The Danish Experience with Integrating Variable Renewable Energy

Lessons learned and options for improvement

STUDY

Agora
Energiewende

Ea Energy Analyses

The Danish Experience with Integrating Variable Renewable Energy

IMPRINT

STUDY

The Danish Experience with Integrating Variable Renewable Energy

Lessons learned and options for improvement

COMMISSIONED BY

Agora Energiewende
Rosenstraße 2 | 10178 Berlin

Project lead: Dr. Stephanie Ropenus
stephanie.ropenus@agora-energiewende.de

WRITTEN BY

Ea Energy Analyses
Frederiksholms Kanal 4, 3. th.
1220 Copenhagen K
Denmark

Anders Kofoed-Wiuff, János Hethey, Mikael Togeby, Simon Sawatzki and Caroline Persson

Proof reading: WordSolid, Berlin
Typesetting: neueshandeln GmbH, Berlin
Cover: © jeancliclac/Fotolia

082/16-S-2015/EN

Publication: September 2015

Please quote as:
Ea (2015): *The Danish Experience with Integrating Variable Renewable Energy.*
Study on behalf of Agora Energiewende.

www.agora-energiewende.de

Preface

Dear Reader,

In 2014 wind energy alone supplied 39 percent of Danish electricity demand. Danish energy supply is moving away from a system based on fossil fuels, especially coal, toward an entirely renewable energy based system. In fact, Denmark is striving for complete independence from fossil fuels by 2050. In the electricity and heating sectors, fossil fuel phase-out is expected even earlier. Denmark aims to meet 50 percent of electricity demand with wind power by 2020. Thus, increasing the integration of wind energy is one of the key challenges in the Danish renewable energy transition, the so-called *grøn omstilling*.

What steps has Denmark taken to enable the deployment of ever-greater shares of wind power? What flexibility measures has the country implemented to keep its power system reliable and stable? And can other European countries learn from the Danish experience – based on the understanding that sooner or later, they will face the same challenges?

The following report, which was drafted by the Copenhagen-based research and consultancy company Ea Energy Analyses, takes an in-depth look at the Danish experience with integrating wind power. It is hoped that the lessons learned in Denmark in recent decades can serve as a valuable aid to other countries in their efforts to transform their energy systems.

We hope you find this report to be a worthwhile contribution to the current debate and wish you a nice read.

Kind regards,
Patrick Graichen
Director, Agora Energiewende

The Results at a Glance

1. **Denmark is the world's leader in the deployment of wind power, with 39 percent of electricity consumption supplied by wind.** The challenge of integrating a high share of wind power led Danish institutions and market participants to develop several flexibility options early on, including use of interconnectors to other countries, increasing the flexibility of thermal power plants, making district heating more flexible, encouraging system friendly wind power, implementing demand side flexibility as well as introducing alternative options for procuring ancillary services.

2. **Market based power exchange with neighbouring countries is the most important tool for dealing with high shares of wind power in Denmark.** With 6.4 GW of net transfer capacity to Norway, Sweden and Germany (Danish peak demand: 6 GW), Denmark is able to sell electricity during times of high wind production, and to import electricity in times of low wind production. The use of the 2.4 GW net transfer capacity to Germany is sometimes limited for export depending on the wind conditions in Northern Germany.

3. **A great deal of attention has been devoted in recent years to the flexibilisation of conventional power plants.** Danish coal power plants have been optimised to allow very steep ramp-up gradients, shorter start-up times and low but stable minimum generation levels. Flexibility in providing ancillary services has further reduced must-run capacity.

4. **Denmark has a large number of combined heat and power (CHP) plants in its power system.** Regulation has been reshaped to reduce heat bound electricity generation in situations with high wind energy feed-in. In the future district heating systems are envisioned to become electricity consumers rather than producers in times of high wind power production. In spite of changes already adopted to the energy tax system, further regulatory measures are still needed to tap the full potential of using power for heat.

Content

Preface 1

Key Findings and Conclusions 7

1 Executive summary 9

The Danish experience 9
Value of wind in the market – a benchmark for successful wind integration 11

2 Challenges to the integration of wind power 13

Challenge 1. Ensuring that wind power remains valuable when it is very windy 13
Challenge 2. Ensuring sufficient generation capacity when it is not windy 14
Challenge 3. Balancing wind power 14
Challenges are both short and long term 15

3 Wind power integration: The Danish flexibility experience until now 17

3.1 Wind power development 18
3.2 A well-functioning electricity market 20
3.3 Utilisation of interconnectors 22
3.4 Integration with the heat sector – reshaping regulation 25
3.5 Flexible power plants 30
3.6 Encouraging system-friendly wind power 33
3.7 Procurement of ancillary services 35

4. A brief analysis of Danish market data – What happens when wind energy feed-in is high? 36

5. Enhancing system flexibility – A deep dive into implementing cross-sectoral flexibility options 45

5.1 Flexibility of thermal power plants 45
5.2 District heating as a system integrator 47
5.3 Alternative options for ancillary services 51
5.4 Demand side flexibility options 52

Appendix: List of wind integration measures 57

List of figures and tables

Figure 1:	Discrepancy between observed prices for wind power generators (power price weighted by wind power generation) and average (time-weighted) wholesale electricity market price for West Denmark from 2002 to 2014.	11
Figure 2:	Wind capacity and share of wind power production in Denmark, 1980-2015.	17
Figure 3:	Distribution of energy production from onshore wind turbines within Denmark in 2013.	19
Figure 4:	Duration curve of consumer load and residual load.	20
Figure 5:	Nord Pool countries and their price zones.	21
Figure 6:	Historic development of electricity prices in Western Denmark, Germany and the overall Nord Pool Spot system.	22
Figure 7:	Snapshot of the Danish power system on 2 June 2015 at 13:17.	23
Figure 8:	Physical flow and price difference on the interconnection between Western Denmark and Germany.	24
Figure 9:	Correlation between wind power generation in Western Denmark and flows to Sweden/Norway and Germany	24
Figure 10:	Market available interconnector capacity between Western Denmark and Germany during 2002-2015	25
Figure 11:	The supply of district heating increased from 80 PJ (Petajoule) in 1972 to 140 PJ in 2012.	26
Figure 12:	Heating installations in Danish dwellings (1000 units). In the 1980s, individual oil boilers were the dominant heat generation technology.	26
Figure 13:	Stylised illustration of heat generation at a large Danish power plant in relation to the power price.	28
Figure 14:	Installed capacity of electric boilers (MWel). Statistics and future expectations from Energinet.dk, Danish TSO.	30
Figure 15:	The flexibility challenge for thermal power plants as a result of fluctuating consumption and variable renewable electricity (VRES-E) production.	31
Figure 16:	Optimisation of power plant flexibility at different organisational levels.	32
Figure 17:	Correlation between wind power production in Western Denmark and the market price of electricity in euro per MW.	34
Figure 18:	Reservation price for upward regulation power. Average price for East and West Denmark.	37
Figure 19:	Stylised demand/supply curve for the Scandinavian and German electricity markets.	39
Figure 20:	Monthly average market price for central, decentral, wind, solar and consumption.	40
Figure 21:	Development of discrepancy between observed prices for wind power generators and average market price for West Denmark.	41
Figure 22:	Generation mix in Western Denmark – different levels of electricity spot prices.	42
Figure 23:	Duration curve of 1000 lowest electricity prices in Germany (EEX) and Western Denmark (Nord Pool) in 2014.	43
Figure 24:	Stepwise approach for increasing power plant flexibility.	46
Figure 25:	Start-up optimisation of a coal power plant.	47
Figure 26:	Daily cyclic operation of a gas fired Ultra Super Critical steam power plant.	48
Figure 27:	Illustration of operation points with different electricity to heat ratios for a combined heat and power extraction plant.	49
Figure 28:	Short run marginal heat production cost for different units depending on the electricity price.	50
Figure 29:	Electricity consumption – example of development of flexible consumption.	53

Table 1:	Key figures – Danish electricity system.	10
Table 2:	Challenges and possible solutions related to the integration of variable renewable energy.	14
Table 3:	Key figures – Danish electricity system.	18
Table 4:	Typical prevailing and possible flexibility parameters for thermal power plants in Denmark (DK) and Germany (DE).	33
Table 5:	Existing, planned and future potential wind power integration measures.	44
Table 6:	Assessment of the properties required to maintain power system stability.	51
Table 7:	Savings for consumers with adoption of smart meters.	54

Key Findings and Conclusions

1. Denmark is the world's leader in the deployment of wind power, with 39 percent of electricity consumption supplied by wind. The challenge of integrating a high share of wind power led Danish institutions and market participants to develop several flexibility options early on, including use of interconnectors to other countries, increasing the flexibility of thermal power plants, making district heating more flexible, encouraging system-friendly wind power, implementing demand side flexibility, as well as introducing alternative options for procuring ancillary services.

Denmark aims to supply half of its electricity consumption with wind by 2020. This is an intermediate step toward the goal of achieving a 100 per cent fossil-free energy system by 2050. With increasing wind energy deployment, more wind power production is sold during times of low or negative wholesale electricity prices. The green transition necessitates increased flexibility in the entire power system while ensuring security of supply. To date, power exchange with neighbouring countries has played a major role in integrating Danish wind power, as Denmark can export or import electricity depending on current wind production levels. In addition, Danish institutions and market participants have implemented a multitude of other cross-sectoral flexibility options early on. On the supply side, power plants that originally provided base load have been made more flexible in their operations so they can react more quickly to fluctuating wind power feed-in. Regulatory changes have provided incentives for increasing the flexibility of CHP plant operations, in particular of the large share of heat led CHP. At the same time, regulating power markets have been made more accessible to wind energy producers. The support scheme for wind power was changed in order to incentivise the deployment of more system-friendly wind power turbines. On the demand side, electric boilers, heat pumps, load management by large industrial customers and other flexible consumption units can contribute to counterbalancing the fluctuations in variable renewable power production.

2. Market based power exchange with neighbouring countries is the most important tool for dealing with high shares of wind power in Denmark. With 6.4 GW of net transfer capacity to Norway, Sweden and Germany (Danish peak demand: 6 GW), Denmark is able to sell electricity during times of high wind production, and to import electricity in times of low wind production. The use of the 2.4 GW net transfer capacity to Germany is sometimes limited for export depending on the wind conditions in Northern Germany.

A larger portion of Danish wind power is located in Western Denmark, where the wind share reached 51 per cent in 2014, compared to 21 per cent in Eastern Denmark. Within the Nordic power exchange Nord Pool, there has been implicit market coupling of Denmark with Norway and Sweden since 1999/2000. There is a correlation between the amount of wind power produced in Western Denmark and the magnitude and direction of power flow on interconnectors to Norway and Sweden. In general, high Danish wind power feed-in translates into exports. The price at which wind turbine operators can sell their production can be understood as the socio-economic value of wind power generation on the market. The export bottlenecks to Germany that occasionally result during high wind situations are a relatively new problem; southbound interconnector capacity has decreased gradually over the past six years. Most German wind production is located in the northern and eastern parts of the country, meaning there is little capacity to absorb Danish exports when winds are high.

3. A great deal of attention has been devoted in recent years to the flexibilisation of conventional power plants. Danish coal power plants have been optimised to allow very steep ramp-up gradients, shorter start-up times and low but stable minimum generation levels. Flexibility in providing ancillary services has further reduced must-run capacity.

Danish coal power plants that were originally designed as base load units have been transformed into some of the most flexible power plants in Europe. In case of a renewable power shortage, there is an increasing demand for steep positive ramp rates of already running plants as well as a need for fast start-up times at thermal plants. Alternatively, when renewable power production is high (renewable power surplus), there is a need for steep negative ramp rates as well as low but stable minimum generation levels. The flexibilisation of conventional power plants starts at the systems level, and includes conducting long-term scenario studies for assessing the expectable magnitude of load fluctuations. Flexibilisation measures can then be undertaken at the level of the individual power plant. These measures can be conducted using an iterative, stepwise approach once flexibilisation bottlenecks (for example by means of data analyses) and achievable flexibility levels have been determined. Such an iterative process can be applied to increasing ramp rates, decreasing minimum load, improving start-up times and lowering start-up costs. In Denmark as a whole, the need for must-run capacity has been reduced over the years. Ancillary services necessary for the reliable operation of the system were traditionally supplied by thermal power plants along with the production of electricity. However, increased system flexibility has involved the need to find alternative options for the provision of ancillary services. The Danish transmission system operator has adopted a strategy of incorporating system-stability properties into the grid when it is economically advisable.

4. Denmark has a large number of combined heat and power (CHP) plants in its power system. Regulation has been reshaped to reduce heat bound electricity generation in situations with high wind energy feed-in. In the future district heating systems are envisioned to become electricity consumers rather than producers in times of high wind power production. In spite of changes already adopted to the energy tax system, further regulatory measures are still needed to tap the full potential of using power for heat.

A very large portion of Danish electricity production is connected to the district heating system. The strong integration of the electricity and heating sector brings both opportunities and challenges for wind integration. Flexibility measures entail switching between operation modes that allow only for producing electricity or heat during certain periods. Under the old regulation of CHP plants with fixed feed-in tariffs (graduated depending on the time of the day), there was a lack of responsiveness to power market prices. In 2006 regulations were changed; all decentralised CHP plants above 5 megawatts now settle at market prices. In order to compensate for the lower prices on the spot market, a financial subsidy was provided, independent of production. Simultaneously, tax discounts on heat generated from CHP plants posed a further challenge to wind power integration. This was because CHP plants had an incentive to produce electricity and heat even at very low electricity prices to obtain the tax discount. In 2005 regulatory changes introduced a discount for boilers that is similar to the one provided for CHP plants. However, the rebate is only offered to boilers located in district heating systems with CHP capacity available. In times of low electricity prices, district heating companies are incentivised to shift production from CHP plants to boilers or to "bypass" the steam turbines at the CHP plants. At low or negative power prices, this bypass is used for exclusive heat production. When prices recover, the plant can quickly switch back into a cogeneration model, producing combined heat and power. In spite of further regulatory changes in the tax system to stimulate investment in heat pumps, heat pumps still play a rather limited role in district heating in Denmark, so their potential has yet to be fully tapped.

1 Executive summary

Introduction

The Danish government aims to supply more than half of traditional electricity consumption[1] with wind power by 2020. Furthermore, over the long term the share of wind power in Denmark can be expected to increase even further, as the government pursues the objective of achieving an energy system independent of fossil fuels by 2050.

The purpose of this project is to analyse options for improving the integration of wind power. In particular, we examine the Danish experience with the integration of variable renewable energy in the hope of highlighting valuable lessons learned in Denmark that may be of use to Germany and other countries around the globe as they increase their shares of wind energy.

The report is divided into two parts:
→ A review of the Danish experience with wind power integration.
→ An analysis of selected key measures for wind power integration (so-called "deep dive" of selected flexibility options).

Status

In 2014, wind power accounted for 39 per cent of Danish electricity demand, supposedly the highest figure of any country in the world. The electricity system in Denmark consists of two sub-systems: a Western part, consisting of Jutland and Funen, which is synchronous with continental Europe, and an Eastern Part, consisting mainly of Zealand, which is synchronous with the Nordic countries. A larger portion of the wind power is located in the Western part of Denmark, where the share reached 51 percent in 2014, compared to 21 percent in Eastern Denmark.

1 "Traditional" electricity consumption refers to the kind of electricity consumption that exists today, such as electricity used for lighting and household appliances. "Non-traditional" electricity consumption (so-called "derived electricity demand") is the anticipated electricity consumption for heat pumps and electric vehicles, which will cause total electricity demand to rise.

On a number of occasions in 2014 with high wind speeds and relatively low electricity demand, the wind share exceeded 100 per cent in Western Denmark. In total, there were 1,230 of these hours in 2014 in Western Denmark.

The Danish experience

The market-based exchange with Denmark's neighbouring countries is one of the most important means of integrating wind power production. With 6.4 gigawatts (GW) of net transfer capacity (Danish peak demand = approx. 6 GW) to Norway, Sweden and Germany, Denmark is able to sell electricity in times of high wind production, and to import power in times of low wind energy feed-in. The electricity market ensures that the cheapest generators are prioritised for electricity production. For example, it allows the Nordic hydropower stations to function as cheap and effective energy storage for wind power.

The utilisation of the 2.4 GW net transfer capacity to Germany for export is dependent on wind conditions in Northern Germany. During the last five years the available southbound capacity from Western Denmark to Northern Germany has declined year by year, reaching a low of approximately 300 megawatts (MW) in the first months of 2015. The reductions in available capacity are caused by bottlenecks in the internal electricity grid in Germany and are dependent on the level of wind power generation in Northern Germany, which has increased significantly in recent years.

In addition to cross-border market integration, Danish institutions and market participants developed several flexibility options early on in order to integrate increasing shares of wind power.

Integration with the heat sector

A very large portion of Danish electricity production is connected to the district heating system. With the exception of a few plants, all power plants in Denmark have the possibil-

Key figures – Danish electricity system

Table 1

Key figures 2014	Western DK	Eastern DK	Denmark
Electricity demand [TWh]	20.1	13.3	33.4
Peak demand [MW]	3,541	2,500	6,033
Wind power [TWh]	10.3	2.7	13.1
Wind share of demand [%]	51	21	39
Wind peak [MW]	3,527	947	4,444
Interconnectors to Norway/Sweden [%]	2,372	1,700	4,072
Interconnectors to Germany [MW]	1,780	600	2,380
Heat demand – district heating [TWh]	–		37.5
Heat demand – individual heating [TWh]			25.3

Own elaboration based on market data from Energinet.dk and energy statistics from Energistyrelsen

ity of co-generating electricity and district heat. This limits the integration of wind, as options for electricity production are to some extent restricted by the requirement of supplying heat demand. However, integration of the power and district-heating sector provides additional opportunities for the enhanced integration of variable renewable energy.

During the last 10 years a number of regulatory measures have been taken to encourage a flexible interplay between the electricity and heat sectors. This includes regulatory changes that expose combined heat and power (CHP) plants to market prices – as opposed to fixed tariffs – as well as changes to the tax system to incentivise district heating companies to shift production from combined heat and power plants to boilers or to "bypass" the steam turbines at the combined heat and power plant when electricity prices are low. Bypassing the steam turbines allows a combined heat and power plant to exclusively produce heat. When the prices recover, the plant can very quickly go back to co-generation mode, producing combined heat and power. The taxation scheme has also been changed in order to encourage electricity consumption for heat generation when electricity prices are low. Nevertheless, electric boilers and heat pumps still play a limited role in district heating. To date, the market for ancillary services has been the main driver of the deployment of electric boilers.

Flexible power plants

The high share of wind power that has developed in Denmark over the last 25 years provided an early incentive for increasing the flexibility of thermal power plants. From the power plants' perspective, the high fluctuation in residual load associated with wind power generation leads to steep load gradients. It also requires fast start-ups at low cost, and as low minimum stable generation as possible. Consequently, Danish coal power plants that were originally designed as base load units have been transformed into some of the most flexible power plants in Europe. For example, the load gradients of existing Danish coal power plants (3-4 % P_N/min) already achieve what is termed the "possible state of the art" for German technology.

Provision of ancillary services

Traditionally, most ancillary services such as reserve capacity, inertia, frequency control and voltage control were provided by large thermal power plants. Central power stations used to produce a significant amount of power during hours with low wholesale electricity prices. The Danish transmission system operator (TSO) Energinet.dk's strategy is to build the system stability properties into the grid when this is economically advisable, thereby allowing the services required to be provided without co-generation of electricity. Among other things, Energinet.dk has procured a number of new synchronous compensators. As a result of these initiatives the need for must-run capacity has been reduced from three large units to 0–1 units in Western Denmark and in Eastern Denmark the requirement has been reduced from 2–3 to 1–2 units.

Value of wind in the market – a benchmark for successful wind integration

In a market-based system the marginal value of wind power can be stated as the value that the market ascribes to production, directly expressed as the price of electricity. The first megawatt of wind power capacity can often have a relatively high value – even higher than the average wholesale market price, because wind turbines usually produce more in wintertime, when power prices tend to be higher. However, when wind turbines are producing, they drive the expensive power plants out of the electricity market, thereby lowering the market price of electricity. In this way, wind power reduces wholesale electricity prices during periods of high wind energy feed-in.

