Paul-Frederik Bach
http://pfbach.dk/

Towards 50% Wind Electricity in Denmark
Dilemmas and Challenges

Abstract

Electricity and heat supply systems are essential contributors to a fossil free future in Denmark. The combined production of heat and power (CHP) and the production of wind energy are already well developed in Denmark. Combined heat and power covers about 40% of the demand for space heating in Denmark, and the production of wind energy is supposed to exceed 50% of the demand for electricity by 2020.

The changing electricity and heat production has some consequences already now:

- Decreasing wholesale prices in Denmark and in other countries.
- Thermal power plants are closing down. Denmark is no longer self-sufficient with electricity under all conditions.
- The electricity production pattern does not match the demand pattern. The result is that the neighbouring countries must absorb the variations from wind and solar power.

Essential challenges:

- The future of combined heat and power in Denmark is uncertain.
- Denmark will need new backup capacity for filling the gaps in wind power and solar cell output.
- Flexible electricity consumers are supposed to contribute to balancing the future power systems. There is still a long way to go before the Smart Grid visions are implemented in large scale.
- The transformation of the power system will create new risks of power failures.

1. Moving Targets

After the Second World War a centralization of electricity production in Denmark was planned, but with the constraint that the locations of the new power plants should allow heat supply for large urban areas. The purpose of this policy was to reduce the total fuel consumption by combining the production of heat and electricity.

After the oil crises in 1973 and 1979, the main target was to reduce oil consumption. It was decided to utilize natural gas from the Danish part of the North Sea. During the years 1977 to 1987, most large power plants were converted from oil to multi-fuels, mainly oil and coal, in some cases also gas.

In 1979, the first Danish law on heat supply was adopted and a heat planning process began. Small urban areas were designated for either direct gas supply or district heating from small gas fired CHP[1] plants.

In 1987, the Brundtland report[2] highlighted the importance of reducing emission of greenhouse gases.

Most local CHP systems in Denmark were built during the nineties. The CHP penetration reached nearly 50% of all space heating about 2000, but has since then declined due to competition from wind energy. The increased use of the CHP principle and the replacement of other fuels by natural gas have contributed to a reduced emission of greenhouse gases.

The combination of electricity production and heat supply had a considerable impact on the location, design and operation of power stations. In 2014, there were 648 local and 298 industrial CHP plants in Denmark. Most of the thermal electricity production in Denmark was combined with heat production.

Wind power gained increasing political support after 1995. In the Danish "Energy Strategy 2050" from 2011[3], offshore and onshore wind power plays a decisive role in the development towards a fossil free society by 2050.

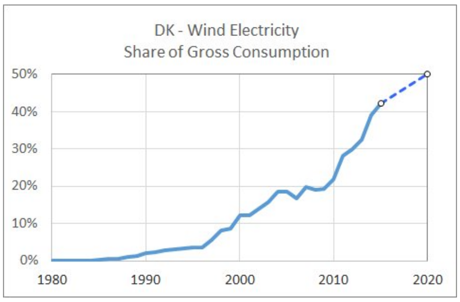

Fig. 1 – Denmark, wind energy share of electricity consumption and target 2020

Wind energy has gradually replaced electricity from the CHP systems. In 2015, the Danish wind energy output reached 42% of the electricity demand. The 42% include exported overflow of wind energy. The target for 2020 is 50% (fig. 1).

The Danish energy policy has changed focus since World War 2. The effects of the energy initiatives are not always additive. The targets have usually been defined in terms of penetration of certain production technologies and not as desired effects on service to consumers, cost, emissions and security of supply. The result is over-capacity in CHP systems and stranded assets[4].

[1] CHP: Combined Heat and Power
[2] The United Nations World Commission on Environment and Development (WCED): Our Common Future, 1987
[3] Energy Strategy 2050 – from coal, oil and gas to green energy, the Danish government, February 2011
[4] Stranded asset: An asset that is worth less on the market than it is on a balance sheet because it has become obsolete in advance of complete depreciation. (www.investorwords.com)

2. Electricity Markets and Smart Grids

There are electricity markets in most European countries (fig. 2). Denmark has joined the Nordic power market, Nordpool Spot. Nordpool was the first international electricity market.

