced prices) to preserve the integrity of domestic grids.

The need to backup the variable supply of wind power with electricity from combined heat and power plants for internal use, and the necessity to export large surpluses of wind power, mean that domestic savings in carbon emissions are relatively small at the present time.

Investigations to develop novel power transmission and usage systems for the greater exploitation of wind power within Denmark are in hand, but public opposition and concerns about safety have temporarily halted the deployment of wind turbines on land.

1. Background

Denmark's commitment to industrial wind power has so far produced mixed results, and requires many more years of developmental work. Nevertheless, the prominent position of this small country (pop. 5.4 million) in world turbine markets and the associated employment of about 20,000 of its citizens have undoubtedly brought it economic rewards (59).

The country's state-owned electricity supply network comprises two independent grids, both operated by its Transmission System Operator (TSO), Energinet.dk. West Denmark (mainly Jutland and Funen) functions as part of the major Continental system, while East Denmark (mainly Zealand) is a component of the Nordic system. In 2010, these two AC systems will be joined by a 600 MWe DC connection across the Great Belt (41; 43; 72).

Both grids are also heavily implicated in the transmission of coal-, gas-, hydro-, and nuclear-based electricity between neighbouring countries (88), the transfer involving long-established DC and AC inter-connectors, totalling about 5.4 GWe of capacity (corresponding to about 42 percent of the country's total electricity generation capacity). This is a proportionately much greater inter-connector capacity than the UK's 2 GWe link to France (i.e.: about 4 percent of generation capacity), and gives the Danish control system much greater operational flexibility (85; 86).

To cope with more power and an expanding electricity market, by 2011 the capacities of the north- and south-going connectors at the Danish-German border will be raised from 0.95 to 1.50 GWe and from 1.50 to 2.00 GWe, respectively; while by 2014 the trading capacity between Denmark and Norway will have increased from 1.00 GWe to 1.60 GWe (42).

When water reserves in the Norwegian and Swedish hydro-reservoirs are adequate, the international transfer of power through Denmark is usually in a southerly direction, but when dry periods prevail in Scandinavia the net movement of electricity is typically northwards.

2. Danish electricity production

Three quarters of Denmark's generating capacity (12.71 GWe) (88) is represented by 16 central and 728 local combined heat and power (CHP) plants. These installations can produce electricity at up to 85-90 percent efficiency (84) on the basis of imported coal, or gas derived from dwindling North Sea reserves. Of the 728 smaller decentralised plants (total: 2.17 GWe), 43 are of over 10 MW capacity, 56 are between 5 and 10 MW, and 629 are of less than 5 MW (22). Denmark's remaining capacity is associated with wind turbines, developed over two decades with the aim of reducing reliance on fossil fuels and cutting carbon emissions. The country operates no nuclear power stations, though in 2005 possibly 9 percent of its electricity consumption was satisfied by nuclear-based energy produced elsewhere (88).

In 2005, Denmark operated 5,267 wind turbines (3.126 GWe) (23), including about 200 (i.e. 0.42 GWe) offshore (31). Three-quarters of these were located in the western region. Since then the installed capacity of turbines has hardly changed, estimates of 3.11 and 3.12 GWe of potential wind power being recorded in 2006 and 2007, respectively (40). New 200-MWe offshore windfarms are currently being developed at Horns Rev and Rødsand, and will be ready in 2009 and 2011 (14; 55). Other turbines are planned (partly in association with current scrapping arrangements) to give a total of 1.300 GWe new plant, or 1.175 GWe of extra wind turbine capacity, in 2012 (56). This corresponds to a proposed increase of close to 40 percent in turbine capacity over the next four years (87).

3. Efficiency of wind power generation

The technical efficiency of wind power generation is affected by geographical location, prevailing wind speeds, turbine and rotor heights, and breakdowns.

Over a year, Danish wind conditions are comparable to those found in much of the UK (82). In 2005, 2006 and 2007, for example, annual load factors (i.e. average output of electricity expressed as a percentage of the maximum output potential over time) for Danish wind turbines were about 24, 22 and 26 percent, respectively (see 23; 40). This is of similar magnitude to factors reported for many onshore windfarms in England and Wales, though somewhat lower than in Western Scotland or at some offshore sites (61).