The price that a wind turbine can obtain for its production on the market can be regarded as the socioeconomic value [2] of wind turbine power production.[3]

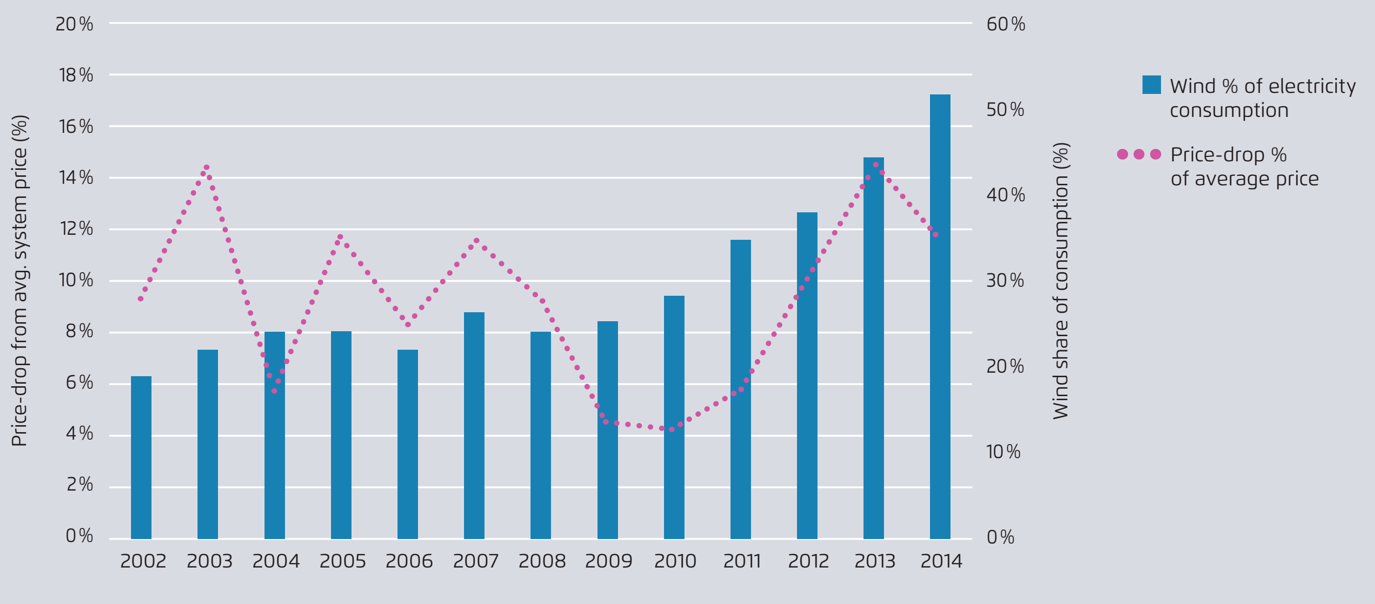
Figure 1 shows the difference between the average electricity wholesale market price (time-weighted) and the wind power price (power prices weighted by wind power generation) in Western Denmark in 2002–2014 (red dashed line). We compare this to the share of the consumption covered by wind power (blue columns).

Perhaps surprisingly, we see that the price drop is relatively high in the beginning of the period, at around 10 to 14 per-

2 It should be noted that if electricity prices are skewed by subsidies or taxes that do not attempt to correct externalities, they may not represent the real socio-economic value of electricity.

3 In a cost-benefit analysis the value of the sold production must be compared to the costs involved in erecting and maintaining the wind turbine.

Discrepancy between observed prices for wind power generators (power price weighted by wind power generation) and average (time-weighted) wholesale electricity market price for West Denmark from 2002 to 2014 Figure 1



Own figure based on data from Energinet.dk

cent in 2002 and 2003, before dropping to about five per cent in 2009–2011. We attribute this trend to the flexibility measures induced during the same period – particularly to the incentives for flexible CHP operation. During the same period (2002–2010), the share of wind power grew only moderately.

Since 2011, the wind share has increased significantly, and during the last three years, the price difference has returned to around 10 to 14 per cent. The increasing limits to export on the interconnection between Western Denmark and Germany is part of reason for this increasing discrepancy.

2 Challenges to the integration of wind power

In contrast to conventional dispatchable power plants, the production of electricity from wind varies, and can be relatively difficult to predict.[4] Furthermore, there are periods in which large amounts of wind energy are available, as well as long periods without any wind power production at all.[5]

These large fluctuations in production require the rest of the overall energy system to be quite flexible, as electricity supply shortfalls or excess supply could otherwise result.

Three main challenges

Generally speaking there are three main challenges associated with integrating wind power:

1. To ensure that wind power remains valuable when it is very windy.
2. To ensure sufficient production capacity when there is no wind. With increasing wind power deployment, it becomes economically less attractive to build base load plants.
3. To balance wind power production, i.e. by managing the unpredictable production patterns caused by variations in wind speed.

4 Despite systems becoming better and better at predicting wind patterns, there is still a challenge in predicting electricity production, especially during periods of medium-strong wind speeds. The energy potential of an expected wind front can often be predicted with relatively high precision but it can be difficult to anticipate precisely when the front will pass. The average deviation in wind prognoses in Denmark is approximately six per cent (12–36 hours forecast). Overview of wind resources in Denmark: http://www.emd.dk/files/windres/WinResDK.pdf

5 Wind turbines also have relatively low capacity factors. The capacity factor is defined as: yearly generation/(capacity * 8760 hours), i.e. actual electricity production from a given generation unit over one year divided by the potential electricity production of that generation unit if it were able to continuously operate at full nameplate capacity in every hour of the year. Onshore wind turbines have capacity factors of around 0.25 to 0.35, while offshore wind turbines, with their more stable wind conditions, have capacity factors around 50 per cent.

All three of these challenges associated with integrating wind power are fundamentally economic challenges, as technical solutions to cope with these issues already exist today. In addition to the three above-mentioned challenges, a transition from conventional power plants to more variable generation means that system services ensuring the consistent stability of supplied power (i.e. ancillary services such as short circuit power, voltage control and reactive reserves from other units) will have to be provided from other sources.

Challenge 1. Ensuring that wind power remains valuable when it is very windy

Currently, the dominant support scheme in Denmark for onshore wind energy is a price premium paid on top of the wholesale market price for electricity.[6] If a large part of the wind power based electricity is sold at low or negative prices, this is detrimental to the revenues of wind turbine operators, and reduces the incentive to invest in new wind turbines. For this reason, it is essential to ensure the value of wind, both to maintain its socioeconomic value, and in order to preserve the economic basis for continued wind power deployment. This necessitates the **increasing use of flexibility options within the entire system.** During times of high wind power feed-in, there are several flexibility options, including exporting electricity to neighbouring countries, reducing dispatchable power production at conventional power plants, as well as increasing electricity consumption when this is economically attractive. When traditional and new electricity demand (electricity for heat generation, electric vehicles, etc.) is made more flexible, this can assist by reducing consumption during times of high

6 The date of grid connection primarily determines which kind of support scheme applies for the wind turbine operator. The level of the price premium (i.e. a supplement on top of the market price) plus an extra allowance for balancing costs has been changed several times over the years. Since January 2014 a new scheme has been in place, which will be further explained in section 3.6.

prices (which often occur when wind power feed-in is low), and vice versa.

If these options are exhausted, it is also possible to curtail production from some wind turbines, either for shorter periods consisting of a few minutes or for longer periods extending to several hours. Curtailment is technically feasible for all modern wind turbines. Excess electricity is therefore not a technical problem but rather an economic one, which can be minimised when the rest of the energy system becomes more flexible. In order to move toward such a system, incentives are needed for market actors that adequately reflect and reward the value of increased flexibility. In a future with a large share of wind power, it will likely be economically beneficial to reduce the output of some wind turbines over selected periods of time rather than investing in flexibility options. The wind turbines that are curtailed would then be available for providing positive regulating power.

Challenge 2. Ensuring sufficient generation capacity when it is not windy

The challenge of ensuring sufficient generation capacity can be dealt with in several ways. Possible solutions include the provision of peak generation capacity (for example from gas turbines) as well as enabling more cross-border imports and exports via increased integration of the power grid with neighbouring countries. Flexible electricity consumption and the activation of emergency power generators are also viable possibilities that are, to a certain extent, already in use. The value of a respective measure depends in particular upon the maximum possible duration of its application. While certain types of flexible electricity consumption can only provide a solution for a limited number of hours, other possibilities such as peak load plants or international grid connections can be used over longer periods of time without wind power production (for example over several weeks).

Challenge 3. Balancing wind power

The need for balancing arises if the production from wind power falls unpredictably, typically as a result of altered wind conditions. Balancing can be achieved either by power plants or by consumers being prepared to change their production/consumption patterns with relatively short notice (see the text box below). On the supply side, gas turbines in particular (as well as other quickly adjustable units) are well suited to meet this need. On the demand side, electric boilers or heat pumps, large industrial consumers, and other flexible consumption units can provide balancing services. Last but not least, increased integration with neighbouring countries' energy systems can provide access to more generation and consumption sources capable of providing balancing. A precondition for tapping this potential is sufficient interconnection capacity and international agreements that allow for the cross-border trading of balancing power.

Challenges and possible solutions related to the integration of variable renewable energy — Table 2

Challenges	Short term operational	Long term investment perspective
Ensuring the value of wind when it is very windy	Short term demand response	New demand, for example heat pumps, industrial processes; Increase transmission capacity to load centres
Ensuring sufficient generation capacity when it is not windy		Invest in peak generation; Increase transmission capacity to other generators
Balancing wind power	Flexible dispatchable generators; cross-border trade of balancing power	Flexible demand response; participation of wind turbines in the balancing market

Own illustration

Challenges are both short and long term

As presented in Table 2, the challenges posed by wind power and other variable renewable energy sources relate both to the short-term operational perspective as well as the long-term investment perspective.

3 Wind power integration: The Danish flexibility experience until now

This section explores how the Danish electricity system has responded to the **flexibility challenge** posed by large and increasing amounts of wind power during the last 20 years.

The integration of wind power has led to changes at all levels of the energy system, including technical measures and the adaptation of energy markets, support schemes, taxes, new arrangements for system services and integration with the heating sector.

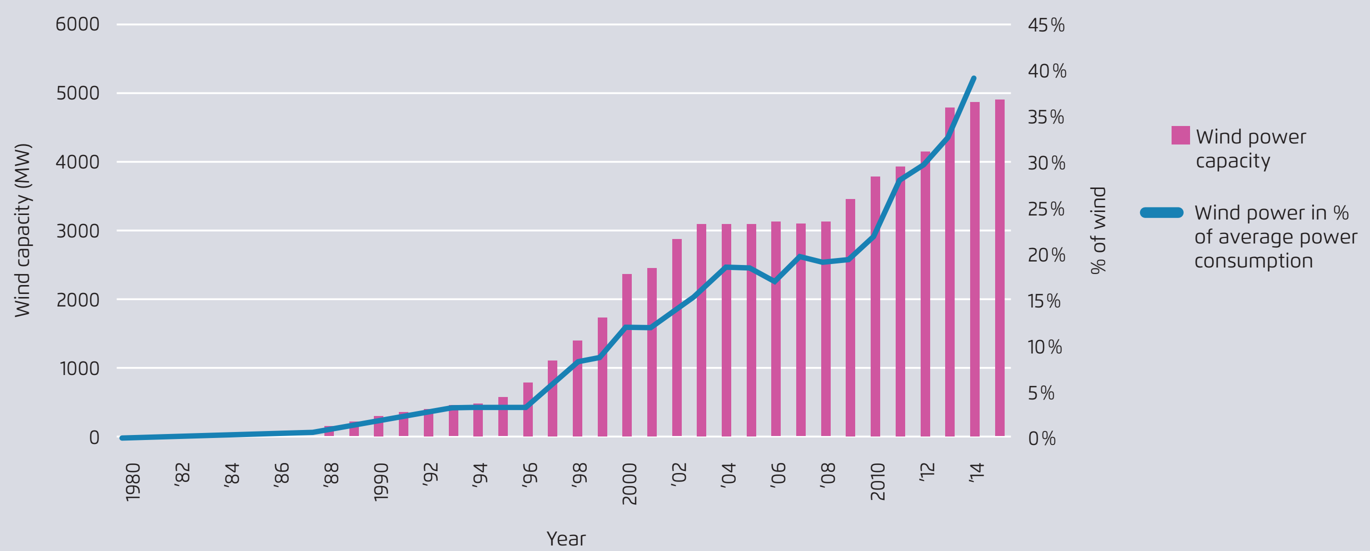
After a brief introduction to the historical development of wind power in Denmark and an overview of the current status of the Danish energy system, we will explore the following issues, which have all been important for efficient wind power integration in Denmark:

→ A well-functioning electricity market
→ The utilisation of interconnectors
→ Integration with the heating sector – reshaping regulation
→ Flexible power plants
→ Encouraging system-friendly wind power
→ Procurement of ancillary services

Finally, we will conclude with a statistical analysis of the Danish experience with wind power integration based on market data from 2002 to 2014.

It should be emphasised that this report does not encompass all measures taken to integrate wind power in Denmark, as the focus of this report primarily lies on flexibility measures. For example, there have also been substantial ef-

Wind capacity and share of wind power production in Denmark, 1980–2015 — Figure 2



Own elaboration based on market data from Energinet.dk and Energistyrelsen (www.ens.dk) forts devoted to improving wind power forecasting and grid codes. These measures are not covered in this report.[7]

3.1 Wind power development

The oil crisis of the 1970s was a watershed moment in Danish energy policy. It led to the creation of a dedicated and active energy policy in Denmark. The four cornerstones that arose then – namely, reducing consumption, promoting combined heat and power generation, encouraging renewable energy development and extraction of hydrocarbons from the North Sea – continue to define Danish energy policy today.

The electricity sector has been radically transformed from a system dominated by centralised power plants to decentralised generation and wind power.

During the 1980s Denmark saw steady growth in the number of wind turbines, laying the foundation for the development of a strong domestic turbine manufacturing industry. However, the turbines that were installed in the 1980s were relatively small. Even though there were more than 2,600 turbines by 1990, their cumulative capacity was only just over 300 MW. This changed during the late 1990s with the introduction of 500 kW+ (kilowatt) turbines. In 2000, total wind power capacity had reached almost 2,400 MW. Since then, a considerable share of wind energy deployment has taken place offshore. By the end of 2014 the total wind power capacity amounted to just below 5,000 MW. Of this amount, 1,271 MW is located offshore.

Figure 2 shows the growth of installed wind power capacity and wind power production as a share of total power consumption in Denmark from 1980 onward.

Status

In 2014, wind power accounted for 39 per cent of national electricity demand, supposedly the highest figure of any country in the world. The electricity system in Denmark consists of two sub-systems: a Western part, consisting of Jutland and Funen, which is synchronous with continental Europe, and an Eastern Part, consisting mainly of Zealand, which is synchronous with the Nordic countries. Since 2010, Eastern and Western Denmark have been connected by a 600 MW Direct Current (DC) connection.

7 The Danish Energy Agency has produced an Energy Policy Toolkit on System Integration of Wind Power, providing a short description of the Danish experience with wind power forecasting and grid codes: http://www.ens.dk/sites/ens.dk/files/supply/renewable-energy/wind-power/System%2Integration%2of%20Wind%20Power.pdf

Key figures – Danish electricity system — Table 3

Key figures 2014	Western DK	Eastern DK	Denmark
Electricity demand [TWh]	20.1	13.3	33.4
Peak demand [MW]	3,541	2,500	6,033
Wind power [TWh]	10.3	2.7	13.1
Wind share of demand [%]	51	21	39
Wind peak [MW]	3,527	947	4,444
Solar PV [MW]			598
Interconnectors to Norway/Sweden [%]	2,372	1,700	4,072
Interconnectors to Germany [MW]	1,780	600	2,380
Heat demand – district heating [TWh]			38
Heat demand – individual heating [TWh]			25

Own elaboration, based on market data from Energinet.dk and of energy statistics from the Danish Energy Agency

The Danish electricity system is very well interconnected to both Germany, Norway and Sweden. The total net transfer capacity to Norway and Sweden is 4,072 MW and to Germany is 2,380 MW. As we will discuss in section 3.3, this provides an efficient means for the integration of wind power.

Table 3 provides an overview of key figures for the Danish electricity system. We also provide information on the heat load for district heating as well as individual heating (mainly gas and oil boilers), since electricity is expected to play increasingly a role in heating.

Generation from solar photovoltaic (PV) amounted to 0.56 terawatt hours (TWh) in 2014 corresponding to 1.7 per cent of electricity demand.

More wind turbines are located in Western Denmark

A larger portion of the wind power is located in the Western part of Denmark, where the share reached 51 per cent in 2014 compared to 21 per cent in Eastern Denmark.

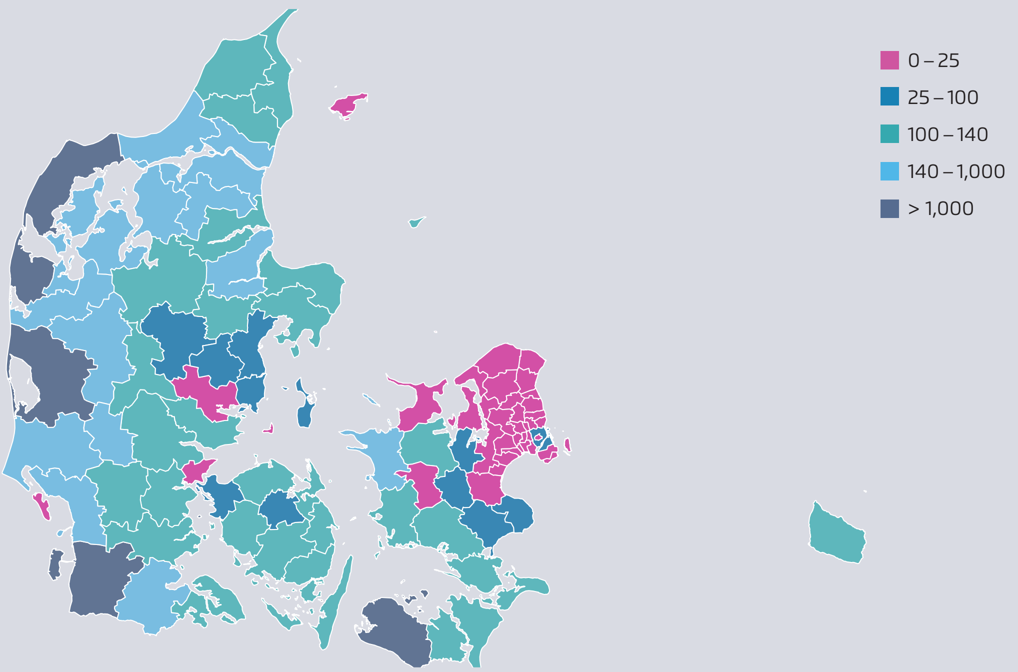
Wind power induced challenges in Denmark

Figure 4 shows how the residual load that power plants have to supply is impacted by the feed-in of wind power. The graph reflects each of the three integration challenges listed in section 2.

In a number of occasions in 2014, when wind speeds were high and demand was relatively low, the wind share exceeded 100 per cent in Western Denmark. **In total, there were 1,230 excess production hours in 2014 in Western Denmark** (challenge 1).

At the same time, we see that the peak demand of the residual load is only slightly lower than the peak of the consumer load. Thus, the need for dispatchable generation capacity is almost unaffected by the deployment of wind (challenge 2), but the operation time of the dispatchable capacity is reduced, substantially favouring power plants with low fixed costs.

Distribution of energy production from onshore wind turbines within Denmark in 2013 (in TJ per municipality) Figure 3



Danish Energy Agency, "Energy Statistics 2013"

Finally, the electricity system has to cope with stronger variations in the net load (challenge 3). Without wind power in the system, the total annual deviation in load is around 2,000 MW – stretching from around +1,500 MW to + 3,500 MW – whereas it is around 4,000 MW when looking at the residual load (from around -1,000 MW to +3,000 MW).

3.2 A well-functioning electricity market

Traditionally, the Danish energy sector was organised by means of consumer or municipality ownership and non-profit regulation. Throughout the 1990s, there was a growing pressure in the Nordic Countries and from the EU to increase efficiency and trade through liberalisation. With the liberalisation of electricity markets in the Nordic countries from the mid-1990s, the electricity sector had to work under completely new conditions.

Today, as in the rest of the EU, electricity production and trade in Denmark is a commercial activity governed by free competition, while the transmission and distribution networks are overseen as regulated monopolies.