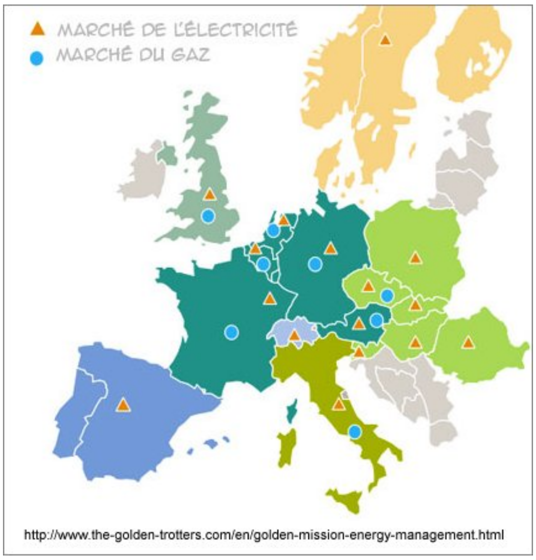

Fig. 2 - European energy markets

The wholesale markets have replaced the traditional central load dispatch. The market distributes price signals to the market participants. Proper price signals will encourages an optimal allocation of resources.

There are trading arrangements for all time horizons. Financial markets serve trading months and years ahead. For trading closer to the operating hour, there are day-ahead markets and hour-ahead markets. The system operators can activate resources in regulating power markets.

The markets have different rules. Exchanges between markets are less efficient than exchanges within markets. Market couplings between different markets have been developed, but they are not yet as efficient as trading within a market.

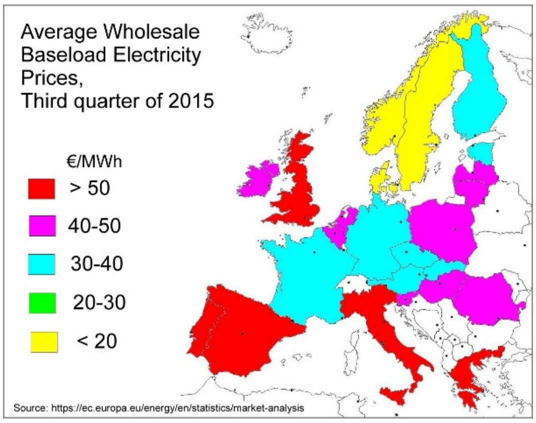

Fig. 3 - An example of European wholesale prices

Prices are the main control signals in a market. Fig. 3 and table 1 show that Northern and Central Europe are low price areas while the UK, Spain, Italy and Greece are high price areas.

A perfect market without grid bottlenecks has the same price everywhere. However, there are bottlenecks in all transmission systems. Therefore, there are different prices in Europe.

A grid without bottlenecks would be oversized. Transmission projects are expensive and they can have considerable impact on the environment. The investments must be justified by the value of improved security of supply or by profits on the energy transport. The energy transport on a given transmission line depends on sto-

	€/MWh		€/MWh		€/MWh
FI	30.1	IE	48.3	EE	30.3
SE	15.5	UK	58.1	LV	45
DK	19.9	NL	40.2	LT	45
DE	32.8	BE	45.9	PL	41.2
CZ	34.2	FR	36.3	SK	36.1
AT	33.1	ES	56.4	HU	46.7
IT	56.6	PT	55.7	RO	41.3
NO	11.9	SI	47.3	GR	53.8

Table 1 - Average Wholesale Baseload Electricity Prices, third quarter of 2015[5]

[5] Quarterly Report on European Electricity Markets, European Commission, DG Energy, third quarter of 2015.

chastic variables such as hydrology, wind and forced outages of power stations. In some combinations, the production must be re-dispatched in order to avoid overloads, but the cost of redispatch cannot always justify investments in grid reinforcements.

In properly operated markets, electricity will flow from low price areas to high price areas. In Europe, the typical flow direction is from north to south. Loop flows between three or more price zones occur. This is an indication that the grids and the markets are not yet properly developed and organized.

