How Denmark Manages Its Wind Power

By Richard Green*

Introduction

Denmark was an "early adopter" of wind power and generates an unusually high proportion of its electricity from wind – 21% in the country as a whole in 2010, and 24% in the region of West Denmark. Almost all of the rest of the country's electricity is generated in CHP plants, a mix of "primary" stations (58%) and "local" plants (21%). The key difference between these is partly one of scale, and partly that until 2005 electricity distributors had to buy the power produced by the local plants at a fixed price (IEA, 2008). They accordingly tended to run to meet their heat load, with electricity as a by-product. The central stations, on the other hand, faced the market prices set by Nord Pool and it was changes in their output, together with the flows on international interconnectors, which ensured total generation matched demand.

Denmark is well-connected to its neighbours, Germany, Norway and Sweden, with a total interconnector capacity of 5.5 GW (importing, or 4.5 GW for exports), compared to a peak demand in 2010 of 6.3 GW. The Nordic countries have a high proportion of hydro generation (95% in Norway and 46% in Sweden). Germany has installed a large absolute amount of wind capacity, but it provided just 6% of the country's overall generation in 2010.

Financial Support

Wind power offers two key challenges. The first is financing the stations when their costs are typically greater than the market price for the power that they produce. The economics of supporting renewable energy are discussed in an article in the IAEE's new journal, *Economics of Energy and Environmental Policy* (Green and Yatchew, 2012). For its onshore wind farms, Denmark has adopted a system of Feed-in-Tariffs. These offer fixed prices for up to 20 years. The relative simplicity of this instrument means that smaller companies and co-operatives are able to develop wind farms. A number of studies have concluded that countries with "well-adapted" Feed-in-Tariffs have supported wind generators at a lower cost per MWh than those using the main alternative policy used in the EU, a quantity obligation (which is typically called a renewable portfolio standard in the U.S.) enforced through some kind of tradable green certificate scheme (see, e.g., European Commission, 2008). The renewable generator is given certificates for its output, which it can sell to retailers (or other market participants) who are required to procure these in proportion to their electricity sales, or pay a penalty. The prospect of avoiding this penalty gives value to the certificates, and the generator thus has a second income stream alongside the market value of its power. These schemes are typically more complex to administer than Feed-in-Tariffs, deterring smaller companies, and the generator may be exposed to volatility in the price of both its electricity and the certificates, raising its risk and its cost of capital. A long-term contract with a retailer might mitigate this volatility, but countries with certificate schemes have typically found that they have developed less of their wind resource, at a higher cost, than those using Feed-in-Tariffs.

The greatest disadvantage of a Feed-in-Tariff is the risk of getting the price wrong. Too high a price could trigger a gold rush that produces more capacity than the government wanted, unless there is a well-designed mechanism that can reduce the price (for new schemes) as the capacity connected rises. It is easier to correct a price that was too low to trigger investment, but the initial mistake will create a delay. The risk of setting the tariff at the wrong level may be quite low for a mature technology, but rises with technical uncertainty.

Denmark has responded to this risk by using auctions to set the level of the tariff for offshore wind generators. Furthermore, to reduce the risk of the winner's curse (which implies that the auction is won by the most optimistic bidder, who later discovers that it was too optimistic and cannot deliver the project for the promised price), the auction is for projects that are nearly "shovel ready". In particular, environmental assessments and grid connection studies have been completed and the results are available to the bidders

Variability

The second major problem with wind generation is that it depends on wind speeds that vary and cannot be predicted far in advance. The relative unpredictability of wind output forces system operators to carry extra reserves of con-

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See footnote at end of text.

ventional plant, both when operating and in terms of total capacity. The costs of this are noticeable but manageable; Gross et al (2006) estimated them at 0.5 to 0.8 pence per kWh of intermittent renewable energy (in UK conditions with up to 20% of wind power). More recently, the Committee on Climate Change (2011) suggested that the cost would only be around 1 p/kWh, even with the share of (all kinds of) renewable generation approaching 80%.

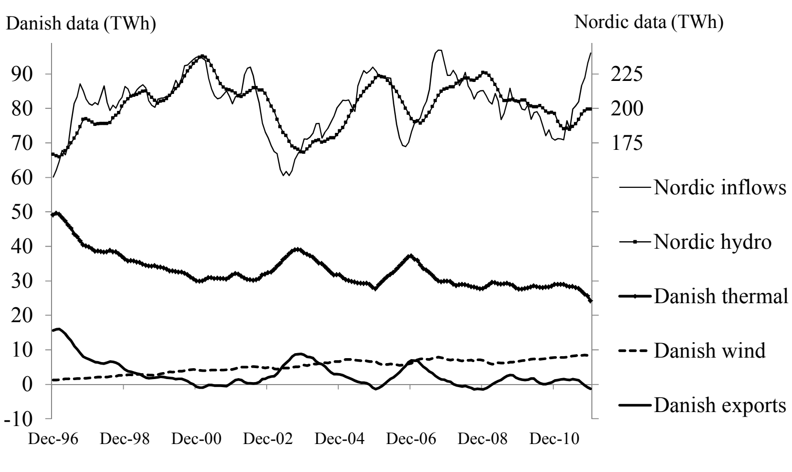
The main focus here, however, is on the volatility of wind output, which would have impacts even if it could be predicted perfectly, and is studied by Green and Vasilakos (2012) in a forthcoming article in *The Energy Journal*. In 2010, Denmark had an average (mean) wind output of 892 MW, with a standard deviation of 742 MW. Wind output was below 100 MW for just under 10% of the year, and greater than 2000 MW for almost 11%. Its maximum was 3342 MW at a time (midday on 11 December) when the total demand was 4682 MW. A few days later, at 6pm on 15 December, the total demand was 6312 MW and the wind output just 76 MW. That produced a maximum for the demand net of wind output of 6236 MW; the minimum (at 5 am on 25 August) was just 33 MW.