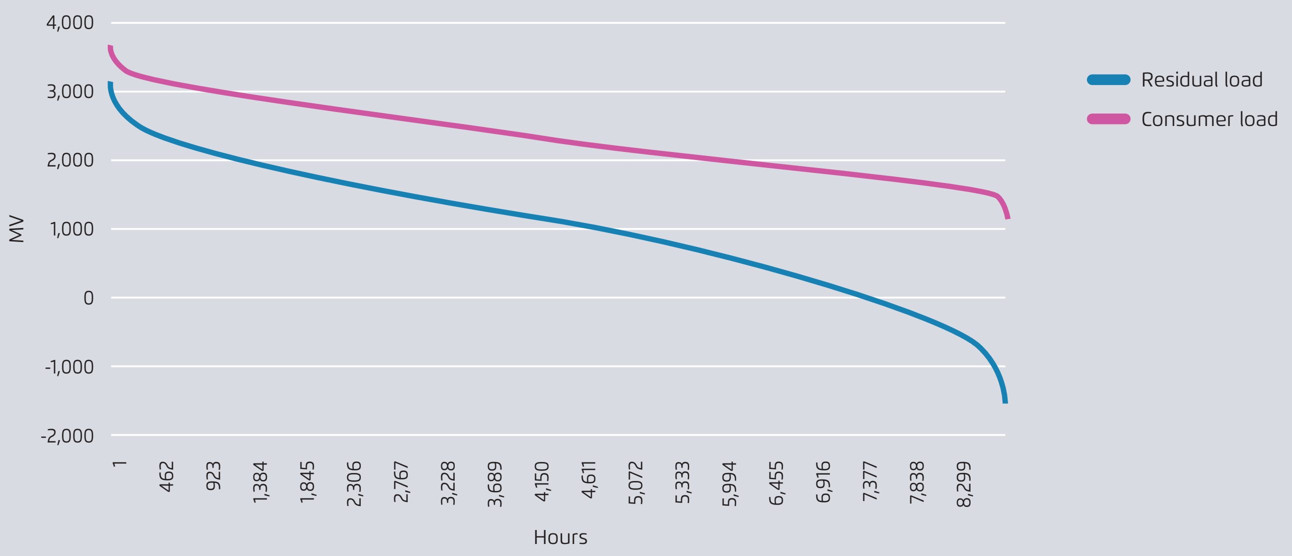
Exchange with neighbouring countries, hydropower as storage for wind

The market-based exchange with Denmark's neighbouring countries is one of the most important means of integrating wind power production. The electricity market ensures that the cheapest generators are prioritised for electricity production. For example, it allows Nordic hydropower stations to function as cheap and effective energy storage for wind power. When electricity prices are low due to high levels of wind power in the system, hydropower stations withhold their production. Alternatively, when electricity prices are high, they increase their production.

The electricity prices are determined via auction through the spot market managed by Nord Pool Spot. Figure 5 shows an overview of the Nord Pool countries participating in the Nord Pool Spot, which covers the Nordic countries (except Iceland) and the three Baltic countries. A price is deter-

Duration curve of consumer load and residual load (= consumer load - wind and solar power generation) in Western Denmark for the year 2014

Figure 4



Own figure based on market data from Energinet.dk mined for all the participating zones as well as for the overall system (average system price). Practically speaking, price differences only occur when there is congestion on transmission lines. In this way, the electricity prices send a clear signal to the transmission system operators (TSOs) and the market actors about where investment in additional transmission capacity is needed.

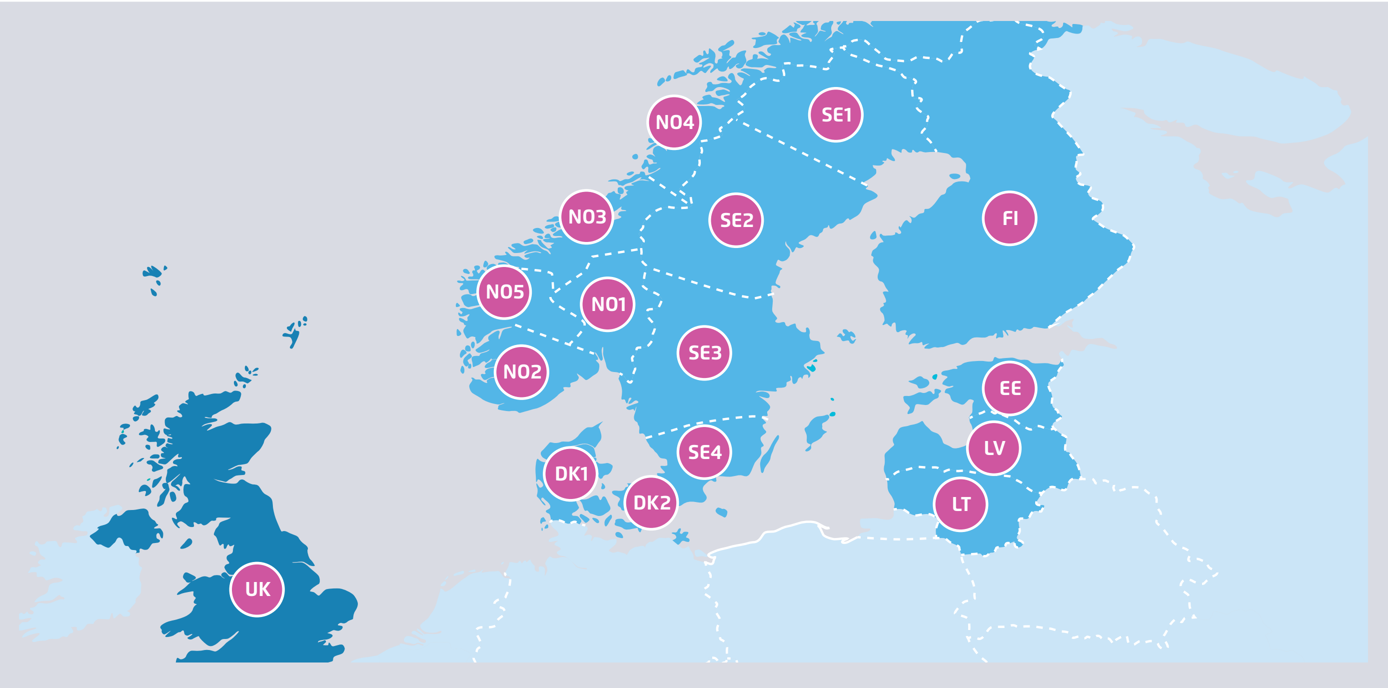
Figure 6 shows the monthly average electricity prices from January 2002 to April 2015 in DK West (Western Denmark) and Germany compared to the average in the Nordic countries. The Nordic electricity prices are highly influenced by the amount of precipitation in Norway (whether it is a dry or wet year), which relates directly to the available hydropower in Norway. A wet year results in lower electricity prices and vice versa. As shown in Figure 6, the price fluctuations can be partly explained by the amount of precipitation, CO_2 and fuel prices, and the development in electricity demand.

In the overall Nordic context, wind power still only represents a limited share of total electricity supply. The storage capacity of the Nordic hydro reservoirs, for example, is approximately 100 TWh, which is over three times more than annual Danish electricity demand. This provides an opportunity for the integration of wind via stored hydropower. However, bottlenecks on the interconnectors between the Nordic countries and internally within Norway and Sweden are still limiting the potential for trading wind and hydro-based electricity between the countries.

During the 2000s the Danish system operator advocated the adoption of an implicit market coupling between Nord Pool and EEX (European Energy Exchange). This was achieved in 2009, and a joint auction for North-Western Europe has been in operation since February 2014[8] (market coupling is discussed further in section 3.3).

8 North-Western European Price Coupling (NWE), http://www.nord-poolspot.com/How-does-itwork/European-Integration/NWE/

Nord Pool countries and their price zones — Figure 5



Nord Pool website

Handling wind power predictability

The predictability of wind power is highly dependent on the time horizon. For the day-ahead market the time horizon is 12 hours for the first hour of the operating day, and 36 hours to the last hour. With this horizon, the mean average percentage error (MAPE) is 19 per cent (according to our calculations, based on 2014 market data from Energinet.dk). However, adjustments to the day-ahead plan can be made, for example via the intra-day market Elbas. This is possible until one hour before the operating hour. With one-hour notice, wind power has a high degree of predictability. The trade volume on Elbas is limited, with typical volumes between 50 and 110 MW (2014 and 2015 data, each Danish price area).

3.3 Utilisation of interconnectors

Due to the uncertainty of wind power production, it has been necessary to have a flexible energy system that is able to cope with deviations in wind power production. Efficient **capacities for transmission to neighbouring countries**, as well as the national transmission of electricity, play an important role as a **flexibility instrument.** Figure 7 shows an instant snapshot of the current power system in Denmark for a day in June, including the interconnections with Norway, Sweden and Germany.

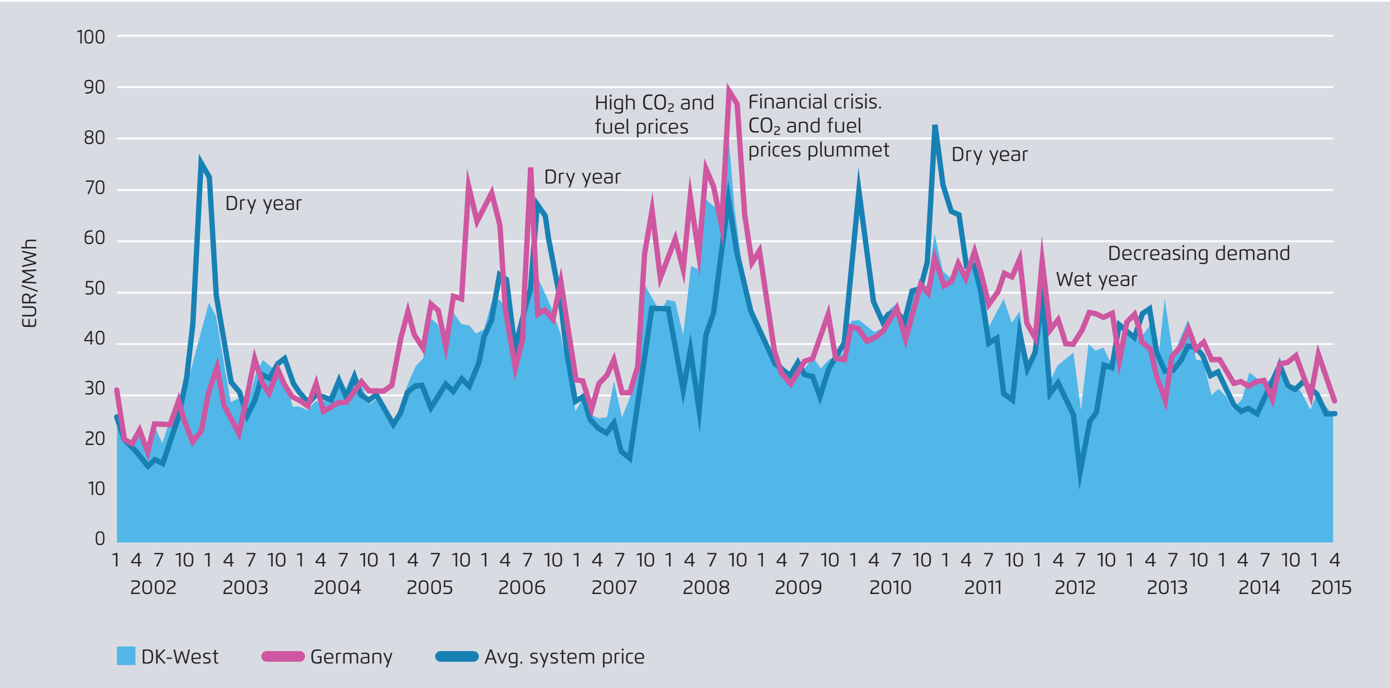
Currently, the total technical export capacity to Norway and Sweden is 4,072 MW and to Germany 2,380 MW. Moreover, Eastern and Western Denmark is connected by a 600 MW DC connection.

Interconnectors are planned to the Netherlands (700 MW by 2019) and to the UK (1,000 – 1,400 MW by 2020). In addition, Energinet.dk and the German TSO TenneT have agreed to upgrade the interconnection between Western Denmark and Germany to 2,500 MW in both directions.

Market coupling

Market coupling has been an important measure to ensure efficient utilisation of interconnectors. Within Nord Pool, Denmark has been coupled implicitly with Norway and Sweden since 1999/2000, whereas an explicit day-

Historic development of electricity prices in Western Denmark, Germany and the overall Nord Pool Spot system — Figure 6



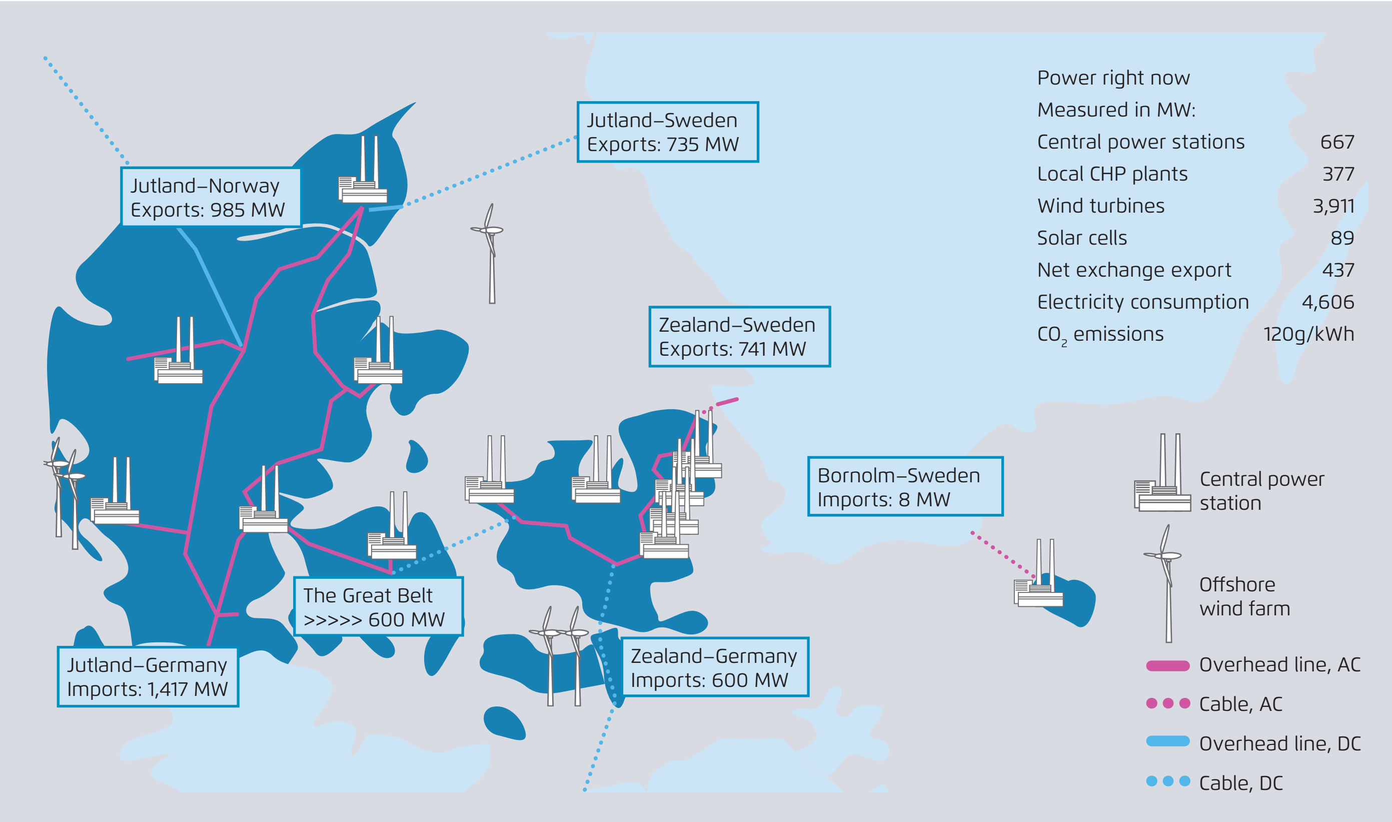
Our figure based on market data from Energinet.dk ahead auction was used for the connections to Germany until 2009. Explicit auctioning means that the transmission capacity on an interconnector is auctioned to the market separately and independently from the marketplaces where electrical energy is auctioned. Because the two commodities – transmission capacity and electrical energy – are traded at two separate auctions, there is a risk that the flow on the interconnectors will go in the opposite direction of what the market prices would suggest.

Comparing market data from 2002 (when there was explicit auctioning on the interconnector between Western Denmark and Germany) to market data from 2014 (when there was implicit market coupling) shows that the interconnection is now used more efficiently (see Figure 8). Most notably, in 2002, there was a very large number of situations where spot prices were higher in Western Denmark than Germany, but still the interconnector was used to export power from Western Denmark to Germany.

A comparison of the level of **wind power generation in Western Denmark** and the **magnitude and direction of power flow on the interconnectors to Norway and Sweden reveals a clear correlation.** When Danish wind power production is high, the interconnectors are predominantly used for export, and vice versa. This was the case in 2002 and it is still the case in 2014. This indicates that Norwegian and Swedish energy systems are used as a form of storage for Danish wind power.

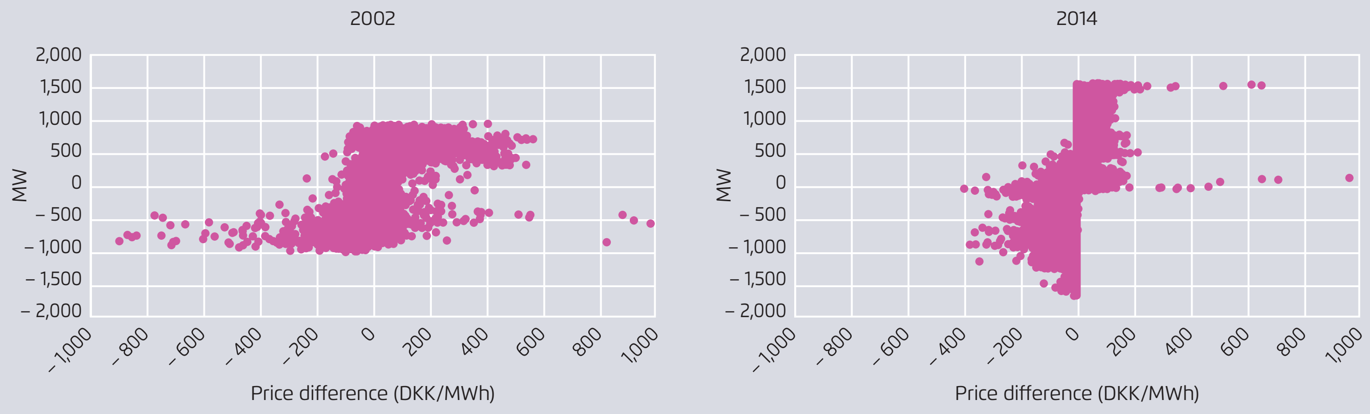
The **interconnector between Western Denmark and Germany** shows a similar pattern for 2002, though not as distinct. **By contrast, in 2014, there is no clear relation.** Particularly notable in the graph for 2014 is the fact that as soon as Danish wind power production exceeds around

Snapshot of the Danish power system on 2 June 2015 at 13:17 Figure 7



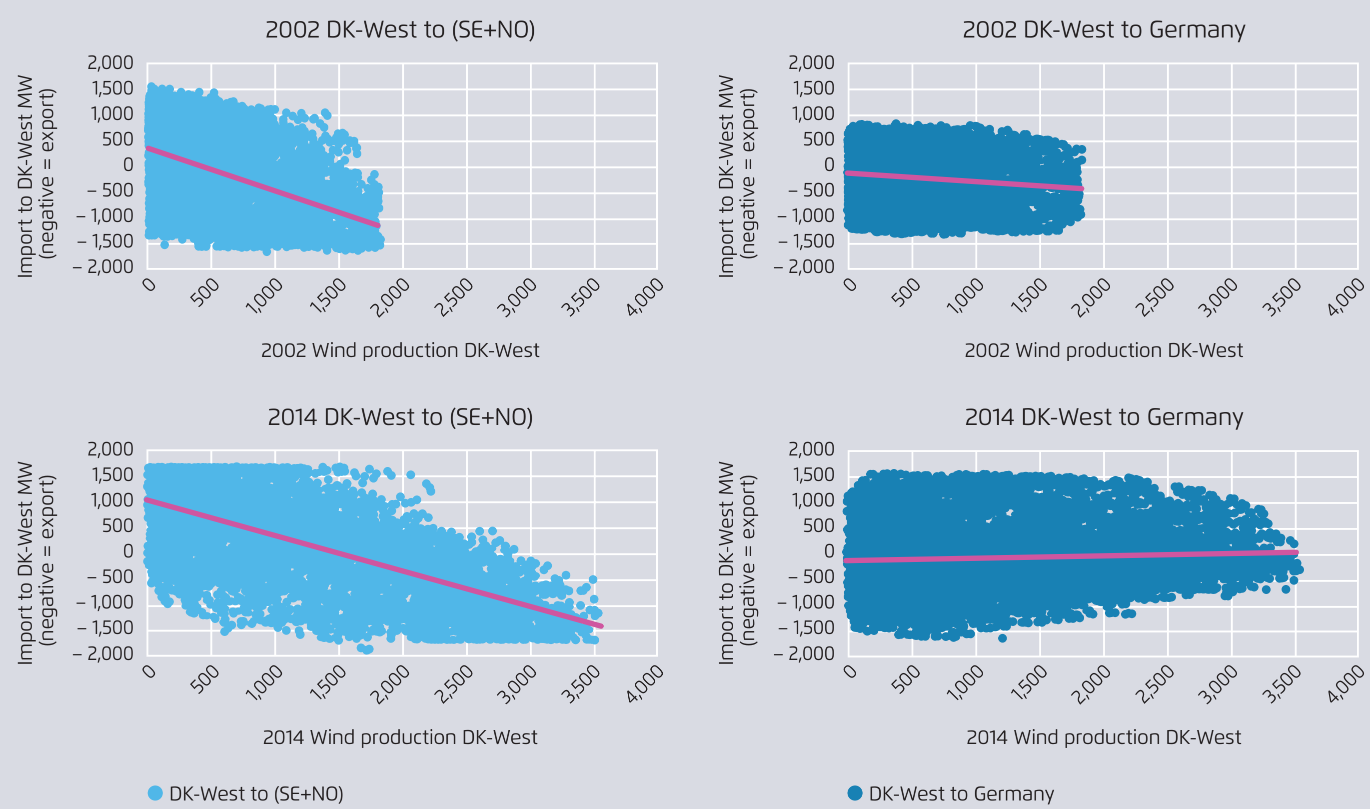
Energinet.dk

Physical flow and price difference on the interconnection between Western Denmark and Germany. Price difference: Price in Western Denmark minus price in Germany. Positive flow: Import to Western Denmark. Negative flow: Export to Germany. It is notable that even in 2014 and with implicit market coupling, there were situations with the flow direction being contrary to the direction incentivised by price differences. This is likely due to subsequent arrangements in the markets for ancillary services. Figure 8



Own elaboration, figure based on data from Energinet.dk

Correlation between wind power generation in Western Denmark and flows to Sweden/Norway and Germany Figure 9



Own elaboration, based on data from Energinet.dk

1,000 MW (less than one third of total capacity in Western Denmark) the full export capacity is not utilised anymore.