Wind power and solar power (PV[6]) are non-dispatchable. Wind power production can be very low at the same time for large parts of Europe. For about half the year there is no PV output. Therefore, a dispatchable backup capacity for most of the electricity demand must be available for filling the gaps in wind and solar power. Power plants for this purpose will have a low utilization and a large number of stops. Therefore, the cost of filling the gaps will be high.

As an alternative or a supplement, it has been suggested to control both production (where possible) and demand of electricity. The idea is known as *Demand Side Management* (DSM). The theory is that it is possible to move electricity consumption from periods with low production and high prices to periods with electricity surplus and low prices. Price signals are supposed to give consumers incentives to change the pattern of electricity consumption.

DSM is an old idea, which has evolved into the *Smart Grid* concept. There are many Smart Grid definitions. This one from the International Electrotechnical Commission[7] gives a fair impression of the ideas:

> *"Smart Grid" is today used as a marketing term, rather than a technical definition. For this reason, there is no well defined and commonly accepted scope of what "smart" is and what it is not.*
>
> *The general understanding is that the Smart Grid is the concept of modernizing the electric grid. The Smart Grid comprises everything related to the electric system in between any point of generation and any point of consumption. Through the addition of Smart Grid technologies, the grid becomes more flexible, interactive and is able to provide real time feedback.*
>
> *It is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.*
>
> *A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies to*
> - *facilitate the connection and operation of generators of all sizes and technologies;*
> - *allow consumers to play a part in optimizing the operation of the system;*
> - *provide consumers with greater information and choice of supply;*
> - *significantly reduce the environmental impact of the whole electricity supply system;*
> - *deliver enhanced levels of reliability and security of supply.*

A Smart Grid will require the development of separate retail markets with access to relevant price information for all consumers. Communication and market design are research areas of special importance.

[6] PV: photovoltaics
[7] http://www.iec.ch/smartgrid/background/explained.htm

Several Smart Grid experiments have been made, but so far only in limited scales. One of the most ambitious is Ecogrid.eu[8]. It includes the Danish island, Bornholm, in the Baltic Sea (see map fig. 4). The population of Bornholm is about 40,000 people.

The Smart Grid will be developed gradually over the next decades as a natural modernization of the power grids.

3. Denmark is a Transit Country

Denmark has since 1965 been an electricity link between Scandinavia and the continent.

During wet periods, surplus hydro energy has been sent southwards, and during dry periods, energy from thermal power plants has been sent northwards.

Wind power in Germany and Denmark gained during recent years an increasing influence on the flow.

Denmark has two price zones within the Nordpool spot market, west and east.

West Denmark is connected to the continental AC[9] grid and has HVDC[10] interconnections to Sweden, Norway and to East Denmark. East Denmark is connected to the Nordic AC grid and has HVDC interconnections to Germany and to West Denmark (fig. 4).

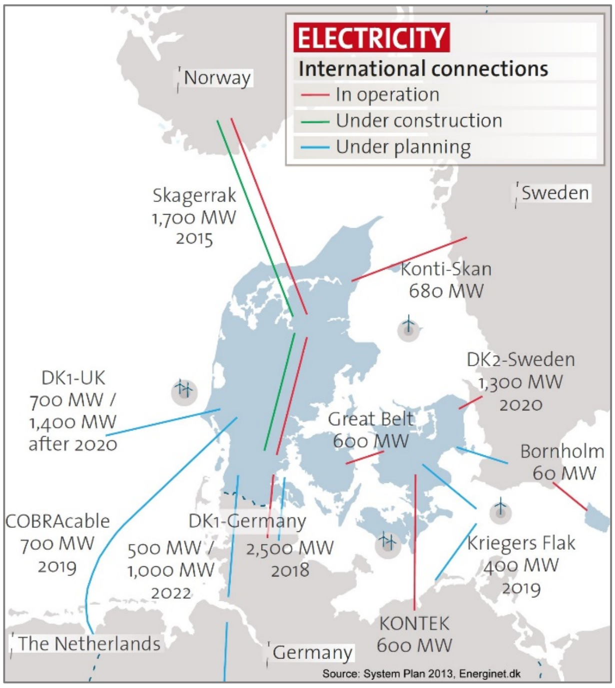

Fig. 4 - Present and future interconnections

The two Danish price zones are small markets between large neighbours. Therefore, the Danish price zones in most cases adopt the spot prices of one of the neighbours.

