ENERGINET

OPERATING AN ELECTRICITY SYSTEM

Dominated by wind power

A RED-LETTER DAY FOR DENMARK

Wednesday, 2 September 2015 was a red-letter day for Denmark. It was the first day the entire Danish electricity supply was provided exclusively by wind turbines, practically speaking.

The Danish electricity system was supplied with energy from wind power that day, with only a very minor contribution from local CHPs and solar cells. The major power stations in Jutland were completely idle, and the ones on Zealand were almost idle, supplying just 15 MW.

The day shows that Denmark has already come a long way in its transition to renewable energy, but is still far from independent of the old electricity generation methods.

Power stations and other flexible technologies still needed

The relatively new wind technology is not enough on its own. There is still a need for flexible local and central thermal power stations and good interchange connections to neighbouring countries, so that foreign power stations and hydroelectric power can be utilised and excess Danish wind power generation can be exported. There is also a need for flexibility among domestic electricity consumers, including the flexible use of electricity for heat production and heat storage by the heating sector.

Energinet.dk's analyses show that the electricity system is generally robust enough to run without power stations in situations with favourable wind conditions. The challenges arise on days with too much or no wind. On such days, the electricity system is dependent on the flexibility offered by thermal power generation from central and local plants, and using the cable links to Denmark's neighbours.

Many power stations stand idle on windy days (as the high supply of electricity from wind turbines leads to low electricity prices), and the electricity system then lacks the power stations' grid stabilising properties – something wind turbines currently only offered to a limited extent. In these situations, the power stations receive separate payment in order to remain in service.

On days with no wind, the problem is that power must be sourced from elsewhere in order to meet the electricity consumption. The alternatives the market can offer are use of the Danish thermal power stations, or imports from neighbouring countries.

Another area in which thermal power stations continue to be needed is the provision of properties required to maintain power system stability. These are properties that must be present in the electricity system to prevent short circuits and other faults in the transmission grid causing breakdowns and consumer disconnections. These properties are also supplied primarily by thermal power stations.

A third area where thermal power stations are needed is in situations where the power grid has to be restarted from a 'dead grid' state (powerless grid). Such a situation cannot be handled using wind turbines, as these need a functioning grid to connect to. There therefore continues to be a need for emergency start-up agreements with thermal power stations and neighbouring countries, to ensure the grid can be restarted in the event of a failure.

How has so much wind power been successfully built into the energy system?

What factors over the last 30 or more years have made it possible for

Wind turbines are a distinctive feature of the Danish landscape in many areas today.

Denmark to have reached the point where the electricity system can essentially run on wind power during certain periods?

One key reason for the size and quality of the current Danish wind power generation capacity has been the historical political support and the resulting predictable economic framework. This stability has reduced the risks associated with investment during conversion of the energy system and encouraged the development of new market models, technical regulations and operating strategies.

A second essential factor has been the long term work – in cooperation with other electricity sector players – to develop new market models and new technical and market regulations.

A third essential factor for the practical integration of the fluctuating electricity production from wind turbines into a traditional energy system has been the development of new procedures, tools and competencies to manage the operating situation.

"Electricity generation was previously based primarily on large thermal power stations around the clock, but in future energy will come increasingly from fluctuating energy sources such as wind and solar power or via international connections"

Fourthly, Denmark has established a very flexible energy infrastructure, where flexible power stations, adjacent energy systems and strong power transmission connections with neighbouring countries facilitate integration of the fluctuating wind power generation. Denmark's location between Norway's hydroelectric power and central Europe's thermal power has also provided great opportunities for the exchange of electricity across national borders.