The explanation for limited export of electricity from Western Denmark to Germany in high wind situations is based on the fact that the southbound interconnector capacity available to the spot market has decreased gradually over the last six years. Figure 10 shows the historical development of the trade capacity between Western Denmark and Germany (annual average). Until 2008, the available southbound capacity was on average 1,100 – 1,200 MW. Since then, it has declined year by year and reached a low of approximately 300 MW in the first months of 2015. At the same time, the maximum technical capacity has increased from 1,200 MW in 2002 to 1,780 MW in 2015.

The reductions in available capacity are caused by bottlenecks in the internal electricity grid in Germany and are dependent on the level of wind power generation in Northern Germany.[9] These bottlenecks result from the fact that, in Germany, wind power capacity has mainly been established in the north, while the load centres are located in the west and south of the country. A failure to alleviate these bottlenecks in the German grid could have considerable negative implications for the integration of wind power in Denmark.

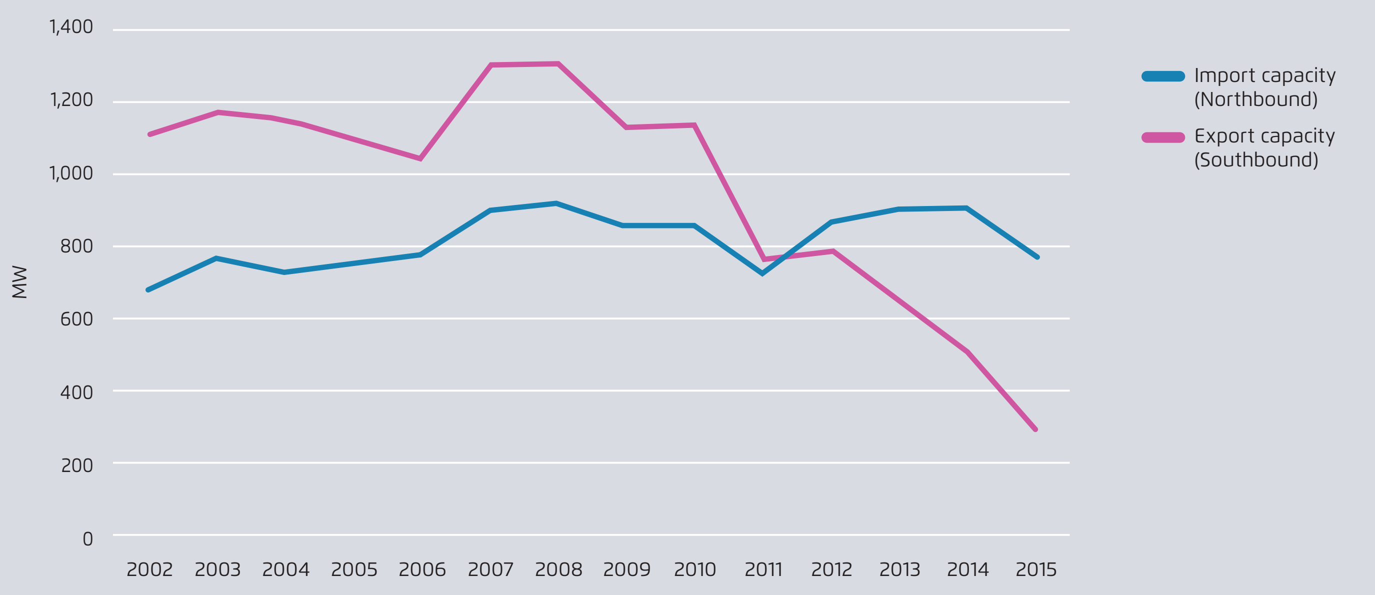
3.4 Integration with the heat sector – reshaping regulation

The fuel supply challenge during the oil crisis of the 1970s was met not only by wind power but also through the development of district heating and combined heat and power technologies. Figure 11 shows that the supply of district

9 TenneT (2012). "Determination of Transfer Capacity at trade relevant CrossBorder Interconnections of TenneT TSO GmbH". http://www.tennet.eu/de/fileadmin/downloads/Kunden/bestimmungenubertragungskapazitat20120924_fin_en.pdf

Market available interconnector capacity between Western Denmark and Germany during 2002–2015
Data for 2015 only covers the period from 1st January to 5th May

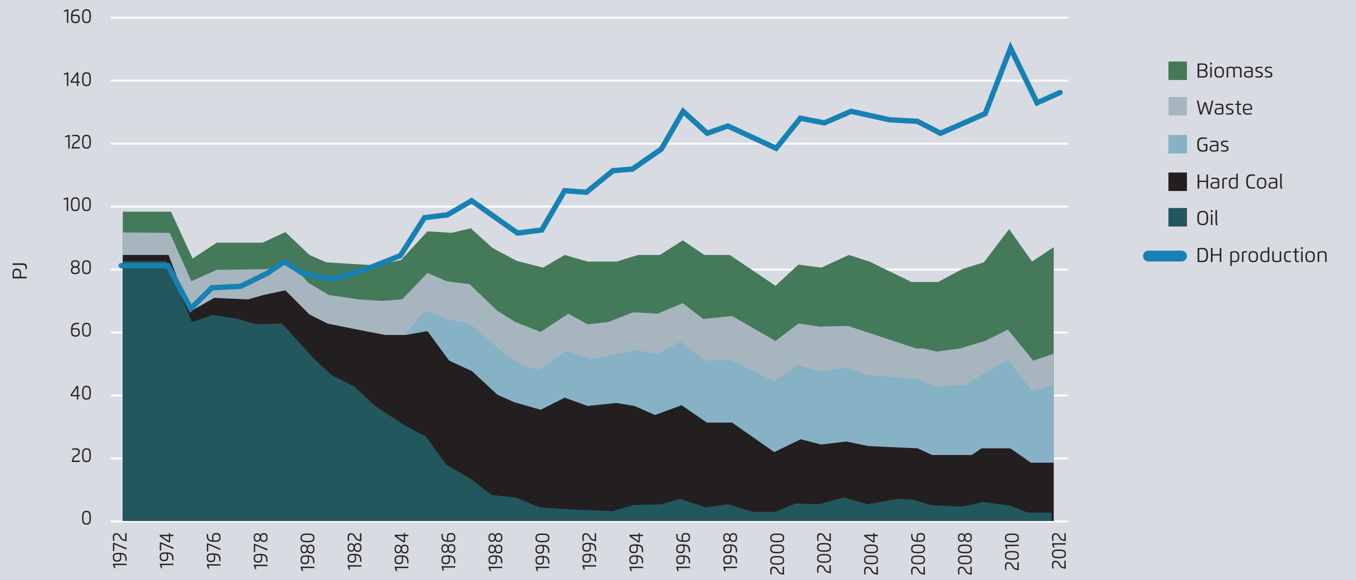
Figure 10



Own elaboration, based on data from Energinet.dk

The supply of district heating increased from 80 PJ (Petajoule) in 1972 to 140 PJ in 2012. Due to the energy efficiency of combined heat and power (CHP) production, fuel consumption decreased from 100 PJ to 80 PJ over the same period.

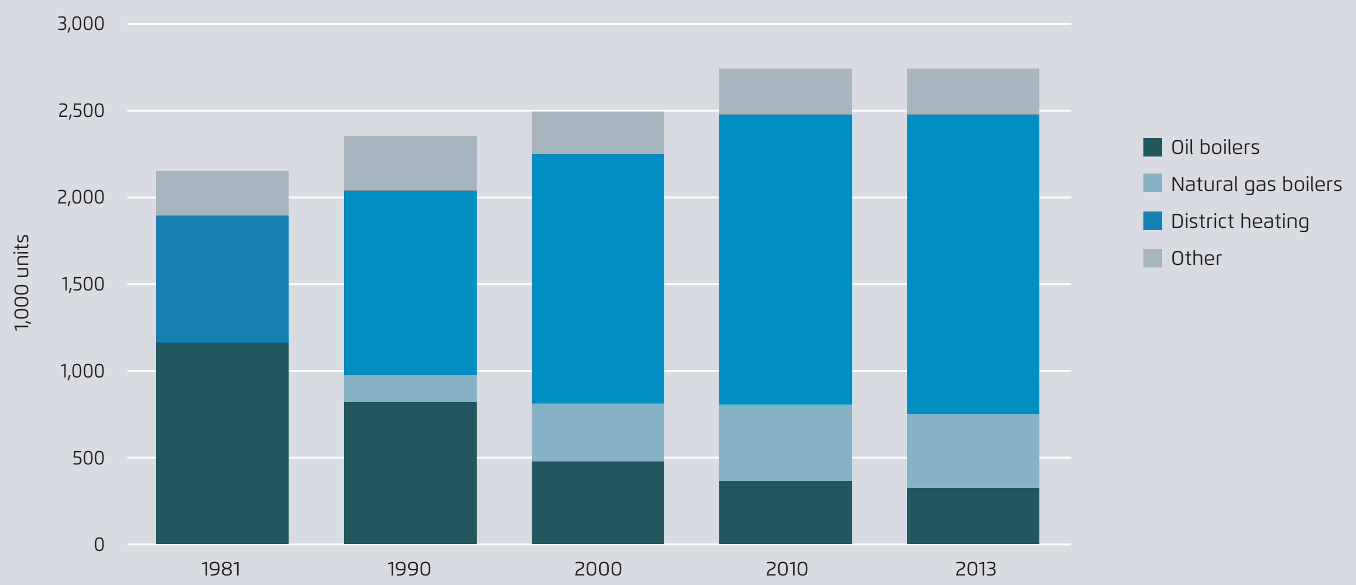
Figure 11



Own elaboration, based on data from the Danish Energy Agency

Heating installations in Danish dwellings (1,000 units). In the 1980s, individual oil boilers were the dominant heat generation technology. Today, more than 62 per cent of all dwellings have a district heating connection.

Figure 12



Danish Energy Agency, "Energy Statistics 2013" heating in Denmark has increased by almost 75 per cent since the 1970s while fuel consumption has been reduced by 15 per cent during the same period. It also shows how the supply, during a period of 10 to 15 years, changed from a one-sided dependency on oil to a multi-layered supply based on coal, natural gas, waste and renewable energy (biomass). Presently, close to 75 percent of the district-heating supply is produced by cogeneration.

CHP support – from feed-in tariffs to spot prices

During the 1990s, the deployment of natural gas fired combined heat and power (CHP) plants was supported through fixed feed-in tariffs that were graduated depending on the time of day (peak, intermediate and base load). The fixed tariffs were important during the built-up phase as they provided a high level of certainty to investors.

With the rising share of wind power in the system it increasingly became a problem that a considerable portion of thermal power generation did not respond to market prices. Regulatory action was taken, and since 2006 all decentralised combined heat and power plants above 5 MW electric capacity have been settling at market prices. As a compensation for the lower prices in the spot market the combined heat and power plants were provided a financial subsidy, independent of their production. Today, the vast majority of decentralised combined heat and power plants are selling their power on the electricity market. This includes a large part of small plants below 1 MW of capacity even though these plants may still choose the fixed feed-in tariff, which is graduated depending on the time of the day.

It should be noted, however, that the subsidy rules for decentralised combined heat and power plants led to considerable debate in the years up to 2006. On the one hand, importance was attached to maintaining the economic viability of the decentralised combined heat and power plants established in the 1990s. There was also a wish to promote combined heat and power generation so as to improve energy efficiency. On the other hand, there is the increasing need for more flexible operation to facilitate the integration of wind power. The latter has gained great importance in recent years with the increased deployment of wind power.

Energy taxation in brief

Since the 1980s, taxation of energy consumption has been a very important tool for reaching environmental objectives and increasing security of supply. Simultaneously, the taxation of energy consumption has served as an instrument for creating tax revenue. The energy tax system in Denmark provides for different levels of taxation for different end users. In general, households and the public sector pay a high tax (on the order of 100 per cent of the energy price); this high tax rate is assessed to all classes of consumers for comfort heating.

To avoid impairing the international competitiveness of electricity producers, the electricity tax is placed on electricity consumption as opposed to fuel used for electricity generation. The taxation of electricity has traditionally been on the order of three times the fuel tax, corresponding to the efficiency of a traditional fossil-fuel-based condensing power plant.

Changes to accommodate wind power

The tax system also includes a **discount on heat generated from combined heat and power plants.** For the purpose of taxation, combined heat and power plants are treated as if heat were produced with an efficiency of 120 per cent. In other words, CHP plants are required to pay heat tax only on the amount of fuel corresponding to the generated heat divided by 1.2.[10] This discount system has been a crucial subsidy for promoting combined heat and power technologies over traditional boilers. However, **in its original form, it posed a challenge to the integration of wind power, because combined heat and power plants had an incentive to continue producing electricity even at very low electricity prices** in order to obtain the above-mentioned tax discount.

Therefore, in 2005, the regulation was changed,[11] and boilers were offered a discount similar to that provided to combined

10 Historically, the large CHP plants had special discount systems fitted to their specific characteristics. Also, a special discount is offered for very efficient CHPs, but this plays a minor role.

11 Elpatronloven, law no. 1417, 21 December 2005.

heat and power plants. However, the rebate was only offered to boilers located in district heating systems with CHP capacity available. Thus, in situations with low electricity prices caused (because of, say, high wind power generation), **district heating companies would be incentivised to shift production from combined heat and power plants to boilers or to "bypass" the steam turbines at the combined heat and power plant** (see section 5.2). When bypassing the turbines, the combined heat and power plant essentially operates as a boiler. The advantage of bypass is that the boilers of a combined heat and power plant are still at operating temperatures, allowing the plant to quickly enter the power market again if required.

Figure 13 shows how heat generation at a large combined heat and power plant can be adjusted as a reaction to changing market prices for power. **At low or negative power prices, the bypass is used exclusively for heat production, and when prices recover, the plant can very quickly go back to cogeneration mode, producing combined heat and power.**

Lower taxes on electricity for heat generation

The taxation scheme has also been changed in order to encourage electricity consumption for heat generation when electricity prices are low. In 2005, the tax on electricity consumption by electric boilers, which was traditionally very high, was reduced to the same level as for fuel-fired boilers. Furthermore, in 2013 the general tax on electricity for comfort heating was reduced significantly in order to stimulate investment in heat pumps for district heating generation and in dwellings to replace oil and natural gas fired boilers.

In spite of the reduced electricity taxes, electric boilers and heat pumps still play a limited role in district heating in Denmark. Today, there is just above 400 MW of electric boiler capacity in the district heating systems. According to the Danish transmission system operator Energinet.dk, this figure is only expected to increase to approx. 520 MW by 2020. **To date, the market for ancillary services has been the main driver of electric boiler deployment.**

Stylised illustration of heat generation at a large Danish power plant in relation to the power price — Figure 13

Own illustration, based on experience with the Copenhagen district heating system

Power to heat – benefits and challenges

Traditionally, legislation and taxation in Denmark has aimed at reducing the use of direct electric heating. In 1988, the installation of direct electric heating in new buildings was prohibited. In 1994 the ban was extended to include a prohibition against installing electrical heating in existing buildings with waterborne heating systems. Similarly, the tax on electricity used by households used to be approximately three times as high as on natural gas and oil.

The justification for these measures was to improve energy efficiency. Coal fired power plants – once the dominant source of electrical generation in Denmark – have electric efficiencies of 35 to 45 per cent. Thus, the replacement of direct electric heating with natural gas fired boilers or district heating has brought about significant savings in primary energy use. With the increasing expansion of wind power as well as the establishment of the long-term objective of phasing out fossil fuels in all sectors, including heating, the perception of electric heating has changed somewhat. Here, we would like to consider two technologies for electric heating: direct electric heating (including electric boilers for district heating) and electric driven heat pumps with electricity to heat efficiencies of 300 to 400 per cent.

Due to their high efficiency, heat pumps are now considered a very important element of the future heating supply in Denmark, both for individual heating and for the supply of district heating. Electric boilers, by contrast, are expected to play a role as a supplemental source of heat in district heating schemes. There is a significant difference in the cost of establishing heat pumps compared to electric boilers. Whereas heat pumps installed in a district heating system cost on the order of 0.7 million euros per MW of heat capacity, the cost of electric boilers is only approximately 0.15 million euros per MW. Therefore, both technologies may have a role to play in a renewable energy based energy system. Heat pumps need a high number of operation hours – providing base load or intermediate load – to be economically viable. Electric boilers, on the other hand, offer cheap capacity and may be profitable with less than 500 full load hours of operation. Hence, electric boilers can play a role in "shaving" wind peaks as well as providing regulating power, but their energy contribution (in terms of MWh) is expected to be relatively small.

Direct electric heating only supplies a very small part of the demand for building heat today and its share is not expected to increase in the future.

According to scenario analyses by the Danish Energy Agency (2014b) and the Danish Commission on Climate Change Policy (2010) electric heat pumps are expected to play a key role in the future supply of district heating. Using heat sources like seawater, industrial waste heat and sewage water, electric heat pumps are able to produce heat with high efficiency (at around 300 per cent). However, the application of large heat pumps is currently very limited, as only four plants were in operation at the end of 2014. As mentioned above, electricity taxes have been reduced considerably, but **electric heat pumps are in competition with biomass boilers – which are not subject to energy taxes – as well as with biomass-based CHP plants, which receive a feed-in premium. Under the current regulatory regime, heat pumps are therefore not competitive with biomass technologies.**

Across the country, district heating companies are currently investing in biomass boilers[12] or converting large power plants from coal or natural gas to biomass. Since biomass – particularly locally sourced biomass – is likely to become a scarce resource in a low carbon future, some researchers are questioning this conversion strategy. The climate footprint of wood pellets and wood chips is an additional issue of relevance.[13]

12 If they are allowed to do so. In a large number of heating districts there is a requirement imposed by the Danish state, that biomass base load district heating should be supplied from combined heat and power plants. Therefore, in these heat districts investments in biomass boilers for the generation of base load heat are not allowed.