The Danish spot prices depend on the location of grid bottlenecks. From 2015, the Nordic spot prices have been prevailing for several reasons:

- The 700 MW Skagerrak 4 link was commissioned in 2015.
- Denmark and Germany have different market arrangements. The competition across the border is less efficient than within the Nordic area.
- In the first half of 2015, Germany added 1.8 GW new offshore wind power to the existing 0.9 GW in the North Sea. The 2.7 GW offshore capacity in the German part of the North Sea have caused additional congestion in the internal German grids.

This means that a bottleneck has moved from north to south in Denmark. Fig. 5 demonstrates the change of Danish spot prices from the German level in 2014 towards a Norwegian level in 2015.

[8] http://www.eu-ecogrid.net/
[9] AC: alternating current
[10] HVDC: high voltage direct current

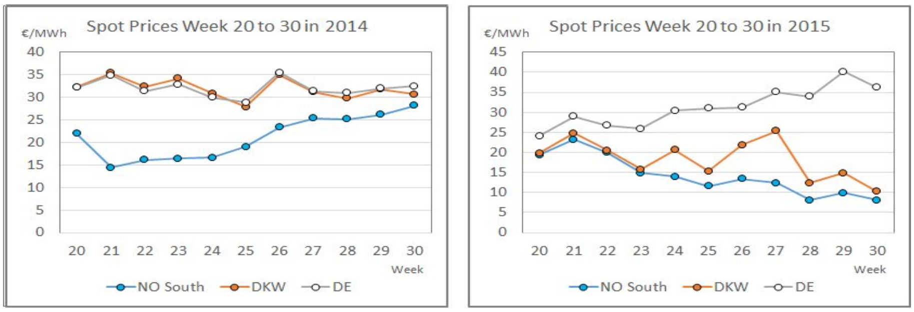

Fig. 5 - West Denmark had German spot prices in the summer of 2014, but approached the Norwegian price level in 2015.

Based on these observations and the prices in table 1, it is a logical Danish conclusion to by-pass the German bottlenecks by the installation of the Cobra cable to the Netherlands.

Large-scale reinforcements of the German grid are underway. They will contribute to a better utilization of the fluctuating energy resources in Europe and more equal wholesale prices. However, the role of market arrangements and market couplings should not be underestimated. Considerable improvements are needed.

4. Decreasing Market Prices and Increasing Subsidies

The electricity wholesale prices have been falling for some years, both for the Nordpool market and for the German EEX-market (fig. 6).

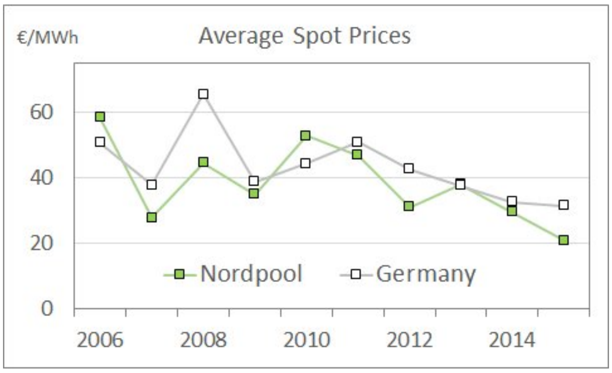

Fig. 6 - Average spot prices 2006-2015

This development has consequences for the production plants, which have their main revenue from the spot market.

In Denmark, thermal power plants are closing down faster than anticipated in recent system plans, published by the transmission system operator, Energinet.dk[11].

Different categories of electricity demand and supply have different time profiles and therefore different market values.

The market value of wind power is for instance lower than the value of the demand and import is more expensive than export. Dispatchable production has a higher value than weather dependent production (fig. 7).