The pattern of wind power production varies with the weather, and may bear little relationship to demands for electricity (39; 78). For example in 2004, strong winds in West Denmark could generate up to 2.3 GW of power for a system in which total demand ranged between 1.3 and 3.8 GW. An increase in wind speed from 9 to 11.5 m/s at the Horns Rev off-shore station could double production from about 80 to 160 MW within a few minutes (33). Conversely, adverse conditions can greatly restrict production (19). Throughout February 2003, wind speeds and the generation of wind power in West Denmark were very low (18), while in January 2005 a hurricane forced turbines to shut down within hours of running at near maximum output (08). Adding to this uncertainty is the difficulty that some land-based machines are outside the direct control of the TSO (04).

Both on land and offshore, electricity production is improved by reducing the turbulence of air passing from adjacent machines. This is attempted by separating wind turbines by a distance of 7 to 10 times their rotor diameter (i.e. 550 - 750 metres at Horns Rev and Nysted offshore windfarms). Nevertheless at Nysted wind power production has been observed to fall by as much as 40 percent from the first to the last turbine in a row, and a reduction in wind speed of 1 m/s has been observed 2 km down-wind of this wind park (10).

A free-standing 144-metre-high 3.6 MW wind turbine can generate more than double the output of a 100-metre-high 2MW machine, and at 88 percent of the cost per unit. For this reason the Danish wind turbine industry has proposed that by 2025 at least 50 percent of the country's electricity demand should be met by 1,400 turbines, each of up to 150 metres total height. Since onshore machines can deliver electricity 20 percent cheaper than offshore turbines, the installed capacity would be spread equally between these locations (15). Other authorities predict that onshore wind turbines will soon reach 150 metres in height, but that future offshore turbines may tower 250 metres, with blade tips over 350-400 metres above the sea (37).

Naturally, breakdowns caused by the wear and tear of turbine gearboxes and roller bearings occur regularly (49). Harsh environments have also caused very expensive longer-term breakdowns in transformers and components of offshore turbines at Horns Rev (05; 34; 66), Middelgrunden (57) and Nysted (58).

4. Balancing the grid

The highly variable nature of wind power generation means that it cannot be used as base-load. Indeed, as its contribution to total supply increases, the predictability and quality of overall electricity production deteriorates (78; 84). At higher levels of wind power output increasing amounts of electricity become surplus to needs at the moment of generation and it becomes ever-more difficult for the TSO to maintain balance in the supply system. According to conditions, the grid must be continually stabilised by regulation of the outputs from domestic coal and gas-burning power stations (44; 68) and smaller local plants (22), as well as the adjustment of imports from or exports to neighbouring countries (21).

During 2006 and 2007, about 6.11 and 7.17 TWh of wind power were generated in Denmark, respectively (40). These amounts equate to about 17 and 20 percent of the country's annual consumptions of electricity (ca. 35.9 TWh), though much of this power had to be exported at a low price to maintain balance in the grid. Significant relationships were detected between the amount of wind power generated in West Denmark and the region's net exports of electricity as early as 2004 (60; 74; 76), when up to 84 percent of the annual output of wind electricity in this region was judged to be surplus to local demand at its moment of generation.

A later study (2005) for the whole of Denmark implied that wind power equated to about 18.5 percent of total electricity production, though exports equivalent to 70.5 percent of this power were sold (84).

A more detailed (2007) investigation (78) showed that interpretations and assessments of wind power disposal can vary markedly, according to the assumptions made. Although the output of Danish wind turbines equated to respectively 18.7 and 17.0 percent of national demand in 2005 and 2006, this study suggested that only about 13.6 and 10.3 percent of electricity consumption was directly satisfied from this source. In the western region wind power generation equated to 21.6 – 23.9 percent of local demand, but there was a strong positive relationship between wind power production and net exports ($r = 0.769$). In contrast, East Denmark's wind power equated to only 10.2 – 11.0 percent of local demand, and most of this power was used locally (02; 78). It thus appears that once wind power reaches about 10 percent of the total demand for electricity, further increases in output from this source result in decreasing proportions being used within national borders at the moment of generation (78; 84). This is an important consideration in the context of recent political proposals to dramatically increase the amount of sustainable energy generated in Denmark (45).