13 Ingeniøren, 8 maj 2015. Biomasse blokerer for klogt elforbrug http://ing.dk/artikel/biomasse-blokerer-klogt-elforbrug-175935 Concito (Green Think Tank). 28 October 2013. Bæredygtig biomasse er en begrænset ressource. http://concito.dk/nyheder/baeredygtig-biomasse-begraenset-ressource

From a wind power integration point of view, the current development also poses changes:

- From a short-term perspective, feed-in premiums to biomass CHP plants encourage them to stay in the market at relatively low electricity prices.
- From a long-term perspective, electric heat pumps are envisioned to help accommodate the growing deployment of wind power.

In the broad energy agreement that was ratified by the Danish parliament in 2012 – which established, among other things, the target of 50 per cent wind power by 2020 – the government decided to analyse options for a revised energy taxation and subsidy scheme that would facilitate a green, cost-efficient and flexible electricity system. However, this analysis has been delayed and an improved scheme has not yet been proposed.

One of the solutions that have been discussed by stakeholders is to reduce both electricity taxes and subsidies to renewable energy generators when electricity market prices are low.[14]

14 A new regulation regime based on this approach was presented in the report "Forslag til ny struktur for CO_2- og energiafgifter i Danmark - med fokus på fjernvarme" (Ea Energy Analyses, 2011).

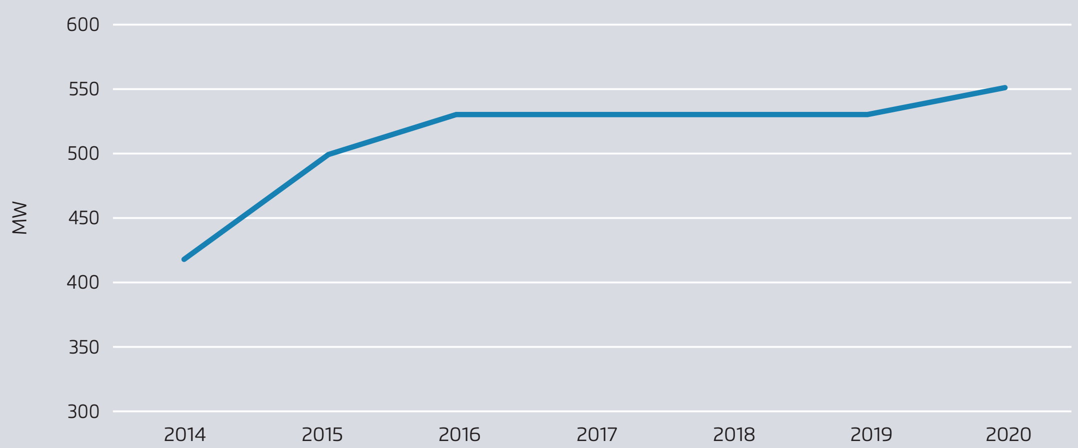
3.5 Flexible power plants

The high share of wind power that has been developed in Denmark over the last 25 years has provided an **early incentive for increasing the flexibility of thermal power plants.** From the power plants' perspective, the high fluctuation of residual load resulting from a high share of variable wind power generation leads to steep load gradients. Furthermore, it requires fast start-ups at low costs and as low minimum stable generation as possible.

Motivation and prerequisites for increasing the flexibility of thermal power plants

Figure 15 illustrates the challenges faced by thermal power plants as a result of increased residual load fluctuations. When there is a renewable power shortage (i.e. when load exceeds renewable electricity generation), there is an increasing demand for steep positive ramp rates at running plants as well as a need for fast start-ups at hot, warm and cold thermal plants. Conversely, steep negative ramp rates at running power plants and the lowest minimum stable generation possible are required when there is a renewable power surplus. Between these two extremes, rapid fluctuations in residual load require large positive/negative ramp rates.

Installed capacity of electric boilers (MW_{el}); Statistics and future expectations from Energinet.dk, Danish TSO — Figure 14



Own figure based on data from Energinet.dk

Consequently, **Danish coal power plants that were originally designed as base load units have been transformed into some of the most flexible power plants in Europe.** Already today, load gradients equal to a four percent change in nominal power capacity (% P_N/min) for coal-fired units are considered standard in Denmark. In other words, a coal fired power plant with a nominal installed capacity of 500 MW is able to change its output by 20 MW up or down per minute. For gas-fired power plants this figure is 9 % P_N/min. The minimum load could be decreased down to 10 % P_N (i.e. to 50 MW for a power plant with a nominal capacity of 500 MW) and a fast start is possible within less than one hour.

According to industry experts (involved engineers),[15] a number of prerequisites need to be fulfilled for the projected flexibilisation to take place. These include precise knowledge of existing technical limits combined with a willingness to approach and exceed these limits during the implementation phase; adaptation to local conditions; as well as full acceptance throughout the power company. For the technical implementation of flexibility measures, access to detailed power plant operational data with a high time resolution is required for all involved engineers.

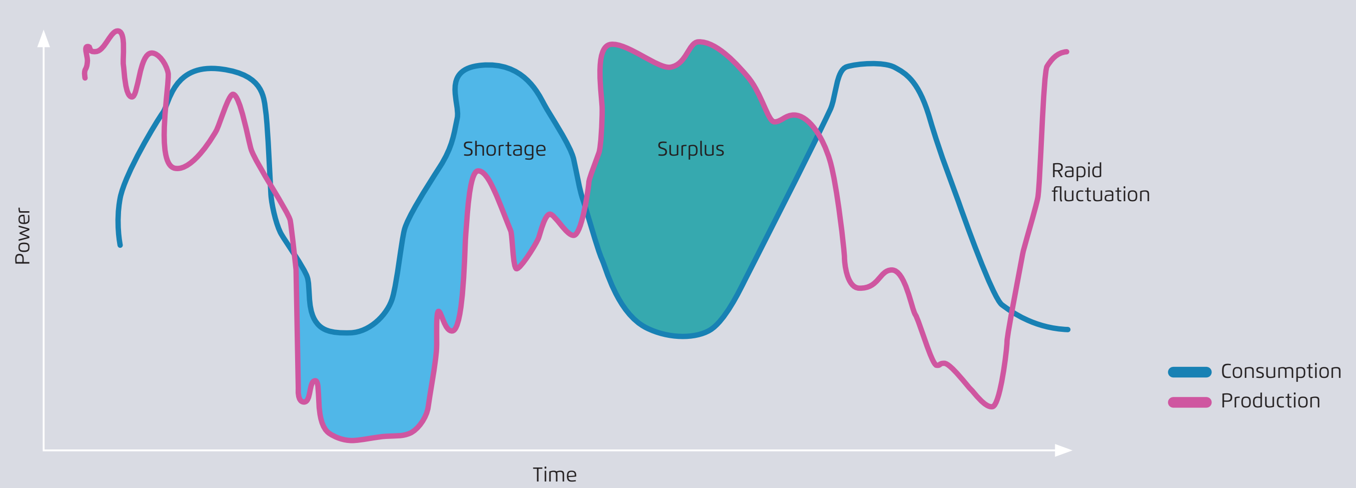
15 The content of this section is based primarily on a presentation by Rudolph Blum, former R&D director for power plant development at ELSAM/DONG Energy and Torkild Christensen, former engineer for design, optimisation and flexibilisation of thermal power plants at ELSAM/DONG Energy (cf. Blum, R., Christensen, T. (2013)).

The Danish experience furnishes a number of best-practice examples that should be considered in efforts to make power systems in other countries more flexible. The organisational integration of the optimisation procedure is illustrated in Figure 16.

As a first step, long-term scenario studies (for the next 10–20 years) are required in order to assess the expectable magnitude of increasing load fluctuations. Next, the economic value of all available flexibility measures has to be estimated and ranked in order to determine which measures should be prioritised. The power plant portfolio can then be optimised using a top-down approach in conjunction with the deployment of custom operational management software. Finally, the individual optimisation of each power plant can be conducted in an iterative, stepwise approach. In this connection, one must first determine flexibilisation bottlenecks by analysing data and interviewing plant personnel. Only then can achievable flexibility levels be defined. The procedure just described can be applied to the

The flexibility challenge for thermal power plants as a result of fluctuating consumption and variable renewable electricity (VRES-E) production

Figure 15



Blum, R., Christensen, T. (2013)

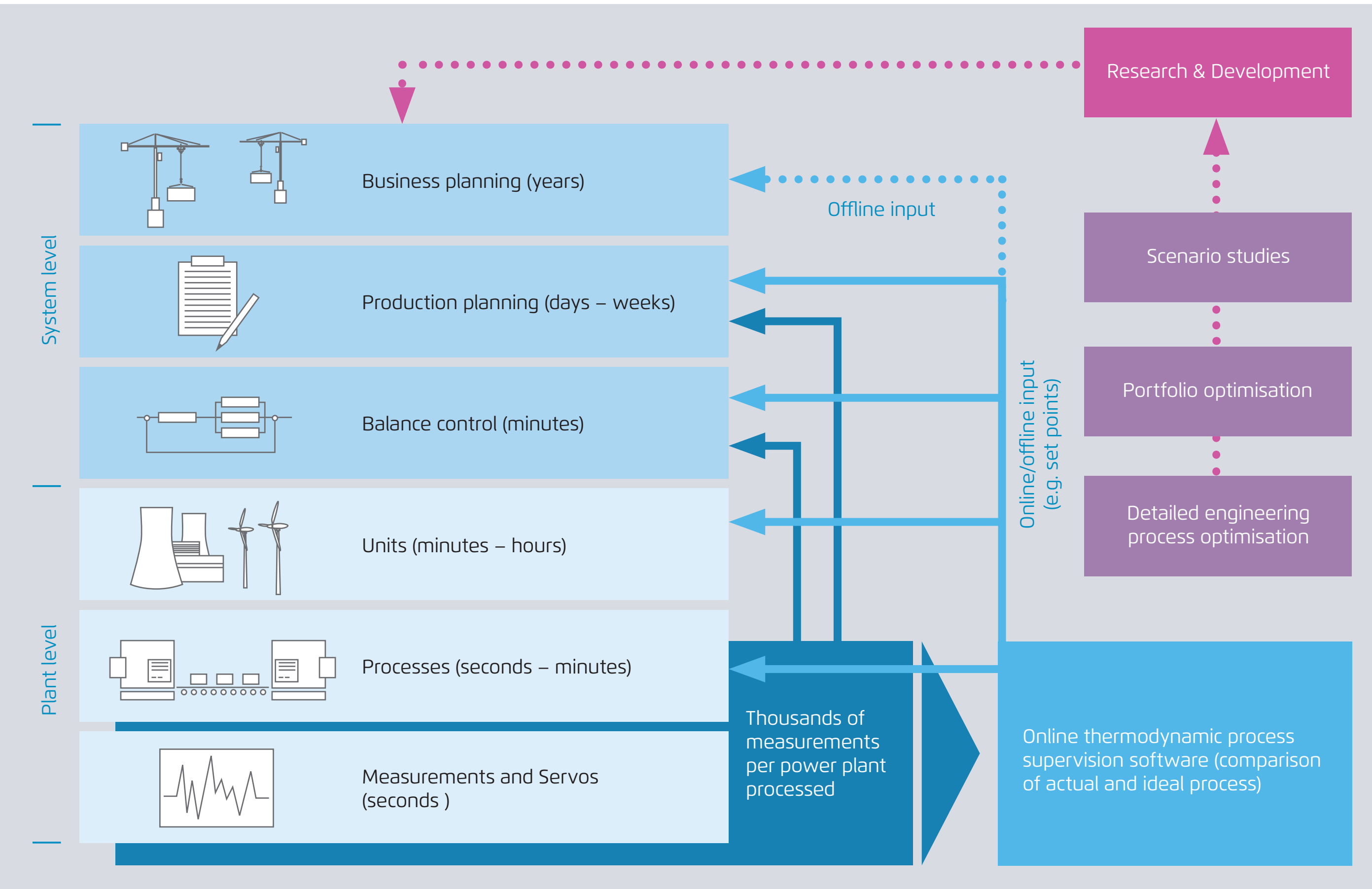
effort to increase ramp rates as well as decrease minimum loads, start-up times and start-up costs.

Table 4 provides an overview of the flexibility parameters of Danish and German power plants based on different sources (Blum, R., Christensen, T. (2013), Feldmüller, A. (2013)). The generally higher flexibility of gas-fired power plants in comparison to coal-fired power plants is clearly visible. Open cycle gas turbines (OCGT) and gas-fired steam turbines (ST) are superior to combined-cycle gas turbines (CCGT) in terms of flexibility. However, the overall efficiency of CCGT power plants is higher, which is not reflected in the table. On average, Danish power plants are more flexible than their German counterparts in all of the considered categories.

The load gradients that existing Danish coal power plants already achieve (3-4 % P_N/min) is labelled in the table as a possible state of the art for German technology. The average German coal power plant has a much lower load gradient of just 1.5 % P_N/min. The minimum stable generation of Danish power plants at 10-20 % P_N is even smaller than or equal to the optimisation potential stated for the German plants (20 % P_N). German coal power plants still operate with minimum generation of 40 % P_N on average.

Danish natural-gas-fired steam power plants achieve load gradients of up to 10 % P_N. The evaluated sources do not provide German data for gas-fired steam power plants that would allow for a direct comparison. But the available data reveal that Danish gas-fired steam power plants already exceed German open cycle gas turbines, which are often

Optimisation of power plant flexibility at different organisational levels | Figure 16



Blum, R., Christensen, T. (2013)

quoted as the most flexible power plant technology in Germany.

The load gradients of Danish CCGT power plants are slightly higher than that of their German counterparts, while minimum generation is comparable. For power plants based on gas turbines (OCGT as well as CCGT), the minimum generation achievable through optimisation is limited by threshold values for the maximum permissible emission of nitrous oxides and carbon monoxide. Natural gas fired steam turbines are not subject to this limitation, because of a different combustion process.

According to Feldmüller (2013), thermal power plants in Germany are not utilising their full technical flexibility potential. Feldmüller cites a lack of incentives as the reason for this failure to maximise flexibility. For example, the required load gradients for primary balancing power in Germany are at 2 %P_N/30 sec, as compared to a stricter 10 %P_N/10sec in the United Kingdom (as of 2013). **This lack of regulatory incentive is accompanied by a lack of financial incentives to invest in more flexible solutions.**

3.6 Encouraging system-friendly wind power

The Danish wind power support scheme has undergone changes in recent years. One driver of change has been the goal of promoting the deployment of system-friendly wind turbine design.

Historically, wind power has been supported through investment grants and net metering schemes. During the last 30 years, onshore wind power has been subsidised. Initially, fixed feed-in tariffs were offered. Later, a market premium was introduced that was added on top of the wholesale market price.

2008–2013 scheme rewarded turbines with high capacity

According to the support scheme introduced by the renewable energy law as of 2008 – provisions that were altered in 2014 – all new onshore wind power projects[16] received

16 As well as so-called "open door" offshore projects, i.e. offshore projects not put out for tender.

Typical prevailing and possible flexibility parameters for thermal power plants in Denmark (DK) and Germany (DE) Table 4

Fuel and plant type	Country	Status	Positive load gradients (%PN/min)	Min. stable generation (%PN)	Source
Coal ST	DK	prevailing	3–4	10–20	a
	DE	prevailing	2–3	45–55	a
	DE	prevailing	1.5	40	b
	DE	state of the art	4	25	b
	DE	optimisation	6	20	b
Nat. gas ST	DK	prevailing	8–10	<20	a
Nat. gas OCGT	DE	prevailing	8	50	b
	DE	state of the art	12	40	b
	DE	optimisation	15	20*	b
Nat. gas CCGT	DK	prevailing	3	50–52	a
	DE	prevailing	2	50	b
	DE	state of the art	4	40	b
	DE	optimisation	8	30*	b

prevailing = average of current status; state of the art = possible today; optimisation = projected future potential. ST = steam turbine, OCGT = open cycle gas turbine, CCGT = combined cycle gas turbine.
*The lower minimum generation limit for gas turbines is constrained by emission threshold values for nitrous oxide and carbon monoxide.

a) Blum, R., Christensen, T. (2013) (values refer to 2011); b) Feldmüller, A. (2013)

a nominal **feed-in premium (FIP)** of 0.25 DKK/kWh (0.034 €/kWh) **on top of the spot market price for the first 22,000 full-load hours**.[17] After the equivalent of 22,000 full-load hours was generated, the wind farm had to source its revenue solely from the electricity wholesale market price (Danish Energy Agency, 2015).

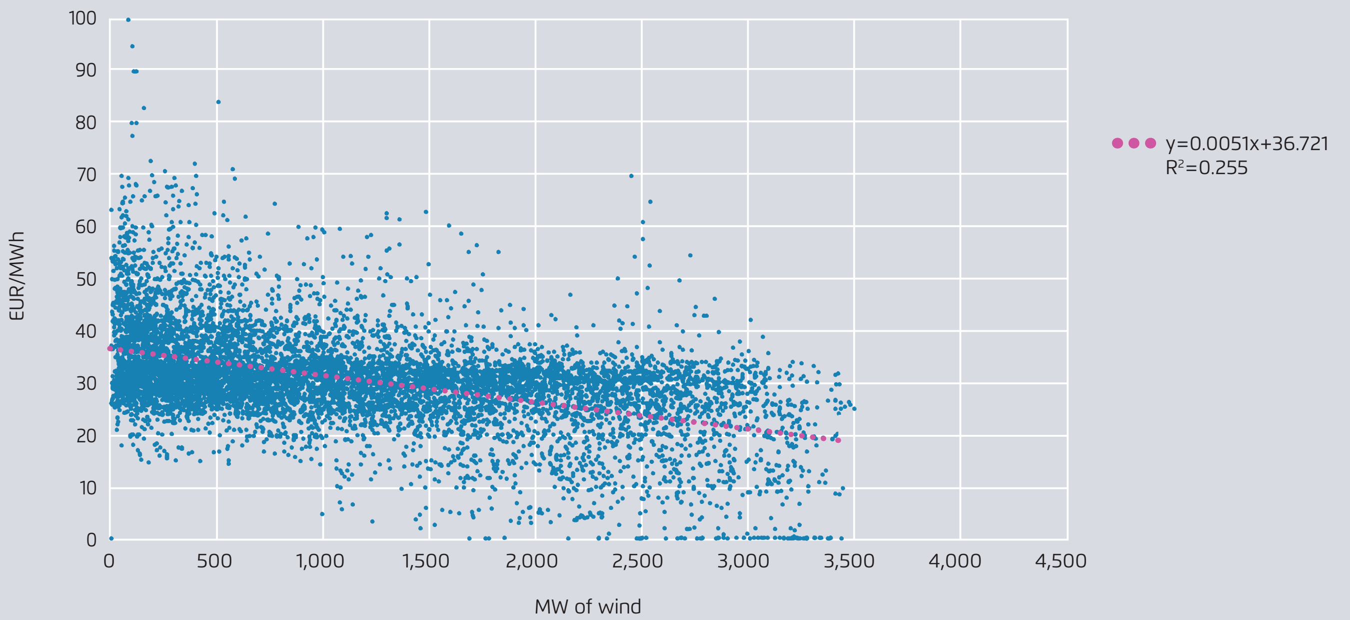
For example, a 2 MW wind turbine received the feed-in premium for 44,000 MWh of generated power, whereas a 3 MW wind turbine obtained the premium for 66,000 MWh of generation.

The system provided incentives for developers to install turbines with a high rated capacity in order to maximise support. The very high average capacity rating of wind turbines installed in Denmark (e.g. averaging 3 MW in 2012) can be attributed to a certain extent to the onshore wind power support scheme that was in effect until the end of 2013.

The support system involved three potential drawbacks. First of all, it contained a risk that the wind turbines were not designed in the most cost-efficient manner. Secondly, there was the risk that subsidies were set too high. Thirdly, and perhaps most importantly, the support scheme worked in favour of wind turbines that were less attractive from a system perspective. A wind turbine may have the same hub height and rotor diameter but different generator sizes (e.g. 2 MW or 3 MW). Whereas the 2 MW turbine will reach its peak generation at wind speeds of around 10 m/s, the 3 MW turbine will reach maximum generation at approx. 12 m/s. From a system perspective, however, the value of the additional generation of the 3 MW turbines is likely to be more limited because the generation takes place at times when wind power generation is already high and market prices in general are lowest (see Figure 17).