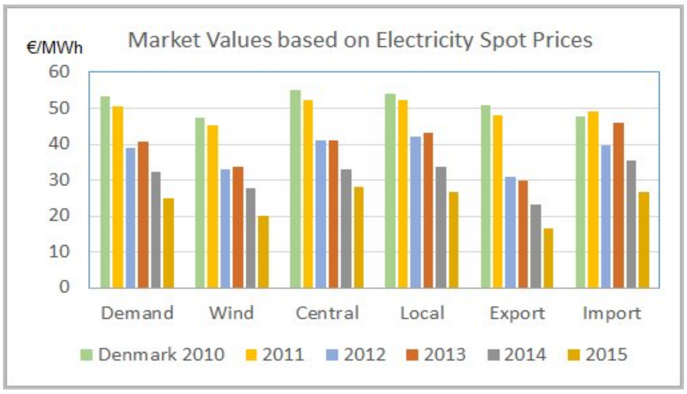

Fig. 7 - Calculated market values for demand and supply in Denmark

[11] Energinet.dk owns the Danish electricity and gas transmission system

For 2015, a high inflow of water in Norway and Sweden has contributed to the low wholesale prices, but the general trend must have other reasons. The increasing inflow of wind energy in Germany and in other countries seems to be the most obvious reason.

In Denmark, decreasing market prices are compensated by increasing subsidies.

The total cost of Danish wind energy has been estimated as the sum of the market value of the wind energy and the subsidies for wind power (PSO[12]). In three years, the support has increased from 47% to 66% of the total cost (fig. 8).

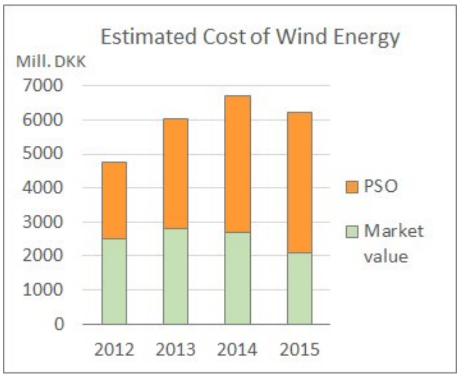

Fig. 8 - Cost estimation based on spot prices and PSO projections by Danish Energy Agency (ens.dk)

This is an unstable control loop. Wind energy has a strong position in the spot market due to its low variable cost. More wind energy means falling wholesale prices and increasing public support. However, EU considers the PSO system as anti-competitive. New support arrangements must be invented.

The intention is to replace fossil-fuelled power plants by renewable energy sources. The falling wholesale prices will support this intention by forcing thermal power plants out of the market. *The problems will be to maintain the necessary dispatchable backup capacity and to find new heat sources for the district heating systems.*

5. Increasing Import of Electricity

The new market conditions have changed the composition of the electricity production (fig. 9).

The marginal cost of non-CHP electricity is high. Therefore, non-CHP is sensitive to spot price variations. At the present market prices, non-CHP production makes losses. Due to the high efficiency of the combined production of heat and power, electricity from CHP-units is still competitive.

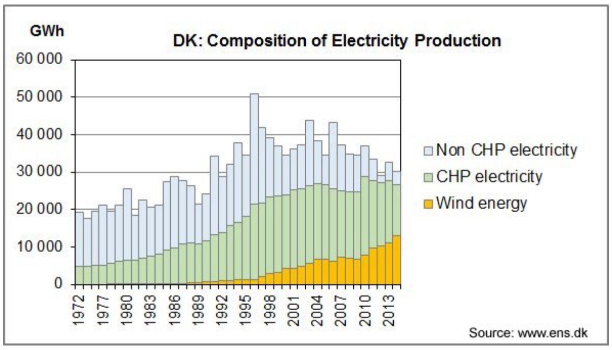

Fig. 9 - Wind energy displaces thermal electricity

The stability of a power system is a sensitive balance, where injection of power must continuously match demand for power. A sudden imbalance, for instance after the loss of a major production source, will cause a system collapse, unless the balance can be restored within seconds. The rotating masses of the large units are decisive for a safe transition, while reserves are mobilized. Therefore, in some cases it has been necessary to keep large units on the grid for security reasons, even when the electricity production was not needed. Cheaper solutions for stabilizing the grid are available. Different static and rotating devices can replace power plants when there is no demand for the electricity. After the installation of synchronous compensators, it has been possible to reduce the need for large power plants connected to the Danish grids.