It is now abundantly evident that at the present time Denmark's access to the much bigger systems of Norway, Sweden and Germany is crucial for the disposal of surpluses, the provision of backup, and the operational integrity of its grids. It is particularly convenient that Norway can conserve its hydro potential by assimilating Danish surpluses (minus transmission and 'storage' losses) during windy weather and providing hydro-electricity as backup when wind conditions in Denmark are poor (85; 86). This robust interaction between Norway's hydro turbines and West Denmark's wind turbines is central to the exploitation of Danish wind power (88). In fact, a planned 600 MWe DC cable between Denmark and Norway (Skagerrak 4) is partly designed to increase the potential for wind power 'storage' in the Norwegian hydro reservoirs (42).

A major consequence of Denmark's earlier large subsidy regimes was the promotion of big surpluses of both wind power and (until recently) electricity from local CHP plants (70). These had to be disposed of abroad at considerable expense to the nation (32; 51; 75). During 2003 such exports of electricity cost Danish consumers about DKK 1 billion (roughly £100 million) (74; 75), though more recent estimates put annual losses at or above DKK 1.5 billion (88). In 2007, there were 83 hours when wind electricity was sold from West Denmark for DKK zero (87)!

It is pertinent to recall that it is not always feasible to export surpluses from Jutland to northern Germany, because of occasional competition between the large amounts of wind power synchronously produced on either side of the border (68; 78). This situation may worsen as Germany increases its offshore production (09). Recognising such difficulties, the Danish energy giant DONG has proposed a sea-cable from the upcoming 'Horns Rev 2' to Holland to help dispose of surpluses (29).

5. Carbon emissions

Denmark's annual carbon emissions represent a tiny part of the amounts released globally into the atmosphere (47). Despite its 'green' reputation, however, this country remains amongst the world's biggest consumers of coal and producers of carbon dioxide per head of population (36), and has yet to demonstrate consistent reductions in domestic carbon emissions (16) or its dependence on fossil fuels.

The intermittent and variable nature of its industrial wind power system and the associated need for dependable sources of spinning reserve mean that the operational efficiency of its backup plant is reduced (i.e. greater amounts of carbon dioxide produced per kWh of conventionally generated electricity (85; 86)). This counteracts a significant proportion of the carbon saving claimed for wind power.

A leading Elsam expert has also intimated that with its present electricity supply system further increases in wind power generation will not reduce Denmark's emissions of carbon dioxide because more wind power leads to greater exports to neighbours (60). Such exports may reduce carbon emissions in some of these countries, but few emission savings will accrue (for example) to Norway at times when high levels of rainfall keep its reservoirs fully replenished (51; 85; 86).

Rarely discussed are the carbon costs of processes involved in the manufacture, installation, maintenance, and subsequent dismantling of massive concrete foundations, turbine components, access roads, cables, pylons, and associated equipment.

6. Reduction of surpluses

Since electricity cannot be 'stored' on an industrial scale within Denmark (20; 86), and any 'over-run' has to be disposed of abroad at considerable expense, novel ways are being actively sought to expand the utilization of surpluses within national borders:

i) Although hot water for district heating is produced most efficiently as a co-product of electricity production at CHP plants (84), as early as January 2002 it was suggested that to reduce the production of subsidised surpluses (sold often at dumping prices), TSOs should be allowed to shut down power production at such plants when the requirement for heat was minimal (03). Following a change in legislation, it is now obligatory for all local CHP plants of over 5MWe capacity to produce electricity under free market conditions (22); and even smaller plants are now moving voluntarily from the three-step tariff payment to the production of regulating power under market rules (26).

ii) It was also proposed that excess wind power should be used in place of coal, oil, or gas to heat the water at such plants (03). It has therefore been agreed to prioritise the opportunistic use of surplus wind power to heat water at both central and district heating facilities (74). Once taxation issues had been sorted (69), this approach is expected to promote a more even and predictable supply of electricity (at least during the colder months of winter), with smaller surpluses (71; 72; 73) and a decrease in carbon emissions.

iii) Another potential option is the use of excess wind power to recharge the batteries of electric cars (27; 87)). If this concept proves to be technically viable, it will help to reduce carbon emissions from the transport sector, reduce surpluses of wind power, and maintain better balance in the electricity supply system.