17 Also, a subsidy of 0.0237DKK/kWh (0.0032€/kWh) was awarded for the technical lifetime of the wind power project to cover balancing costs (Energinet.dk, 2015).

Correlation between wind power production in Western Denmark and the market price of electricity in euro per MW; Data from 2014. Slope: –0.005 (i.e. –5 € per 1,000 MW of wind); Coefficient of determination: 0.21) Figure 17



Own figure based on market data from Energinet.dk

As of 2014, the legislation was changed to cope with the above-mentioned challenges. **The power production eligible for the feed-in premium is now dependent on both the turbine generator size and the rotor size**, and it is calculated using the following formula:

Power production eligible for FIP=
30 % × Turbine rated power (MW) × 22,000 Full load hours +
70 % × 8,000 kWh/m^2 × Rotor swept area (m^2) =
= Turbine rated power (MW) × 6,600 Full load hours +
Rotor swept area (m^2) × 5.6 MWh/m^2

The technological choice of turbines is driven by a number of factors, e.g. land availability, regulations, site conditions etc., yet, ceteris paribus, the support regime reform in Denmark in 2014 provides less incentive for installing turbines with high capacity ratings alone, whilst rewarding turbines with higher yield (lower specific power).

The deployment of offshore wind power has mainly taken place through tenders of large-scale projects in the order of 200 to 400 MW. The applicants' competition is based on who can accept the lowest fixed feed-in tariffs. In the most recent tenders, developers are not offered the feed-in tariff when electricity market prices are negative.

3.7 Procurement of ancillary services

Balancing the electricity system

Transmission system operators sign balancing agreements with Balance Responsible Parties (BRP) in order to maintain system balance. Each consumption and production point and connection point for interconnectors need to have a balance responsible party. Producers, traders and suppliers need to either be a BRP themselves or have a contract with a BRP.

The BRPs have to supply plans to the TSO concerning their planned production and trade, which balances their consumption – hour by hour. The balance is first established on the day before operation as a combination of the day-ahead market (Nord Pool Spot) and bilateral trade.

Gate closure of the day-ahead market Elspot is at 12:00 CET (Central European Time) prior to the day of delivery. The trade participants can alter their plans via intra-day trade (Nord Pool Elbas or bilateral trade) until one hour before the operation hour.

From one hour before the hour of operation the transmission system operator (TSO) has the responsibility of maintaining the balance in the system and protecting the system from any overload caused by unpredicted incidences.

Since 2002 there has been a common Nordic market for regulating power managed by the TSOs with a common merit order bidding list. The balance responsible parties (for load or production) make bids consisting of an amount (MW) and price (DKK/MWh). All bids for delivering regulating power are collected in the common Nordic NOIS list (Nordic Operational Information System - NOIS), and are sorted in a list with increasing prices for up-regulation (above spot price), and decreasing prices for down-regulation (below spot price). These bids can be submitted, adjusted, or removed until 45 minutes before the operation hour. If transmission capacity is available, the lowest bid can be activated.

The majority of the bids in the market are voluntary, i.e. without payment for availability. Because it is a common market, an up-regulation bid from Sweden may be applied for up-regulation in Denmark.

Cost of balancing wind power

The Danish system operator (TSO) Energinet.dk is the balance responsible party for many older turbines, while commercial actors handle most new wind turbines. The costs for balancing wind power vary depending on the wind conditions and the price of balancing power, and can also vary between the balance responsible parties. The average cost of balancing wind power is rather modest – about two EUR per MWh produced by wind turbines in 2013. This is in line with previous years. As of 2018, commercial players will also take over balance responsibility for the older wind turbines.[18]

Types of ancillary services

Ancillary services cover several services, including:

- Energy
  - Primary reserves: Fast reacting, automatic, frequency controlled reserves (time scale 5-30 sec). The reserve is activated when the system-wide frequency deviates from the normal by 50 Hz.
  - Secondary reserves: Automatic reserve, activated based on deviation in the planned exchange between price zones. This reserve is used to relieve the primary reserves. This is done in the zone where the unbalance is introduced.
  - Regulating power: Manual reserve, activated with a notice of 15 min. It is used to relieve the primary and secondary reserves.
- Other types
  - Inertia
  - Voltage control
  - Black start

Many of the ancillary services may be provided from neighbouring countries' electricity systems depending on the available transmission capacity. There are, however, some services, such as secondary reserves and voltage control, that must be delivered locally.

According to Energinet.dk, the **Danish priority** is on regulating power **(manual reserves)**, while the German priority is on automatic reserves.[19]

18 News from Energinet.dk, 13 May 2015: "Energinet.dk udliciterer balanceansvar for vindmøller og små kraftvarmeværker" http://energinet.dk/DA/El/Nyheder/Sider/Energinet-dk-udliciterer-balanceansvar-for-vindmoller-og-smaa-kraftvarmevaerker.aspx

19 The German operating philosophy, with its emphasis on automatic reserves, differs from Energinet.dk's operating philosophy, which places the emphasis on manual regulating power. Consequently, compared with Energinet.dk, the German TSOs purchase many automatic reserves and few manual reserves relatively speaking (Energinet.dk, 2011, page 27).

Secondary reserves

Secondary reserves are an automated reserve (such as the primary reserves) that can be activated very quickly (e.g. within 30 seconds). Typically, this reserve is delivered by power plants running below their full capacity.

In 2015, Energinet.dk entered a five-year agreement with the Norwegian TSO, Statnett, for the delivery of +/-100 MW secondary reserves. This is delivered over the new DC line from Norway to Denmark.

In the Nordic synchronous system (Finland, Norway, Sweden and Eastern Denmark) secondary reserves have traditionally not been used. However, due to numerous situations in which the system frequency deviated from the normal interval (50 Hz +/- 0.1 Hz), secondary reserves are now being introduced.

Research projects – participation of demand side

Electricity demand can also **deliver frequency-controlled reserves.** Together with the Center for Electric Power and Energy (DTU Electrical Engineering), Ea Energy Analyses has carried out a research project on the potential for using frequency-controlled demand as a reserve in the electricity system (Xu, Z., J. Østergaard, M. Togeby, 2011). Electricity consuming devices that are controlled by thermostats, such as refrigerators, freezers, electric heating and heat pumps, can be operated so that their set points[20] are adjusted dynamically to the grid frequency. In the case of a cooling device (a refrigerator or freezer), the set points can be slightly increased if the frequency decreases. This will, in effect, turn off the devices that are close to achieving their set points, and allow them to start up again as soon as the grid frequency returns to normal conditions. The impact on comfort is minimal, and, with a large number of units controlled, a smooth proportional regulation can be obtained. ENTSO-E (2015) has recommended making such a system standard in the long term. In this connection, ENTSO-E has

20 For example the two set points of a refrigerator indicate the temperature where the compressor starts and stops. The temperature in the refrigerator will vary between these values. By changing the set point according to the system frequency, the aggregated demand of many appliances can act as primary reserves.

recommended the development of norms under the EcoDesign framework, so that all future thermostat-controlled devices implement this functionality.

Regulating power

Traditionally, regulating power has been delivered by centralised power plants. Today, smaller CHP units and electric boilers deliver a significant share of regulating power. The market setup for regulating power changed in 2006/7, when a two-step market was introduced. First, there is a **market for supplying the capacity** (conducted in the morning before the operating day) followed by a market for the activation. Suppliers can participate in the **activation market** with or without the reservation payment. In the initial years following this new market setup, the capacity payment was attractive, but competition has resulted in decreasing prices. In Eastern Denmark, a significant share of the capacity is still acquired through long-term contracts.

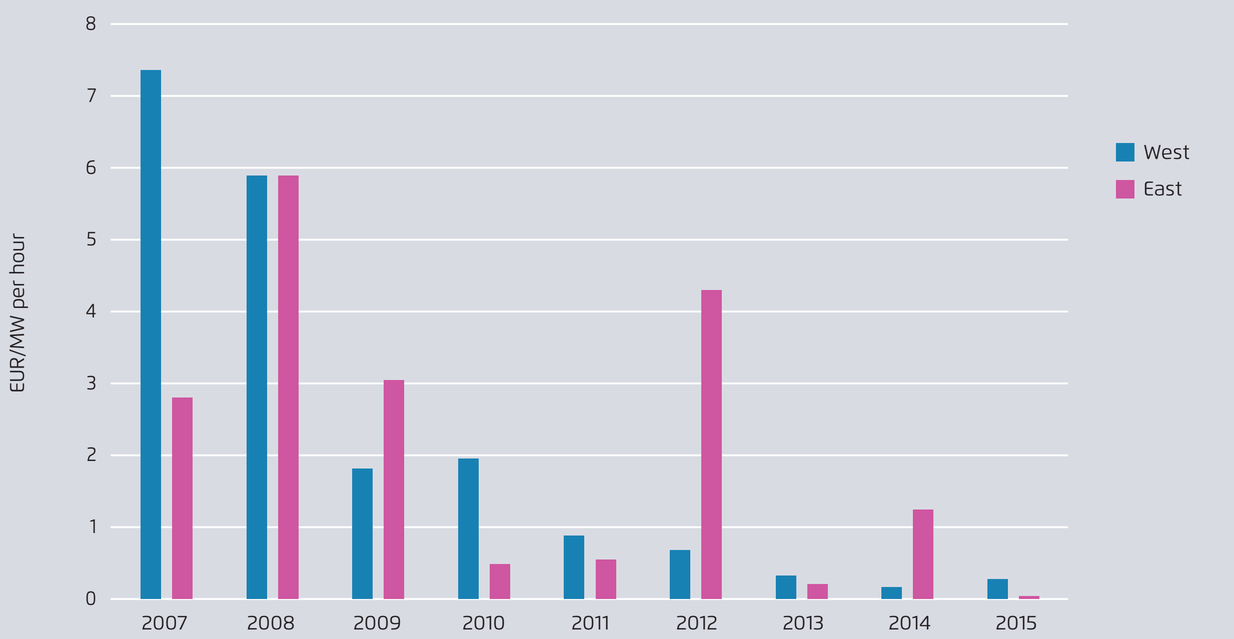
Small CHP plants and electric boilers are aggregated in blocks of 10 MW and activated as one unit. In the period from 2007 to 2009, several new units were installed only to participate in this market. Also, back-up generation (for example, at hospitals) can be used as regulating power.

Strategy for regulating power

Energinet.dk's strategy for developing the market for regulating power is based on four principles (Energinet.dk, 2011):

- → **International markets for regulating power** both increase the opportunities for suppliers and guarantee Energinet.dk an increased amount of regulating resources.
- → **More flexible product definitions** (e.g. longer notice) ensure that more resources can be exploited to balance the power system.
- → **No separate reserves for balancing wind power.** In concrete terms this means that Energinet.dk will not purchase more manual reserves as a result of the wind power expansion.
- → **Manual reserves will be shared over larger areas** – both nationally across the two price areas and internationally – thus reducing the total amount of reserves in the system.

Reservation price for upward regulation power; Average price for East and West Denmark — Figure 18



Own figure based on data from Energinet.dk

Research projects – using demand for regulating power

Several research projects have explored the **possibility of using electricity demand as regulating power.** In the Flex-Power project (Ea Energy Analyses et al., 2013), a proposal for an alternative market for regulating power was developed. A special focus was placed on making it attractive for the demand side to participate. In this context, it is of utmost importance that delivering regulating power is easy for the end user. A key feature of the proposed market design is that the end user should receive a price signal every five minutes. This would be the final settlement price for electricity and the end user can use any amount of electricity. When this system is applied to a large number of users (many with automated control systems) the desired up or down regulation can be realised. The individual end users are motivated to react to price signals; however, they are not obligated to do so. It is the task of the balance responsible party (or aggregator) to predict the amount of activated regulating power. This requires historical data and many participants, meaning that statistical methods can be used. The proposed system can be used for households as well as small and medium sized industrial end users.

The READY project (NEAS Energy et al. 2014) demonstrated how a large number of small heat pumps can be controlled. The flexibility can be predicted and can be used in both the day-ahead market and as regulating power. The concept was tested with the direct control of heat pumps (in contrast to indirect control, e.g. by sending a price signal and letting the end user decide on the action to take). Technically, it can be a challenge to implement direct control of the temperature of an individual house, because many local issues influence the need for heat. The test was performed with 100 active heat pumps and, in general, end user acceptance was high.

4 A brief analysis of Danish market data – What happens when wind energy feed-in is high?

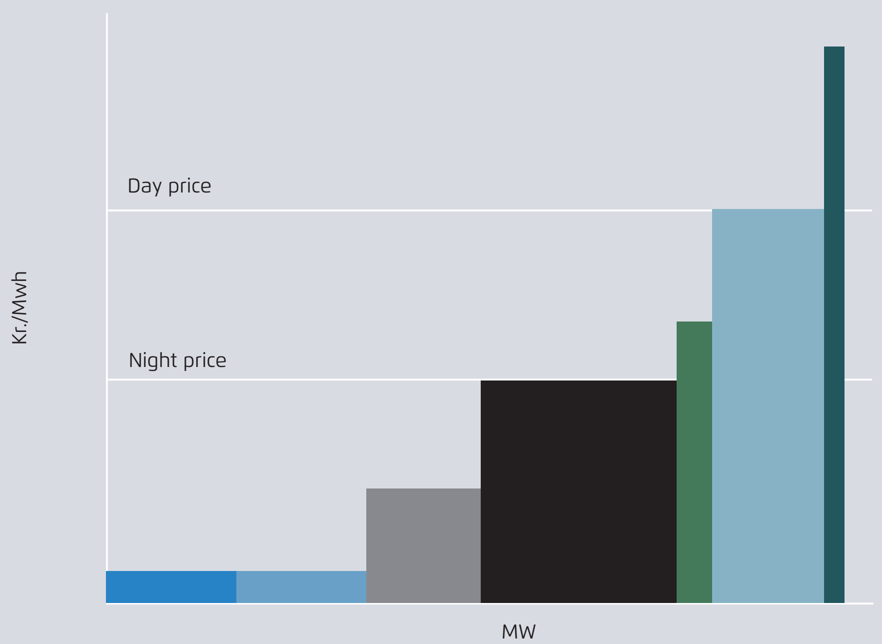
The Danish (and Nordic) market model is auction based. All electricity producers in one market area receive the same price for their product at a certain time. Due to the auction principle, the producer has an incentive to bid into the market with prices based on short-run marginal cost (SRMC). If the market is clearing at a price-level slightly higher than his SRMC, it will still be advantageous for the producer to keep producing electricity. However, his earnings might not necessarily be sufficient to cover fixed costs.

Wind turbines in the electricity market

Wind turbines typically bid in at a very low price on the electricity market. This is because wind power production does not involve any fuel costs. If a wind turbine is entitled to a sufficiently high subsidy, it may even be attractive to bid in at a negative price. When wind turbines are producing, they drive the expensive power plants out of the electricity market, thereby lowering the market price of electricity. In this way, wind power has a diminishing effect on electricity wholesale prices during periods of high wind levels. Large amounts of wind power production can also lead to hydroelectric plants withholding their production until a later time, when electricity prices are higher. This means that wind power can indirectly exert a price deflating effect even when wind power production is low.

Dispatchable technologies with high marginal production cost (like gas fired power plants), will enter the market when the price is high, but only produce for a few hours. Dispatchable technologies with lower marginal production costs (like coal fired power plants) will normally enter the market for a longer time period when the price is relatively low.

Stylised demand/supply curve for the Scandinavian and German electricity markets Figure 19



The y-axis depicts cost per MWh in Danish crowns (Kr). Wind power farms would most likely bid in at the lowest costs in the electricity market, as they do not have any fuel costs to cover. The same applies in principle to hydroelectricity – however hydroelectric plants with a storage capacity can hold back their production and thereby optimise their production in accordance with the expected market prices for electricity. Next in terms of cost are nuclear energy, coal plants, and biomass plants, which are more expensive than hydro and wind, but also have relatively low fuel costs. Gas and oil fired plants usually come last.

Own elaboration

The value of wind power

In a market-based system the value of wind power will be expressed as the value that the market ascribes the production, directly expressed by the price of electricity. The price at the wind turbine can sell its electricity production on the market can be regarded as the socioeconomic value[21] of wind turbine power production.[22]

Figure 20 shows the average monthly price that different types of electricity producers and consumers have settled at since 2002. It appears that the decentralised power stations that are mainly gas-fired have generally produced at the highest electricity price. The operation of wind turbines is clearly associated with the lowest electricity price, and solar power, only visible in a few months of 2014, operates at a higher electricity price. Solar energy has the advantage of producing in hours during the day when demand is usually higher.

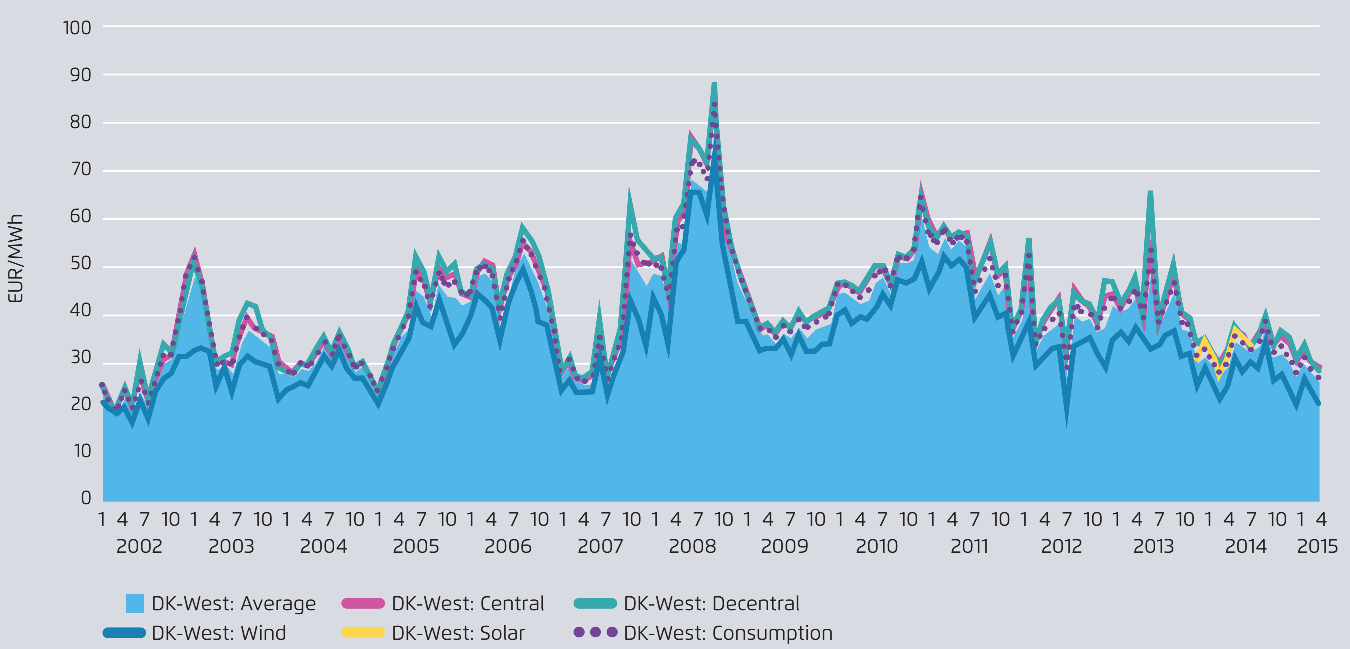
Figure 21 focuses on the value of wind power, revealing the relative difference between the average system price and the wind power price (red dashed line) in Western Denmark. This is compared to the share of the consumption covered by wind power (blue columns).

Perhaps surprisingly, we see that the price difference is relatively high in the beginning of the period at around 10 to 14 per cent in 2002 and 2003, but subsequently drops to about five per cent in 2009–2011. We would attribute this development to the flexibility measures introduced in the same period, in particular the incentives to operate combined heat and power plants more flexibly. At the same time, the share of wind power grew only moderately between 2002 and 2010.

21 It should be noted that if electricity prices are skewed by subsidies or taxes that do not attempt to account for externalities, they may not represent the real socio-economic value of electricity.

22 In a cost-benefit analysis, the value of the sold production must be compared to the costs involved in erecting and maintaining the wind turbine.

Monthly average market price for central, decentral, wind, solar and consumption — Figure 20



Own figure based on data from Energinet.dk

Since 2011, the wind share has increased significantly, and the price difference has returned to around 10 to 14 percent over the last three years. The increasing limitations to export on the interconnection between Western Denmark and Germany are part of the explanation for the increasing discrepancy.