[12] PSO: public service obligation

Denmark had a decreasing electricity production and an increasing import the last few years. It is uncertain if this will be a long-term trend. The annual exchange of electricity had large variations in the past (fig. 10). The variations depended on the hydrological conditions in Norway and Sweden and on the flexibility of the Danish production system.

The current trend is that Denmark will be increasingly dependent on the flexibility of the neighbouring power systems.

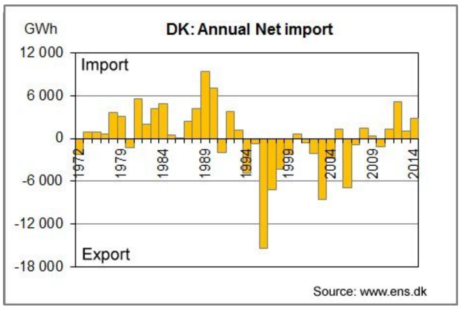

Fig. 10 - Annual exchange variations

6. Combined Heat and Power on the Decline

The decreasing spot prices are a challenge for the local CHP systems. Falling income from the electricity market means increasing heat price. A typical local CHP system has a gas-fired engine and a gas-fired backup boiler. The market price of electricity must exceed a level about € 50 per MWh before it is profitable to start the engine. For the spot market in 2015, this was the case in only 219 and 264 hours (or less than 3% of the year) for the two Danish price zones.

Therefore, it is not surprising that the electricity production on the local power stations is falling (fig. 11). During the installation phase in the 1990s, it was necessary to give the small power stations a special support[13], which was planned to stop in 2018. The local power plants were supposed to be profitable without support before 2018.

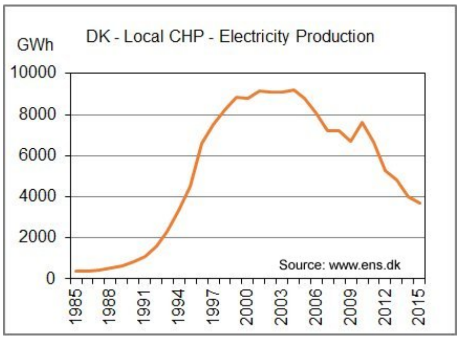

Fig. 11 - Electricity from local CHP systems in Denmark

However, the wholesale prices of electricity did not develop as expected. Under the present framework, it is most likely that only a few local CHP plants will be in full operation after 2020. Even the large CHP units are suffering from insufficient revenues.

Investigations on the future of district heating in Denmark are being carried out. The Danish Minister for Energy, Utilities and Climate has announced that district heating will be cheaper to the consumers in 2020[14]. Several challenges will oppose this promise:

- Decreasing wholesale prices of electricity.
- Repeal of the special support for local CHP units.
- Loss of energy efficiency due to less combined production.
- Conversion to fuels with less emission of CO_2.

7. Denmark will Need New Backup Capacity

The thermal power plant capacity has been adjusted to the business volume for several years.

[13] This support is called “the basic amount” or in Danish: “grundbeløbet”.
[14] Energiwatch, 7 February 2016

There are some uncertainty about the available capacity because several units have been mothballed with different conditions for restart (fig. 12). In some cases, the power stations do not have crews for operating all units at the same time. The typical notice for a restart is 3 months.

Because of this development, *Denmark is no longer self-sufficient with electricity under all conditions.* A combination of high load and calm weather would require import of electricity. The dispatchable capacity in Denmark cannot counter-balance wind and solar variations.

The result is large variations in the exchange of electricity with the neighbouring countries, both from hour to hour and from season to season. The Danish variations of wind power and solar power must be absorbed by the neighbouring systems.

It is uncertain, to which extent this is necessary. The cross-border exchanges are results of market conditions, but the operation of the remaining thermal power plants in Denmark is closely connected to the demand for heat.

The heat systems have hot-water tanks, which allow a certain flexibility for a few hours. Each operator of a CHP system makes his own optimization. Therefore, the market conditions still have the decisive role.