iv) The use of surplus wind power to produce hydrogen as an energy carrier for fuel cells and electricity production is also being considered (06). Attempts to make the Norwegian island of Utsira self sufficient in electricity through a wind power – hydrogen combination were unsuccessful, though this expensive project is thought to provide useful lessons for a proposed 'mini-hydrogen' community project at Veskenskov, Lolland (50). Difficulties with the storage and transport of hydrogen, and the procurement of enough cheap electricity to secure the economy of its production, still need to be resolved. To displace hydrocarbons by enough hydrogen for transport purposes would require roughly nine times as much electricity as was produced by wind power in West Denmark in 2003 (see 74).

7. Changes to the infrastructure

Government intentions to reduce the consumption of coal, oil and gas by 15 percent and increase the proportion of sustainable energy (largely wind power) to at least 30 percent by 2025 will require extensive reconstruction of the domestic electricity system, at an annual extra cost of about DKK 5 billion (45). As mentioned, part of this plan involves the establishment of connectors across the Great Belt and greater transmission capacity to respectively Norway and Germany.

Energinet.dk considers that in the long term, district CHP and wind turbines should no longer operate as separate and passive units in lower voltage distribution lines. Instead, it is testing the splitting of such networks into large numbers of independent, highly automated 'cells', each comprising fully integrated wind turbines and gas-fired CHP plants. These would operate as adjustable virtual power plants under the control of a regional centre or Energinet's national control room. Such 'wind-and-gas' cells must be able to automatically uncouple and run in isolation in the event of an impending fall in voltage (24; 25).

Research at the Centre for Electricity Technology (DTU) is also directed at a new infrastructure which will enable decentralized plants to actively help maintain balance and quality in the electricity supply system, with closer integration of demand and supply system operation (44). The regulating features of most of Denmark's small decentralised CHP plants are thought to be suited to such an approach because a typical gas motor can be started and reach full load within 10 minutes, in contrast to central power plants which require many hours to accomplish this. It has also been suggested that one day the cell structure may involve small household equipment, and it may become possible to run the entire electricity system without central power stations (25; 44). In the short-term, however, some politicians find much of this technology too expensive to support (87).

Flexible supply systems will not ready for deployment for several years. In 2007, the Administrative Director of DONG Energy (Denmark's biggest player in the wind turbine market) commented that : "[*In the foreseeable future, wind power cannot solve the energy problem because it is too unstable and perhaps too expensive*]" (77). In the same year, Vattenfall's Head of Information suggested that it is unrealistic to imagine that wind power can overtake other forms of energy within the next ten years (80). Recently, an energy policy spokesman for Venstre (one of Denmark's bigger governing parties) has even suggested that the burning of wood chippings and straw is a far cheaper option than wind power for the production of renewable energy. The government aim of 30 percent renewables by 2025 may therefore rest with the provision of more biomass (11).

8. Public disquiet

As a major player in the world market for wind turbines (59), Denmark uses its countryside and territorial waters as a 'shop window' (01; 35; 45). It is therefore of little surprise that many Danes feel that the proliferation of these large machines and supporting facilities has restricted public access to many parts of the countryside, detracted seriously from the former charm, beauty and peace of their landscapes and coastlines (46), and impacted badly on many home environments (37) and wildlife habitats (48).

Earlier protests came mainly from electricity consumer organisations and the neighbours of smaller turbines. Between 1998 and August 2000 over 600 complaints about these machines were received by the Environmental Complaints Board. In rural areas, most criticism related to shadow cast, glinting effects, noise, and aesthetic and local environmental considerations, a few cases also alleging infringements of local regulations (63). Groups of citizens even took direct action by obstructing the erection of turbines in sensitive areas. Such headlines as ["Turbine war"] (38), ["Farmers block wind turbines"] (64), and ["Site owners in road blockade"] (12) appeared in national newspapers.