More flexible power plants

The statistics support the perception that power plants have become more and more flexible. Figure 22 compares generation from different generation technologies as well as imports and exports for different electricity prices intervals in 2002-2014 in Western Denmark. There is a clear change in the amount of power contributed by thermal power plants when the price is low. **In 2002, thermal power plants contributed significantly to power production when the price was low, whereas in 2014 wind was clearly dominant during periods with low electricity prices.**

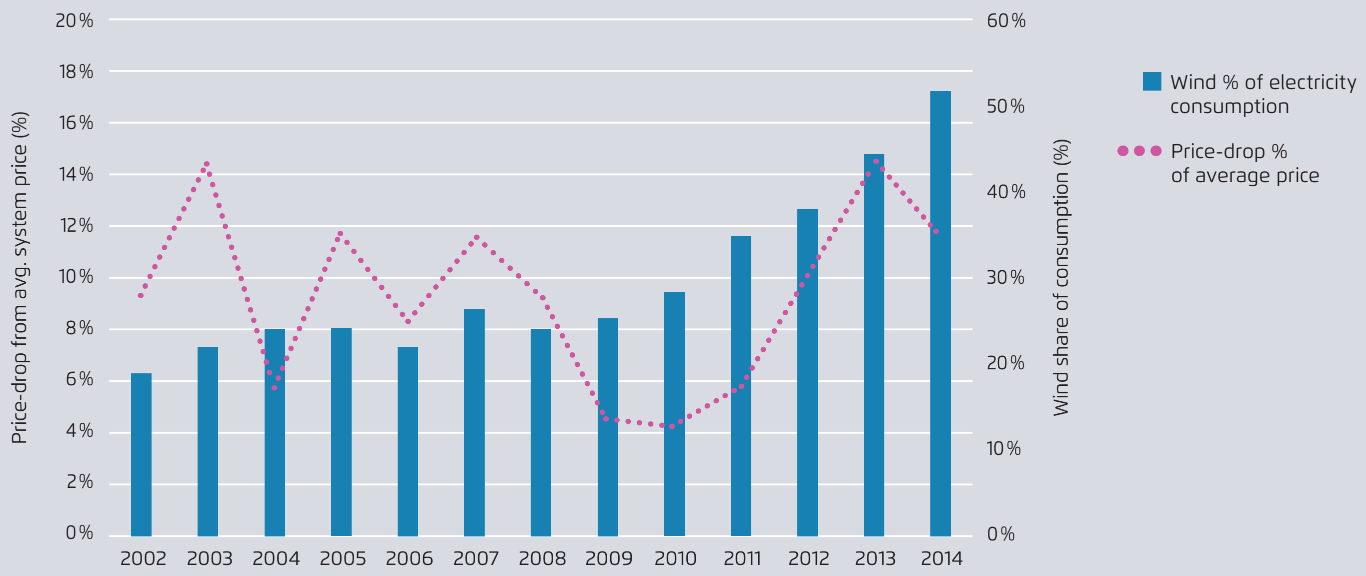
Comparing wind integration in Germany and Western Denmark

The electricity prices in Western Denmark are quite closely correlated. In 40 percent of all hours in 2014, the electricity price was exactly the same in Germany and Denmark, indicating that there were no bottlenecks on the relevant interconnector during these hours.

The number of hours with low electricity prices can be used as an indicator of the "wind integration challenge" faced by a power system. One could expect that given the high share of wind power in Western Denmark, we would see a higher number of occasions with very low prices compared to Germany. In fact we see a close correlation between prices. Furthermore, the Western Danish power system is slightly less stressed than the German power system (see Figure 23), in spite of a much higher wind share (51 per cent compared to 10 per cent). This may be ascribed to the various flexibility measures that have been implemented in Denmark during the last 15 years, but also to the fact that the Danish elec-

Development of discrepancy between observed prices for wind power generators and average market price for West Denmark

Figure 21



Own figure based on data from Energinet.dk

tricity system is very well interconnected with Norway and Sweden, where wind power plays a smaller role.

What are the most important flexibility measures?
What are the most important measures for wind power integration? There is no question that **interconnectors to neighbouring countries** have been extremely important for the integration of wind power in Denmark. The total capacity of interconnectors to Norway and Sweden is approximately 4 GW. This is only slightly less than the Danish wind power peak of 4.4 GW. By comparison, Danish peak demand in electricity amounts to around 6 GW.

In addition, there are 2.4 GW of interconnection capacity to Germany. However, this capacity is partially subject to transmission constraints induced by wind power in the Northern German grid, which can reduce southbound electricity export during certain periods.

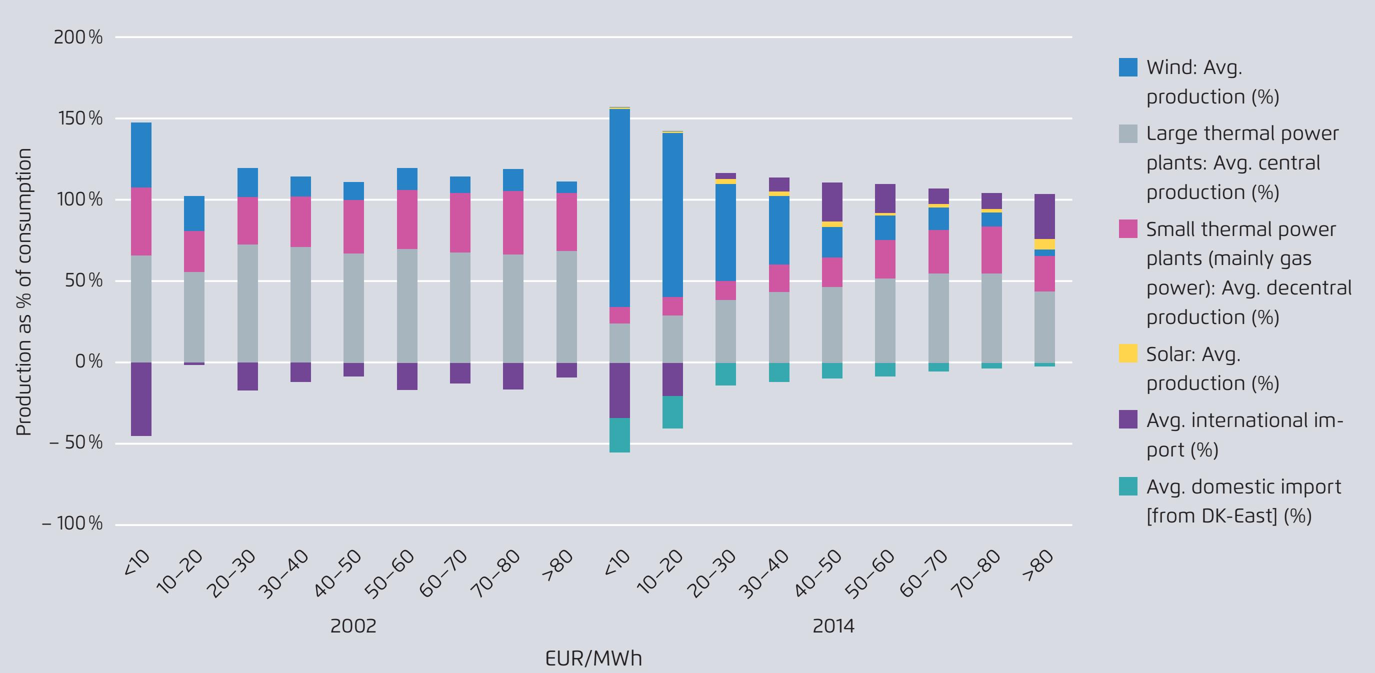
The role of interconnectors, in particular to the Nordic countries, has traditionally been important along with early cross-border Nordic market integration and the establishment of the power exchange Nord Pool since 1999/2000 (Chapter 3.2 and 3.3).

However, despite early integration with the Nordic power markets, Danish institutions and market participants were very active early on in **developing additional flexibility options.** Various measures – both at the regulatory and technical levels – that have been taken to enable the flexible operation of power plants have been key to wind power integration. A statistical analysis of historic electricity prices and generation shows that in 2002 the average thermal generating capacity in situations with very low or negative prices was 3.1 GW, compared to just 1.1 GW in 2014[23] (see also Figure 22). The difference of 2.0 GW may largely be ascribed to the various flexibility measures described in sections 3.4, 3.5 and 3.7.

23 In Western Denmark the analysis considers hours with electricity prices that are zero or negative. In Eastern Denmark there were no zero or negative prices in 2002; therefore in Eastern Denmark the scope was widened to include all hours with an electricity price below 10 €/MWh.

Generation mix in Western Denmark different levels of electricity spot prices

Figure 22



Own figure based on data from Energinet.dk

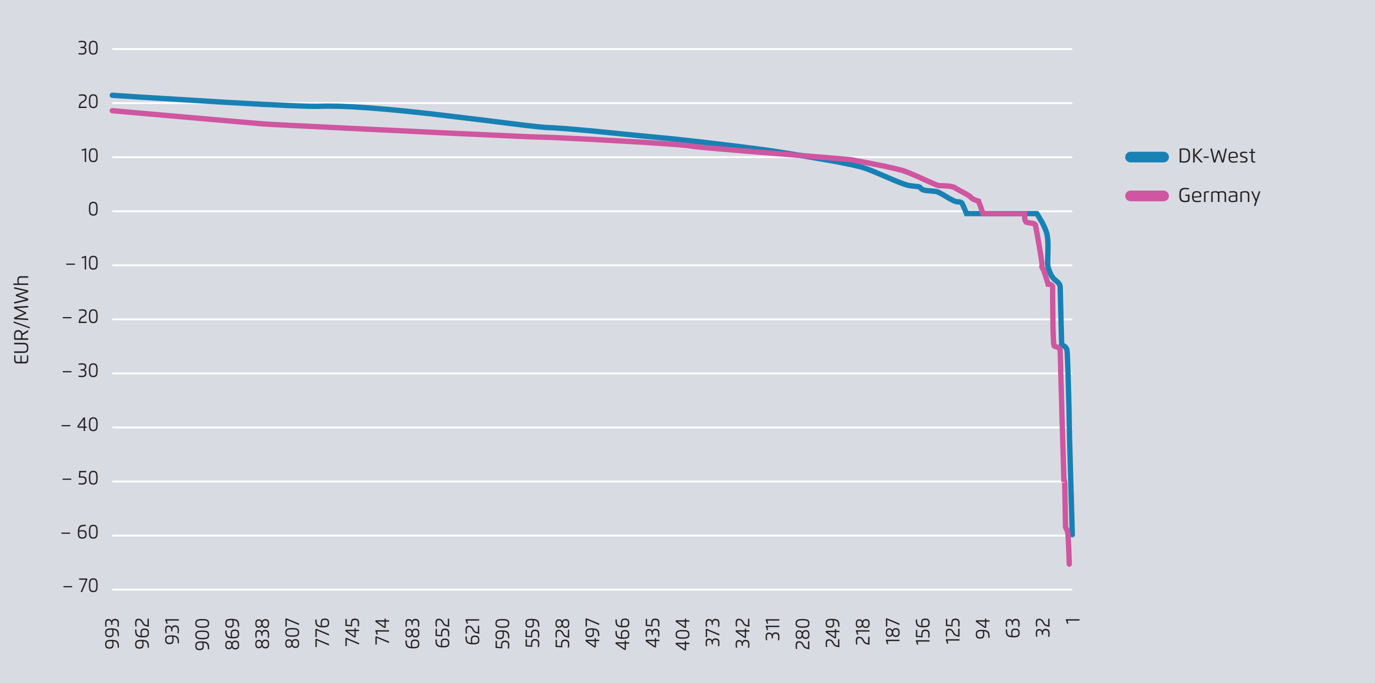
Apart from approximately 0.4 GW of electric boilers, the potential for power to heat has not yet been realised.

Table 5 provides an overview of measures that hold potential for integrating wind power. The table consists of existing measures and planned measures as well as examples of options for further wind power integration towards 2030.

It is important to note that a contribution to wind power integration is only a side effect of some measures. This is the case, for example, for the adoption of electric vehicles, whose main benefit is the reduced consumption of diesel and gasoline. Likewise, the main benefit of individual heat pumps is that they reduce oil demand for heating in buildings. While serving other primary objectives, these options will add load to the electricity system and thereby enable more wind power. Simultaneously, they have the potential to bring additional system flexibility via demand-side response, but it is uncertain to what extent these benefits will materialise.

Other measures, such as the installation of additional electric boiler capacity, will likely be encouraged directly by the low electricity prices induced by wind power.

Duration curve of 1000 lowest electricity prices in Germany (EEX) and Western Denmark (Nord Pool) in 2014 — Figure 23



Own figure based on data from Energinet.dk

Existing, planned and future potential wind power integration measures — Table 5

Measure	Size	Comment
Existing measures		
Interconnectors to Norway and Sweden	4.1 GW	Capacity to Sweden occasionally subject to limitations.
Interconnectors to Germany	2.4 GW	Export capacity very often subject to limitations.
Flexible power generators	2.0 GW	Average observed reduction in output from thermal power plants in periods with very low electricity prices compared to 2002 situation. A result of technical and regulatory measures.
Electric boilers in district heating	0.4 GW	
Planned measures		
Additional interconnection capacity to Germany	0.7 GW	Export capacity likely to be subject to limitations.
New interconnectors to the Netherlands and the UK	1.9 GW	Cobra cable to the Netherlands: 0.7 GW (expected in 2019). Viking link to the United Kingdom: 1.0–1.4 GW (expected around 2020).
Examples of options towards 2030		
Flexible power generators (further measures)	1.1 GW	No generation at all from thermal power plants at very low electricity prices. Ancillary services and regulating power assumed to be provided from grid compo- nents, the demand side or flexible generators.
Heat pumps in district heating	0.6 GW	Assuming that 20 per cent of district heating load is supplied from heat pumps. The specified capacity assumes 4000 full load hours. Average load is 0.3 GW.
Additional electric boilers in district heating schemes	0.6 GW	Assuming that 20 percent of district heating load is supplied from heat pumps. The specified capacity assumes 4,000 full load hours. Average load is 0.3 GW.
Additional electric boilers in district heating schemes	1.0 GW >	Technical potential is very significant. Average load of district heating is 4.3 GW and peak demand more than twice as high.
Electric vehicles (EV)	0.20 GW (2.5 GW)	Average load from 500,000 EVs (20 percent of Danish passenger car fleet) is 0.2 GW. When charging simultaneously load may be multiple times higher as indicated in brackets.
Heat pumps in individual houses	0.15 GW (1.5 GW)	Assuming all oil boilers in homes are replaced by electric driven heat pumps. Average load is indicated; peak load (in brackets) may be multiple times higher.[24]
Fuel shift in industries	0.4 GW	Average heat load in relevant industries is more than 1.6 GW.[25] Assumes that electric boilers are installed to provide a quarter of this capacity.

Own elaboration

24 Oil demand is approximately .14 PJ or 3.9 TWh. Provided by a heat pump with a COP of 3, this equals an electricity demand of 1.3 TWh, corresponding to an average load of approx. 150 MW.

25 Corresponds to an annual fuel consumption of 50 PJ.

5 Enhancing system flexibility – A deep dive into implementing cross-sectoral flexibility options

Section 3 showed that the challenges of integrating wind energy in Denmark are not urgent in the short term. Options for incorporating more wind power production in the current system are good, and a number of measures have already been initiated to integrate increasing shares of wind energy. This includes plans to expand transmission capacity to neighbouring countries as well as to the Netherlands and United Kingdom.

Up to 2020 it is expected that the district heating sector will be able to contribute further to accommodating more wind power by increasing the use of turbine bypass and heat storage. We may also see a further uptake of heat pumps and electrical boilers depending on the development of the regulatory framework. Looking beyond 2020, the challenges are expected to grow, necessitating additional wind integration measures.

The following section takes a **deep dive** into the **implementation of selected flexibility options** with a view to their practical application in systems with high shares of wind energy.

This deep dive examines:
→ Increasing the flexibility of thermal power plants.
→ District heating as a system integrator.
→ The alternative provisioning of ancillary services.
→ Demand-side flexibility.

The last section also addresses flexibility options, which may play a role in the long-term transition toward an energy system totally independent of fossil fuels.

5.1 Flexibility of thermal power plants

In order to address the growing challenge of fluctuating load, efforts have been undertaken over the past 15 to 20 years in Denmark to enable increased load flexibility, reduced minimum load and steeper ramp rates.

A number of prerequisites had to be fulfilled for this purpose. In a case study of DONG Energy and its predecessors that was conducted by Blum & Christensen (2013), all improvements were based on the company's in-house expertise in various engineering disciplines. All of the involved engineers were provided access to reliable power plant process data with high resolution over many years of operation.

It was ensured that control room operators undergo thorough theoretical and practical education. This enabled control room staff to be directly involved in optimising the power plant's operation. Staff were instructed to continuously seek further improvements in flexibility and to develop suggestions for improving plant management and control. The implementation of optimisations was carried out in close dialog between operators and engineers.

A stepwise approach for optimising power plant flexibility

Flexibility improvements were adopted using a stepwise approach. The approach is illustrated in Figure 24 for improvements in minimum load reduction. The same approach was used for increasing ramp rates and optimising start-ups.

Firstly, load was carefully reduced until the first technical limitations appeared. Subsequently, the observed problem was analysed with the goal of finding an adequate solution. Finally, load was further reduced until a new limitation appeared. With an increasing number of iterations, the amount of failures and alarms increases. Therefore, it is essential that the plant is thoroughly protected by alarms and warnings and all required measurements are conducted on a continuous basis.

Control optimisation and/or component redesign are typically the solutions used to address flexibility problems. In some cases, the new process parameters will exceed design tolerances, requiring components to be replaced sooner than anticipated. Optimal trade-offs can be determined with cost-benefit analyses. The optimisation challenges vary from plant to plant. Based on the Danish experience, they typically comprise firing stability, feed water pump flow stability, minimum steam flow through turbines and program limitations of the Distributed Control System (DCS).

Examples of flexibilisation at Danish plants

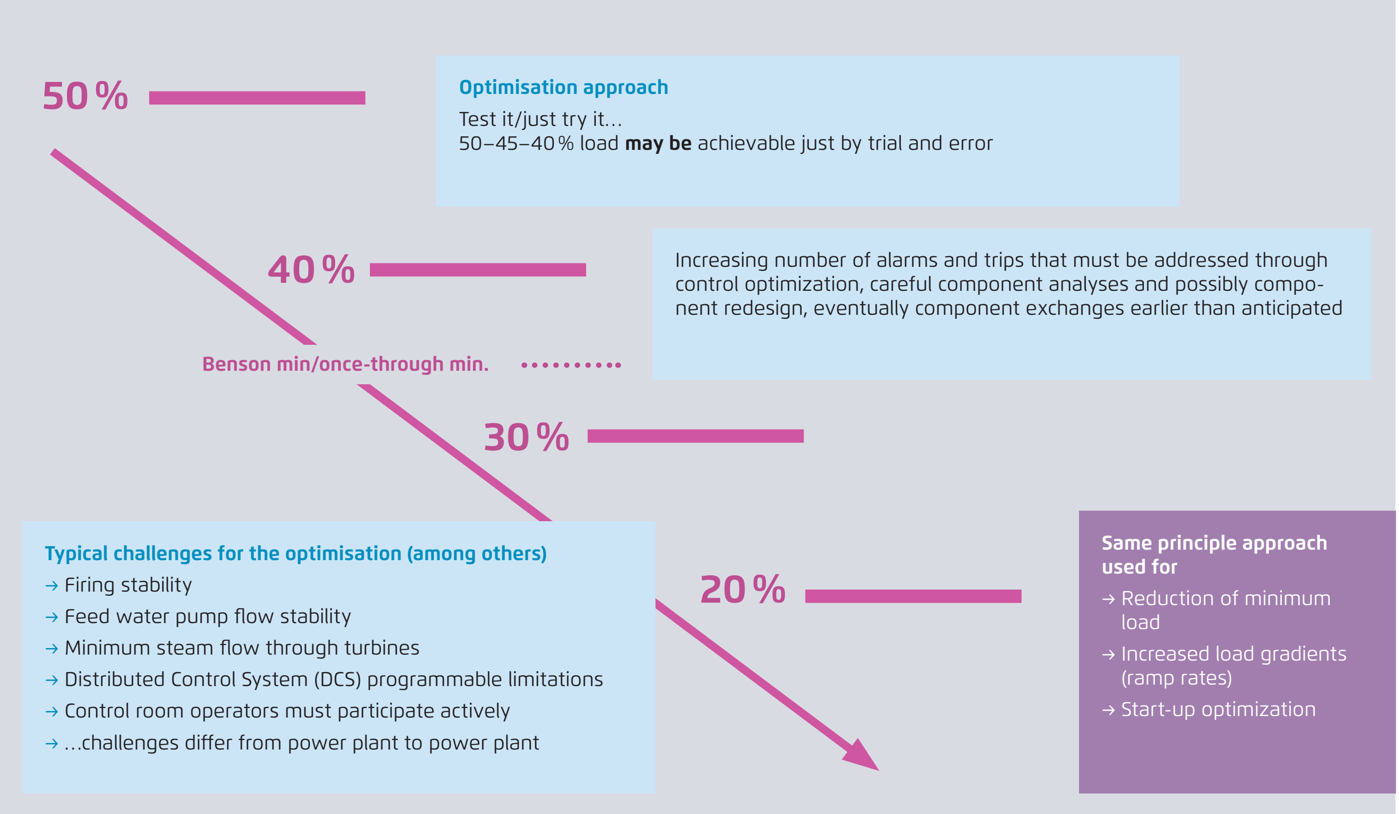
In the following sections, we focus on two examples to illustrate the achievements of the Danish approach to power plant flexibilisation. First, we present an example optimisation routine to show how start-up times can be reduced. Second, we present the daily operational schedule of a Danish power plant to show how minimum load and steep ramp rates can be attained.