Fig. 13 demonstrates the fluctuating exchanges. The average exchange is about 0% during the winter season, while there is a significant import in July. The market prices are in most hours below the marginal cost of non-CHP thermal production.

The daily and seasonal variations of the exchanges indicate that production of electricity in Denmark does not follow the demand for electricity. Wind and solar power are controlled by weather conditions. Thermal power is closely connected to the CHP systems.

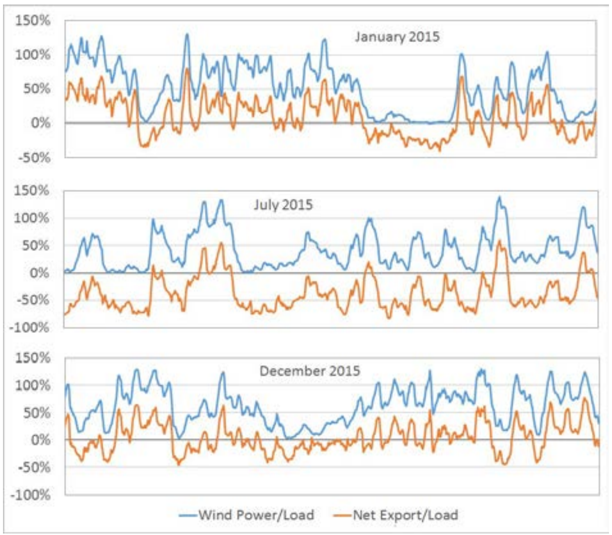

Fig. 13 - Danish wind power and power exchanges are closely correlated

In most hours, the spot price of electricity is set in a neighbouring country and the Danish producers have no incentives to follow the local load, in spite of the flexibility the CHP systems.

The heat demand and the resulting CHP production are low during the summer season. The seasonal variation is reflected in the weekly exchanges of electricity (fig. 14).

The development of international electricity markets has been the essential condition for this efficient utilization of both CHP, wind power and in the future even solar power.

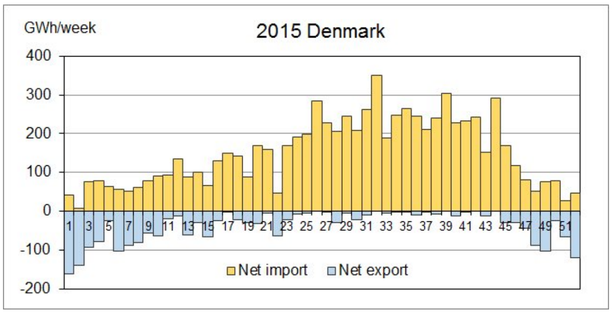

Fig. 14 - Seasonal variations of exchanges

However, the Danish system operator, Energinet.dk, also has a responsibility for security of supply. The reduction of dispatchable capacity will continue.

New backup power will be needed for the supply in periods without wind or sun. Therefore, a capacity arrangement in one form or another will be needed. Most European countries are considering "capacity markets" or "strategic reserves" in order to maintain security of supply for electricity consumers.

The Danish policy includes strategic reserves based on agreements with producers, who are paid for increasing production when needed, and agreements with consumers, who are paid for reducing the demand when needed.

The big question is if the increasing Danish import of electricity will cause neighbouring countries to ask Denmark for contributions to the increasing capacity costs in these countries.

8. Increasing Gap between Wholesale and Retail Prices in Europe

It is a paradox, that while the wholesale prices are falling, the electricity prices for the households are increasing (fig. 15).

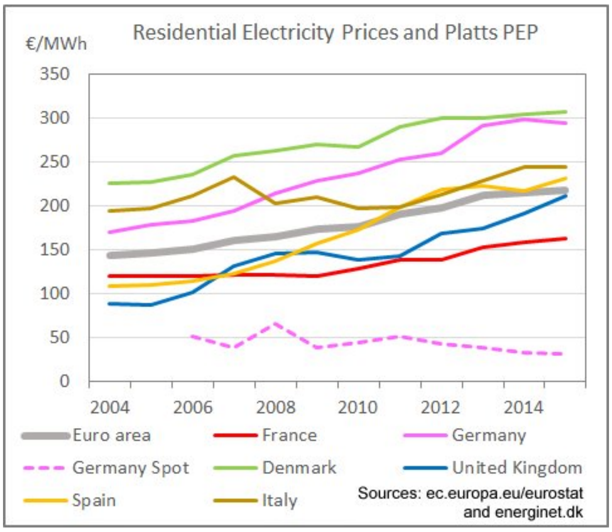

Fig. 15 - Since 2004, the average increase in electricity prices in the Euro area was 3.9% per year.