In response, some local authorities have opposed the deployment of wind turbines on hill-tops, in areas dominated by burial mounds, at the edge of stream valleys, and in the immediate proximity of villages (83). Furthermore, Landsforening Naboer til Vindmøller [i.e. The National Association of Neighbours to Wind Turbines] was set up by opponents specifically to protect the interests of affected people. Amongst other activities, it gave warnings to solicitors and estate agents concerning the scrutiny of planning applications and the reduction of property values close to turbines (54). One beneficial result is that a political majority in Folketing is now willing to compensate householders for a fall in value of their properties (46). Owners of properties which lie within six times the height of a turbine can get a free assessment of whether a successful claim may be made for compensation. Beyond this distance a fee of DKK 4,000 is charged for this service if a claim is not upheld (30).

With better understanding of the technical and environmental limitations of wind technology, public opposition to onshore turbines has grown. Of special importance are safety concerns relating to the deployment of ever-bigger turbines. Many small turbines have collapsed in close proximity to human dwellings (13; 17; 67), and recently two big Danish wind turbines lost blades and scattered sharp pieces of glass fibre up to 500 metres from the tower base in high winds (53). Similar events have also been reported in Sweden, northern England and Scotland (52). This has attracted the attention of senior politicians, who are now demanding much stricter turbine maintenance standards (28).

Relatively little is published about the quantitative impact of wind turbines on birds and bats in Denmark's largely agricultural countryside. A provisional assessment suggested that, at least during daylight hours, offshore turbines may not be a serious danger to bird life, less than one bird being killed annually per turbine (07). In contrast, within eight month's of the opening of a windfarm on the island of Smøla in neighbouring Norway in 2005, nine Sea Eagles were killed by these machines. Six of the birds were fully-developed adults whose loss will have dramatic consequences for a species with low fecundity and a potentially long life span. Radio-emitters were attached to six young eagles, but three of these birds were soon killed by turbine blades (65). More eagles later suffered the same fate at this site. These observations mirror those made for bats and many species of birds in several other countries. Evidently, concentrations of inappropriately located wind turbines can have a devastating impact on wildlife.

Protests have thwarted the erection of industrial wind turbines many places in the Danish countryside, and this is possibly one reason why turbine deployment came to a virtual halt in 2005 (62; 79; 81). One scientist even expressed fears that public opposition may put Denmark's wind technology at risk, with the Industry moving abroad (01). In this situation the Environment Minister has felt it necessary to put pressure on local authorities to grant planning permission for the new generation of turbines: "[*We cannot continue to be the world leader for wind turbines if we do not make room for them in our own country. Municipalities* *have a huge responsibility for the successful local development of wind turbines. And with my compliments I will tell them that if they cannot sort it out, we can prepare a directive about it*]" (62). It thus appears that the promotion of wind technology is now as much to do with commercial and political interests as with the conservation of fossil fuels and reductions in carbon emissions.

9. Conclusions

a) Denmark has the world's highest concentration of wind turbines per head of population. Its 5,267 turbines produce the equivalent of about a fifth of its annual demand for electricity. However, almost half of this cannot be used directly or stored within national borders.

b) The rest of Denmark's annual production of wind electricity has to be exported (often very cheaply, or at dumping prices) to secure the operational integrity of its domestic power transmission systems. The surplus is transferred to Norway, Sweden and Germany via international connectors big enough to take most of the potential output of wind power. Without this option, Denmark would be unable to maintain the integrity of its grids or dispose of large surges of power.

c) To resolve its 'storage' and transmission problems and expand export markets, Denmark is in the initial stages of seeking novel ways to exploit surpluses within national boundaries at the moment of production. The opportunistic use of excess wind power for the resistance heating of water at district heating plants is being examined, as well as the production of hydrogen as a fuel carrier. Another option under investigation is the use of excess wind power to recharge the batteries of electric cars. The country is also having to restructure its modern domestic supply systems. One project is examining the integration of wind turbines with decentralized gas-fired plants in highly automated 'cells'. These gas-dependent systems would operate as independent, adjustable, virtual power plants controlled by regional and national control centres.

Expert opinion is that wind power cannot solve Denmark's energy problem in the foreseeable future. Only time will reveal the extent to which these new approaches conserve fossil fuels and reduce carbon emissions.

Many Danes fear that the deployment of ever-taller wind turbines, cables, pylons and sometimes access roads will detract from the aesthetic value of their cherished landscapes and seascapes, and have a detrimental impact on home environments and wildlife habitats.

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