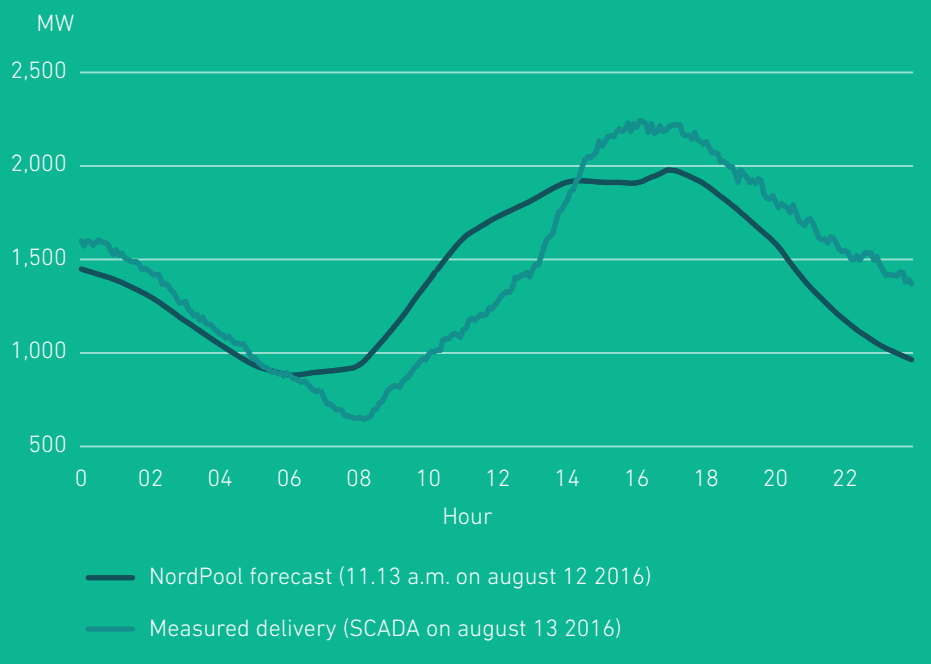
As examined below, the expansion of wind power in Denmark has thus been based on a combination of a long-term stable framework, refinement of market models, new operations management competencies and very flexible infrastructure.

WIND FORECASTS

The wind can change, and it can be difficult to predict how windy it will be. It is therefore important to constantly monitor the wind forecasts and update the calculations, so the control centre can take changes in the forecasts into account and ensure the electricity system remains in balance.

If the wind speed changes by only 1 m/s in relation to the forecast – say from 7 to 8 m/s – this can mean a difference in electricity generation of around 500 MW for the offshore wind turbines along the Danish west coast alone. This corresponds to two large power station units. If the deviation can be predicted 15 minutes or more in advance, the change can be handled using regulating power. If there is less than 15 minutes' notice, the imbalance is normally countered using the automatic reserve.

WIND FORECAST AND MEASURED DELIVERY



Stable framework conditions
The Danish electricity generation system has changed from a system based on a few central thermal power stations in the 1980s, to one based on central power stations, several hundred local CHPs and thousands of solar and wind power systems.

The electricity market has also been deregulated during the same period. As a result, electricity producers and consumers now ensure – via the balance responsible parties – that the most efficient producers at any given time get to supply consumers.

In addition to the wind turbine expansion, the stable framework conditions in Denmark have made a corresponding investment in the development of new market and operating strategies for the electricity system as a whole both possible and necessary.

The market
In the old world – before wind turbines began to populate the Danish landscape – operation of the electricity system was a more simple affair, as electricity generation at the unrivalled thermal power stations could be precisely controlled and demand from consumers was largely predictable.

The challenges facing operations today are twofold. There is still some unpredictability on the demand side, but also a high level of wind power generation which cannot be controlled on the supply side.

However, it has been found that the most cost-effective tool to find the best possible balance between variable demand and a significant amount of uncontrollable electricity generation in the lead up to the delivery hour is the market mechanism.

The electricity price is set hour by hour on the power exchange, as the result of a calculation based on demand and supply. As more renewable energy has to be integrated into electricity supply – in Denmark and the rest of Europe – we are changing the assumptions the electricity market was originally based on. Electricity generation was previously based primarily on large thermal power stations around the clock, but in future energy will come increasingly from fluctuating energy sources such as wind and solar power or via international connections.

One milestone in this regard is the Market Model 2.0 project, under which Energinet.dk, in close partnership with energy sector players, has presented a number of initiatives to secure the future of the electricity market – for example, in relation to the flexibility required in response to the fluctuating electricity generation of the future, and ensuring continued balance between consumption and generation. The process surrounding recommendations for a new market model was concluded in 2015 with a number of specific recommendations. These include setting frameworks and new regulations to make the electricity market more accessible to flexible consumption and production in the longer term. In the short term, Energinet.dk will analyse and identify the system critical properties that will be needed in the future electricity system. Based on the scope of the needs, further work must be done on how they can be satisfied in an expedient manner and whether a solution complies with the common European network codes.

Technical and market regulations
In Denmark it is Energinet.dk – in cooperation with the local grid companies and market players – that defines the technical requirements for system and

FIGURE 1: INTERNATIONAL CONNECTIONS IN THE ELECTRICITY SYSTEM (MW)

New operating competencies
Energinet.dk's control centre takes over responsibility for balancing during the last hour before the delivery hour. At this time, the control centre must assess the imbalance between consumption and production for the coming hour, and a number of operating plans and forecasts are used for this purpose. The control centre receives operations plans from the balance-responsible parties for production. They are required to regularly submit production plans for their plants, so the control centre can always work with the latest information.