In Germany, the average growth of electricity prices for medium size households from 1998 to 2015 was 4.3% per year. The average German inflation was 1.4% for the same years.

The wholesale prices in Germany and in the Nordic area have been falling since 2006 (fig. 6). The decreasing trend for that period is about 4% per year.

In a modern "Smart Grid" the end-consumers are supposed to respond to price variations by adjusting their electricity demand correspondingly. For that purpose, price variations must be signalled to the end-consumers. In 2006, the German wholesale price was 28% of the residential price in fig. 15. In 2015, it was only 10%. When retail prices and wholesale prices move apart, the price signals from the wholesale markets will have a correspondingly smaller weight in the consumer prices.

It has been argued that falling wholesale prices will be for the benefit of consumers. The statistical evidence does not support that view.

There is a poor match between the traditional electricity demand and the sum of CHP electricity and wind power. “Smart grids” with price sensitive demand are supposed to contribute to a better balance between supply and demand. Convincing results have not yet been demonstrated. The weaker price signals are obstacles to this concept.

9. Dilemmas and Challenges

Electricity and heat supply systems are essential contributors to a fossil free future in Denmark. The combined production of heat and power (CHP) and the production of wind energy are already well developed in Denmark. Combined heat and power covers about 40% of the demand for space heating in Denmark, and the production of wind energy is supposed to exceed 50% of the demand for electricity by 2020.

The changing electricity and heat production has some consequences already now:

- The subsidized production in Denmark and in other countries causes lower spot market prices, which force thermal power plants to close down. Denmark is no longer self-sufficient with electricity under all conditions.
- The production pattern for electricity depends on wind and on heat demand. Wind and solar power are non-dispatchable. The flexibility of the combined power system is limited. The production pattern does not match the pattern of the electricity demand, neither from hour to hour nor from season to season. The result is that the neighbouring countries must absorb the variations. Fig. 13 and 14 demonstrate the exchange variations. Electricity supply in Denmark depends increasingly on services from other countries.

This is not necessarily a problem. The international electricity markets were developed for the improvement of interaction between energy systems in different countries. An efficient market encourages an optimal allocation of resources.

There are several electricity market systems in Europe. Grid bottlenecks and differences between market systems prevent the free flow of electricity in Europe and cause the considerable wholesale price differences.

The large-scale use of fluctuating and non-dispatchable power sources such as wind power and photovoltaics (PV) calls for European solutions on market arrangements and transmission. To small nations like Denmark, the dependence on supranational bodies and the abandonment of sovereignty might be a problem.

Essential challenges:

- The future of combined heat and power in Denmark is rather uncertain. CHP provides the remaining flexibility of the production system, and it contributes to the energy efficiency. On the other hand, the CHP systems are based on fossil fuels. Many CHP systems convert to biomass with or without CHP. The decreasing production of CHP electricity is evident already now (fig. 13).
- Denmark will need new backup capacity for filling the gaps in wind power and solar cell output. A perfect backup power plant must be low cost, robust and based on non-fossil fuel. Realistic visions on such units have not yet been presented.
- Electricity consumers are supposed to contribute to balancing the future power systems by moving electricity consumption in time. There is still a long way to go before the Smart Grid visions are implemented in large scale. Essential research areas will be communication systems and the design of energy markets for households.

- New types of electricity demand will be necessary in order to obtain sufficient utilization of wind energy and demand side flexibility. The interaction with heating systems is already widely used in Denmark. Large-scale charging of electric vehicles is underway as a supplement. In a more distant future, even interaction with the natural gas system is being considered. It will take a determined research and development effort to meet these targets.
- The transformation of the power system will create new risks of power failures. New methods and criteria must be developed for maintaining the present level of operational security.