The Interaction Between Wind and Hydro Stations

Denmark is fortunate in its neighbours, however. Norway and Sweden have large amounts of hydro-electric generation which is ideally suited for balancing wind power. Hydro stations need little notice to start and stop generating, allowing them to respond quickly if the wind changes. The variable cost of hydro generation is an opportunity cost – if a station generates power now, it forgoes the chance of using that water at a later time. The value of the opportunity forgone is the expected price of power at that time. The station will try to operate in a way that keeps the price of power stable[1] over a hydrological cycle, as explained by Førsund (2007). This cycle is the period from one large seasonal inflow (a rainy season or a spring thaw) to the next. This means changing the hydro stations' output in line with changes in demand, so that the output from thermal stations changes relatively little from hour to hour or day to day. (If the thermal output did vary, and a hydro generator had some spare capacity at the times when the more expensive thermal stations were running, the hydro station could replace some of that output. Even though it would then have to generate less at some other time (to avoid running out of water), this could be at a time when there was spare capacity among the cheaper thermal stations. Shifting output from expensive to cheaper thermal stations reduces the overall costs.)

While power prices may not vary very much over short periods (except when operating constraints make it hard to reallocate enough hydro output between hours to stabilise them), they do vary from year to year, depending on the overall inflows of water. In a wet year, the hydro stations will be able to meet a high proportion of the countries' demand for power, and the remainder can be met while (generally) using only the cheaper thermal stations. This means that the price of power will be relatively low. In a dry year, much more power is needed from the more expensive thermal stations, and prices are higher.

Figure 1 extends Figure 1 of Green and Vasilakos (2012). Every line gives the average value of its series over the previous twelve months, to smooth out seasonal patterns. The top lines show that hydro generation in Norway and Sweden closely follows the amount of water flowing into the reservoirs, with a bit of a lag (an unusually large inflow in one month is followed by an increase in generation in each of several following months). The lower lines relate to Denmark, and show that the country's exports are greatest when hydro generation in its neighbours is low. The middle line, which gives Denmark's generation by thermal plants, clearly shows that these produce more in years of above-average net exports. The correlation between lines on a figure cannot, of itself, prove causation, of course, but the causation from water inflows to hydro generation should be obvious, and fluctuations in hydro output (not matched by changes in demand) then create a need for corresponding changes in trade patterns, and hence Danish generation. There is practically no relation-



Sources: Nordel, Entso-e, Energinet, Statistics Norway, Statistics Sweden, Nord Pool

Figure 1. Danish Power and Nordic Hydro

ship between Denmark's annual trade in power and its annual wind output. Our paper was written in response to claims that a large proportion of Danish wind power was exported (which the claimants seemed to believe meant that it was "wasted"). While such claims can have no basis in physics (it is impossible to tell which electrons are moving in response to which power station), they would make economic sense if Denmark's net exports had risen in line with its wind generation. This has clearly not happened.

There is a strong relationship between trade and wind patterns over short timescales, however. If wind generation is unusually high, Denmark faces the choice between reducing thermal output to low levels, increasing demand for power (perhaps by using electricity to heat the water for district heating schemes) or raising its net exports of electricity. If it does the latter, Norway and Sweden generate less, keeping more water available for later use. This water can then be released and the resulting electricity exported to Denmark at times when wind output is unusually low, and high-cost thermal plants would otherwise have to start generating.

Changing hydro output in this way means that the thermal stations in Denmark and nearby countries do not have to vary their output so much in response to changes in wind generation. This is just an extension of the way in which the optimal allocation of water between periods, discussed above, aims to minimise variation in thermal output in a "traditional" hydro-thermal system.

Green and Vasilakos (2012) show that Denmark uses variations in its net exports in exactly this way. There is a strong correlation (of 0.673) between excess wind generation (compared to the average for a given hour of the day in a given month) and excess net exports. This is not costless – the prices paid for Denmark's excess net exports at times of additional wind generation are lower than the prices the country has to pay for excess net imports at times when wind generation is below average. The resulting cost of storing wind in Norwegian reservoirs is equal to 4% of the value of the wind output. Denmark would be better off if its wind output did not fluctuate around its average levels. But given that the wind does vary from day to day, using trade to help accommodate the variations is a cost-effective response.

Footnotes

[1] When we remember that income earned now is more valuable than the same amount of money earned in a few months' time, it should become apparent that prices expected to rise at the rate of interest would in fact be needed to offset this incentive to generate now.

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