"To ensure there is balance in the electricity system, Energinet.dk's control centre combines the electricity generation from the operations plans with the wind and solar power generation forecasts and compares the total against the forecast for electricity consumption and electricity exchange with neighbouring countries"

operating parameters, to ensure reliable operation of the electricity system under market conditions, with the volume of wind power the politically agreed objectives specify. The technical requirements are defined in technical regulations, which stipulate the technical requirements for functions and properties wind turbines must fulfil in order to be connected to the electricity system. They also describe how wind turbines should function in order to contribute to the stable and reliable operation of the system.

The market regulations specify the requirements necessary to ensure the electricity market functions properly and that payment for electricity generation is correctly settled.

These technical regulations, in particular, will be largely replaced by pan-European network codes in the coming years.

Ten years ago, information from the central thermal power stations' operations plans was used almost exclusively. This was viewed against estimated electricity consumption, using comparisons with consumption in Denmark the same time the previous week or even the previous month. If the operations plans showed that too much or too little electricity was being produced in relation to the consumption estimate, electricity generation from the power stations would be adjusted to maintain balance.

With the volume of fluctuating wind and solar energy we have in the

TABLE 1: ELECTRICITY TRANSMISSION CAPACITY (MW)

EXISTING	EXPORTS	IMPORTS
East Denmark-Sweden	1,700	1,300
East Denmark-Germany (Kontek)	585	600
West Denmark-Norway (Skagerrak)	1,632	1,632
West Denmark-Sweden (Konti-Skan)	740	680
West Denmark-Germany (East) I	1,640	1,500
Great Belt	590	600
Bornholm-Sweden	60	60
UNDER CONSTRUCTION	**EXPORTS**	**IMPORTS**
West Denmark-Netherlands (COBRA)	700	700
East Denmark-Germany (Kriegers Flak)	400	400
BEING INVESTIGATED	**EXPORTS**	**IMPORTS**
West Denmark-UK (Viking)	1,400	1,400
West Denmark-Germany (East) II	860	1,000
West Denmark-Germany (West)	1,000	1,000

system today, operation of the grid has become more dependent on forecasts. It is now necessary to always have up-to-date predictions for wind and solar power generation and electricity consumption. Energinet.dk prepares electricity consumption forecasts to this end. These are based on historical consumption in Denmark for every hour over the last 10 years. For example, a consumption forecast for the following day, which say happens to be Wednesday, considers electricity consumption for the most recent Wednesdays, and possibly also for the most recent Tuesdays and Thursdays, as these days often have similar consumption patterns. But it can be necessary to look further back in time, possibly up to a whole year, in order to see a regular pattern for electricity consumption on Wednesdays. In contrast to 10 years ago, correction is now also made for temperature differences in the Danish weather, as electricity consumption is dependent on how hot or cold it is outside. The result – an electricity consumption forecast – represents the likely consumption for the next day, hour by hour.

Forecasts for the coming wind power generation are based on two categories of information – input from a model calculation (Numerical Weather Prediction – NWP), and online wind measurements as the delivery hour approaches. Denmark is divided into 25 areas for the purpose of the model calculation. The NWP calculates a forecast for wind power generation in each area based on input parameters such as wind speeds, wind turbine generation data, installed capacity and expected electricity prices. The forecast is calibrated using historical wind data, and adjusted to reflect the fact that lower electricity prices will reduce the wind power generation being offered for sale.

As the delivery hour draws near, the forecast can be significantly improved using on-line wind speed measurements from the anemometers installed at around one third of the Danish wind turbines. Using online wind speed measurements, the forecast can be updated at five-minute intervals in each of the 25 areas. The aim of the online measurements is to estimate the 'future error' of the model calculation, in order to calculate a more accurate forecast – the 'online forecast'. (Energinet.dk prepares a similar solar power forecast in order to provide a total picture of the fluctuating electricity generation for the coming hours).

To ensure there is balance in the electricity system, Energinet.dk's control centre combines the electricity generation from the operations plans with the wind and solar power generation forecasts and compares the total against the forecast for electricity consumption and electricity exchange

with neighbouring countries. The operations plans and forecasts are updated regularly leading up to each hour of delivery in order to minimise imbalances before they arise during the moment of delivery. This reduces the uncertainty linked to unpredictable weather and the wind and solar power that will be available.

If there continues to be a significant difference between production and consumption during the hour of delivery, this can be offset using manual and relatively cheap but less responsive regulating power, which is an adjustment to electricity generation at short notice. This is managed via a common Nordic regulating power list. All Nordic balance responsible parties can report how much they can increase or reduce their electricity generation or consumption to this list, and the price for doing so. This also applies to wind turbine owners, who can be requested/ordered to halt production if there is too much power available, assuming they have submitted a bid to the regulating power list.

If there is a residual imbalance during the hour of delivery, this is handled at the moment of delivery using 'automatic reserves', which are very responsive but more expensive. Automatic reserves are based on set agreements to reserve energy for this kind of situation.

Infrastructure

As more and more wind turbines are installed in Denmark, the need for flexibility in the electricity system increases, as the major fluctuations in electricity generation from wind turbines necessitates a corresponding ability to quickly adjust electricity consumption and other electricity generation. This trend is already underway and will be intensified in the years ahead, due to the continued expansion of wind and solar power.

The Danish system already has a high degree of built-in flexibility, as the market mechanisms help match electricity generation to demand. The heating sector and the major power stations have also improved their technological options for working in concert with an electricity system that is becoming increasingly dominated by wind turbines. Due to extensive heat accumulation tank capacity, Danish CHP plants can adjust their mix of combined heat and electricity production from gas engines and turbines at times when electricity generation from wind turbines is low, and meet their heating needs during these periods by drawing on the heat accumulation tanks. The major power stations have also improved their technology and can now increase and decrease production quite quickly for such large plants. During periods of high wind power generation they can also drop to a low production level, from which they can quickly be restarted.

"Energinet.dk implements continuous analysis of the total Danish electricity- and gassystems, including the Danish system interconnection with the rest of Europe, to be abreast with recent developments in energy"

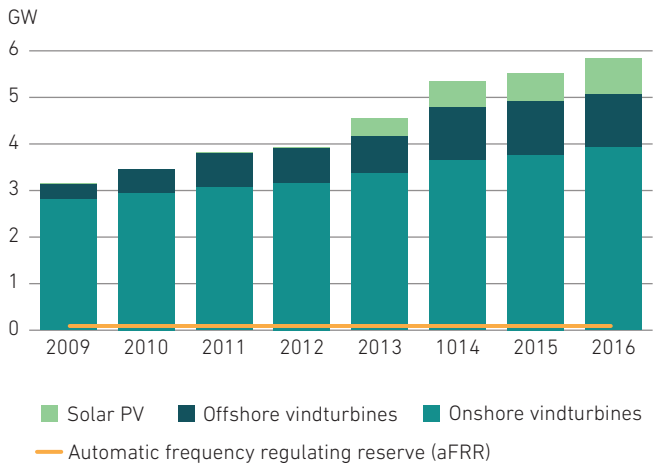
The Danish heating plants also have significant potential to further increase flexibility in the Danish electricity system in future, as it will be technically feasible to provide a major portion of heat production using electricity to power large heat pumps. The Danish heating sector can thereby further contribute to rapid and flexible adaptation to wind turbine production. Flexibility resulting from effective market mechanisms and improvements to the technical capabilities of thermal power stations are key reasons for the successful integration of Danish wind turbines into the energy system to date.

The international connections are another element of the electricity infrastructure which play a key role in the integration of wind turbines into the Danish system. Cables to

Norway, Sweden and Germany, and soon to the Netherlands and possibly the UK as well, combined with the ongoing internationalisation of market functions, make it possible to smooth out electricity generation excesses and shortfalls between countries. These interconnectors allow Denmark to export electricity during times of high wind and import from other countries in times of low wind. Good opportunities for exchanging electricity with neighbouring countries ensure a larger offtake market for electricity generators, and a larger supply market for consumers.

Given the expansion in wind power and in solar power longer term can be expected to grow strongly in the future, there will be a need for further flexibility. This can mean that the as yet largely unrealised potential for flexibility among electricity consumers (both households and enterprises) and in the transport sector will need to be brought into play in the longer term to further improve flexibility and integration across energy systems. This will also require ongoing development of infrastructure and market mechanisms.

FIGURE 2: CAPACITY EXPANSION USING FLUCTUATING RENEWABLE ENERGY SOURCES OVER THE LAST SEVEN YEARS HAS OCCURRED WITHOUT USING OR PURCHASING LARGER QUANTITIES OF AUTOMATIC BALANCE CAPACITY.



What impacts has wind power had on operation of the Danish electricity system?

Through the development of market mechanisms and operating methods and infrastructure expansion, Denmark has succeeded over the last 20 or more years in efficiently integrating wind power generation from a large number of wind turbines (see Figure 2).

This is attributable to both the continued development of effective market mechanisms and new operating procedures and tools.

This does not mean that the ongoing integration of wind power in Denmark and its neighbouring countries can continue to be handled in the same way and using the same means in the future. Given the expectations of the long-term expansion of wind power in Denmark and Northern Europe, it will continue to be necessary in the coming years to invest time and resources in further development of the market, operating strategies, infrastructure and regional cooperation.

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