Example 1: Start-up optimisation of a coal-fired power plant

The optimisation of a coal power plant that was commissioned in 1998 shows how start-up times can be reduced. The suggested measures yielded a start-up time reduction of 28 percent, from 131 to 94 minutes. The procedure for power plant start-up with and without optimisation is shown in Figure 25. The most relevant improvements were achieved within the early phase of the start-up by keeping vital components at a higher temperature. This decreases the time required for providing superheated steam to the turbines. As a result, grid synchronisation is now possible within 60 instead of 90 minutes.

In the next optimisation step, the ramp up time from the point of grid synchronisation to full generation capacity was reduced by 7 minutes. This was achieved by replacing the old, rigid, non-reprogrammable control software with

Stepwise approach for increasing power plant flexibility — Figure 24



Blum & Christensen (2013)

new software that allows for the flexible modification of start-up criteria.

Example 2: Low minimum load and steep ramp rates
Figure 26 shows the daily cyclic operation of a Danish natural-gas-fired steam power plant during a typical day. It provides an example of how low minimum load and steep ramp rates can be achieved.

During the night, the power plant operates below the so-called Benson minimum. The Benson minimum represents the boiler load above which the evaporator feedwater can circulate autonomously. Below this limit, forced circulation is required to maintain sufficient flow rates. The graph indicates that the Benson limit is crossed several times per day, which deviates from the original design criteria. This leads to increased stress on components, which can cause early fatigue. Therefore, component redesign may be required. Alternatively, the replacement intervals can be shortened for affected components. In the considered case, assessments concluded that the components would endure the more flexible mode of operation without compromising their lifetime.

The figure also illustrates steep ramp rates: the plant in question achieves a ramp-up rate of 9 % P_N/min. At Danish coal power plants, 4 % P_N /min is standard. The high ramp rate helps the power plant to adapt to steep load gradients and enable automatic balancing when load variability is high.

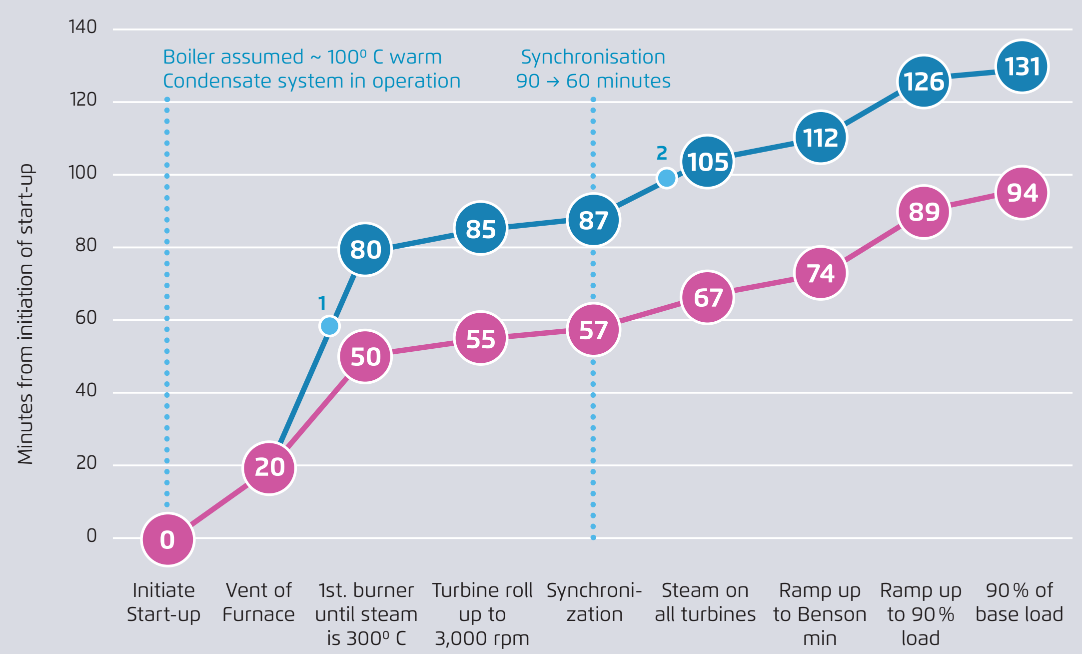
Finally, the figure shows that the rated capacity can be exceeded at times of high load. This overloading is achieved by bypassing the high pressure pre-heater in the steam cycle.

5.2 District heating as a system integrator

A very large portion of Danish electricity production is connected to the district heating system. With the exception of a few plants, all power plants in Denmark have the possibility of co-generating electricity and district heat. This results in limitations with respect to the integration of wind,

Start-up optimisation of a coal power plant

Figure 25



1 Future optimisation though already slightly touched on:

1) Warm-keeping of vital components at higher temperature
2) Redesign: convert creep life time to cyclic operation/fatigue
3) Conservatism in design to be discussed.

2 Rigid, non-reprogrammable control software:

Start-up criteria are fixed today. New software will allow flexible code: if ΔT < x° C then continue start-up…

Blum & Christensen (2013)

as options for electricity production are to some extent limited by the requirements of meeting demand for heat. However, integration of the power and district heating sector also provides opportunities for the enhanced integration of variable renewable energy.

Combined heat and power extraction plants

Most centralised plants are CHP plants that can switch between producing only electricity (referred to as condensation mode) and producing both district heat and electricity. In combined heat and power mode, the low-pressure turbine can be bypassed, ensuring heat production at sufficient temperature. When extra power is needed, the low-pressure turbine is used fully, and district heat is not produced (see Figure 27). This flexibility enables power generation to be adjusted within a very short time horizon, e.g. for balancing fluctuations in the power system.

Today, capabilities of extraction plants in Denmark are used to optimise operation according to power prices (day-ahead or intraday) and to provide ancillary services.

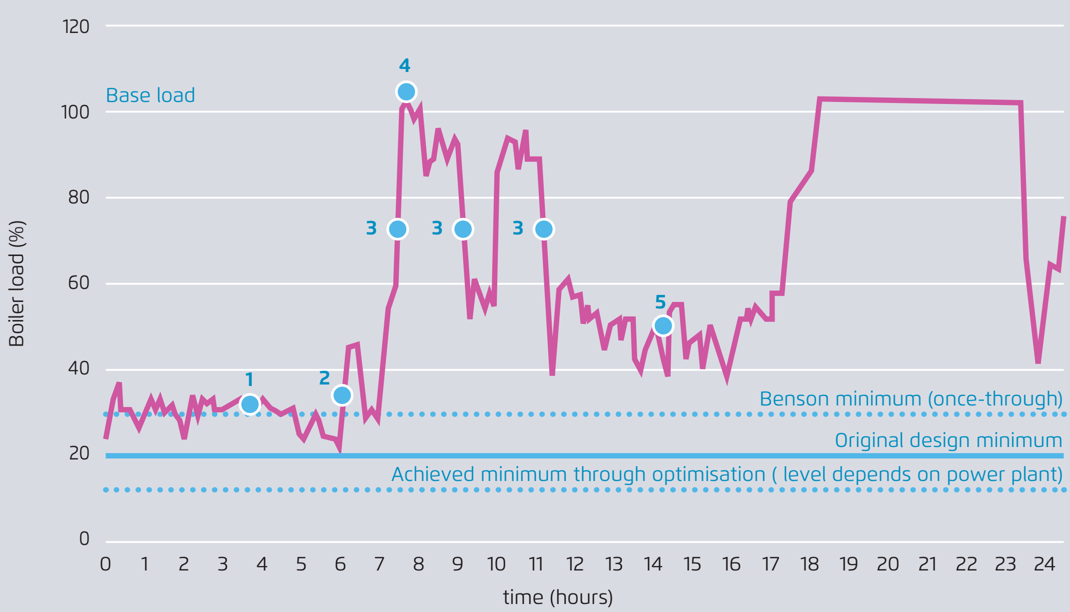
Smaller decentralised power plants are mainly backpressure steam plants, which produce electricity and heat at a fixed ratio. Normally, they can only produce electricity when they also have the possibility of supplying heat to the district heating system. However, it is possible to retrofit these backpressure power plants with cooling options. For smaller decentralised plants, this means installing air-cooled condensers. Today, this option is mainly used in Denmark with biogas-fired CHP plants, which want to use the available biogas production during summer time, when district heating demand is low.

Turbine bypass

Some larger power plants can let steam bypass the turbines for direct use to produce heat if they have a **steam bypass system.**[26] When CHP plants use steam bypass, they effectively function like a boiler. This enables power plants to avoid electricity generation at times with low electric-

26 Steam bypass is most relevant for steam turbine cogeneration plants (there is a total of 5 GW installed capacity in Denmark).

Daily cyclic operation of a gas-fired Ultra Super Critical steam power plant — Figure 26



1 Night operation below Benson Minimum

2 Several Benson-pass cycles in one day! Components designed for 50 passes per year. Redesign of component required due to fatigue. Assessment concluded no problem with life time in this case. In other cases the assessment may conclude that component must be replaced after X years.

3 Load gradient on N_{gas}: ± 9 %/min (4 %/min on coal)

4 Overload: HP preheater bypass mode (sliding in/out)

5 Automatic power balancing of wind, load gradient 9 %/min

Blum & Christensen (2013)

ity prices (e.g. due to high wind penetration), while avoiding a complete shutdown of the plant and continuing heat generation. Steam bypass systems can be installed relatively inexpensively (approximately 0.1 million DKK per MW, i.e. 0.01 euros per MW).[27]

Heat storage

Heat storage units have been installed at the majority of Danish CHP plants. These heat accumulators are usually designed to store roughly eight hours' worth of heat production from the main CHP plants in the district heating system. **Heat storage increases the flexibility of the electricity system, as the CHP plants can reduce or stop production of heat and electricity during windy periods,** and instead supply their heating customers with heat from the heat accumulators. Likewise, CHP plants can supply electricity during times with low wind generation and store the heat production. System analysis show that larger heat storage units provide an economically attractive option for improving the flexibility of a system characterised by both a large share of wind power and a large share of cogenerated heat and power (Ea Energy Analyses, 2014).

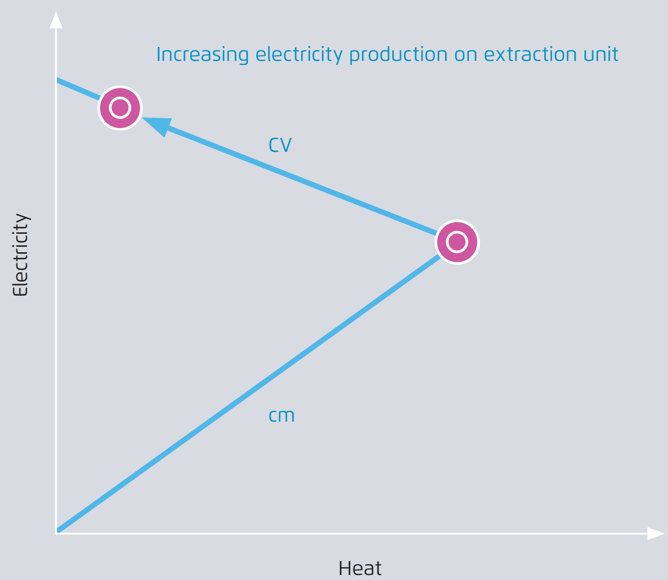
27 There is a significant difference between the extra investments necessary to establish a steam bypass in new plants and the investments involved in adapting existing plants. The magnitude of the required investment is also dependent on the power plant in question, but it is estimated to cost roughly 25 million DKK to establish a steam turbine bypass on a medium sized centralised CHP with a potential decrease in electricity production of approximately 250 MW. This corresponds to a cost of 0.1 million DKK per MW (Source: Ea, 2009: Placing increasing amounts of renewable energy into the electricity system, Report part 2: Catalogue of solutions)

Power-to-heat

One way to ensure the value of variable electricity generation is to introduce new electricity consumption at times of high electricity production. One option is to **use electricity for heat production (power-to-heat)** – for example, through the use of centralised electric boilers or high efficiency heat pumps connected to the district heating system. In terms of energy input/output, heat pump systems can supply up to four times as much heat compared to the electricity they use, and can thereby contribute to a highly efficient overall

Illustration of operation points with different electricity to heat ratios for a combined heat and power extraction plant*

Figure 27



* The Cb coefficient (back-pressure coefficient) is defined as the maximum power generating capacity in back-pressure mode divided by the maximum heat capacity. The Cv value for an extraction steam turbine is defined as the loss of electricity production when the heat production is increased by one unit at constant fuel input.

Ea Energianalyse (2009)

energy usage. On the other hand, heat pump systems involve significant investments. Electric boilers constitute an alternative at a substantially lower investment cost. However, they are also much less efficient, as one unit of electricity is converted to one unit of heat. Heat pumps are therefore well suited for applications with many operating hours, whereas electric boilers are more cost-effective for applications involving fewer operating hours.

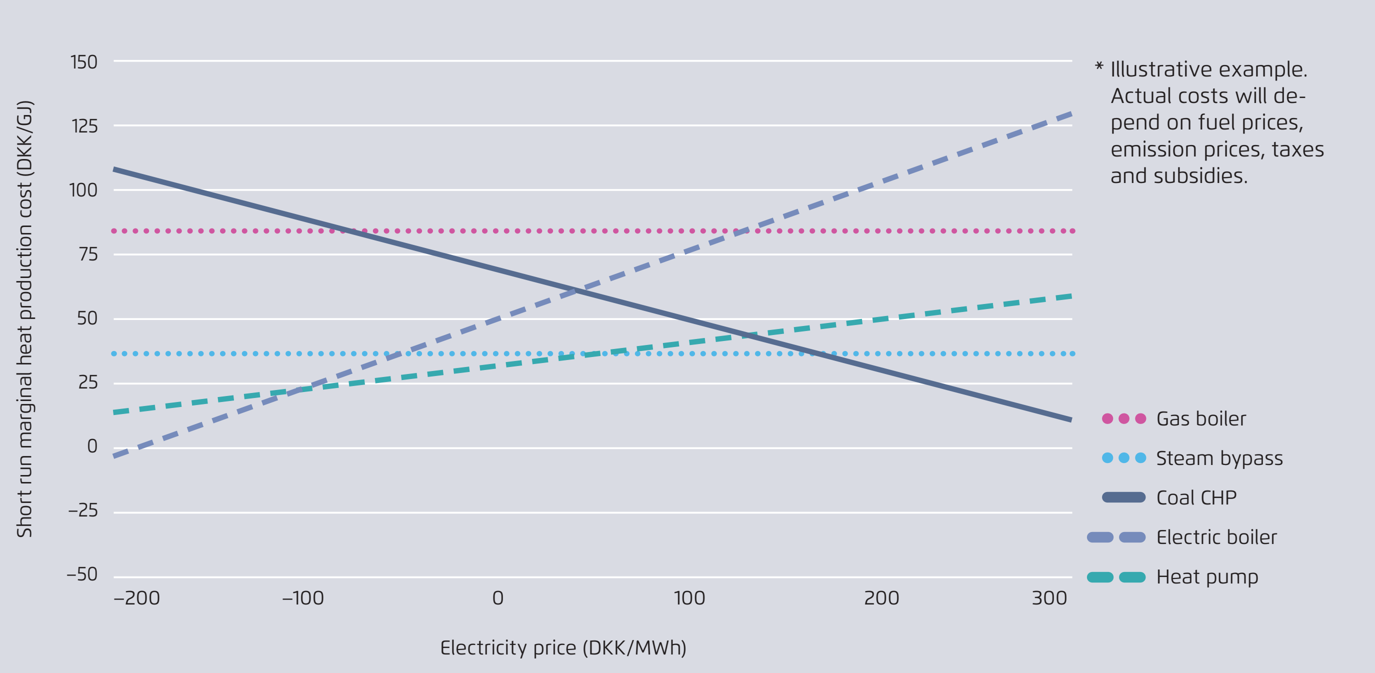
With respect to using the heating system to ensure the value of wind power, it is relevant to note that the cooling of the housing stock, thereby resulting in increased thermal requirements, increases in proportion to wind speed. This positively correlates with increased wind energy production.

Adapting district heating production to variable power prices

The optimal operation of the integrated power and district heating system depends on the power price. Low power prices often indicate high generation from variable renewable energy, while high prices indicate generation from units with higher marginal operating costs and a need for additional power.

Figure 28 compares heat production cost from different units, depending on the electricity price. At very low (i.e. negative) electricity prices, electric boilers offer the cheapest heat, since the boiler can earn money by consuming electricity. As electricity prices increase, it becomes cheaper to utilise first the more efficient heat pump, and then the turbine bypass on the CHP plant. At prices above approximately 180 DKK/MWh (€ 24/MWh), CHP production is beneficial. If the CHP plant is an extraction unit, opportunity cost will occur at very high electricity prices – the plant can choose to produce more electricity while shutting down heat production, thereby increasing income. At very high electricity prices, the gas boiler will therefore provide the cheapest option.

Short run marginal heat production cost for different units depending on the electricity price* Figure 28



Own figure

5.3 Alternative options for ancillary services

Traditionally, most ancillary services such as reserve capacity, inertia, frequency control and voltage control were provided by large thermal power plants. Central power stations used to produce a significant amount of power during hours with low electricity prices (cf. Figure 22). This was partly due to technical restrictions on the plants themselves, and partly due to power system requirements.

Building system stability properties into the grid

Energinet.dk's strategy is to build the system stability components into the grid when this is economically advisable. According to Energinet.dk, the components in question are primarily Static Var Compensators (SVC), static synchronous compensator (STATCOM) equipment and synchronous condensers. The benefit of these components is that they can provide the services required alone without co-generation of electricity (Energinet, 2011). This means that required ancillary services to support system reliability such as continuous voltage support or voltage support during fault can be delivered by these components. In turn, this may contribute to the reduction of must-run capacity in power generation.

Table 6 provides a summary of the various technologies' ability to provide the properties required.

The Voltage Source Converter (VSC) technology, which is used on new HVDC connections, is capable of providing most of the properties required, except inertia. However "Energinet.dk does not consider inertia a critical factor for safe operation of the Danish power system. This is due to the fact that Eastern and Western Denmark are connected to the large interconnected synchronous areas in Scandinavia and Continental Europe, respectively. [...] Therefore, Energinet.dk does not in the short, medium or long term see a need for forced operation of power stations for the sake of procurement of sufficient inertia" (Energinet.dk, 2013: *Amendment to Energinet.dk's ancillary services strategy*, p. 7f.).

Energinet.dk has held a **number of tenders for the provision of system services.** Among other things, the tenders have requested the delivery of a synchronous compensator or the equivalent performance of a converted power station. **In all cases, the establishment of a new synchronous compensator has been the economically cheapest alternative.**

In light of the above, **the need for must-run capacity has been reduced from three large units to 0–1 units in Western Denmark.** In Eastern Denmark the requirement has been reduced from 2–3 to 1–2 units. Towards 2018, a number of projects to strengthen the grid and expand international connections are expected to further reduce the need for must-run capacity (Energinet.dk, 2013: *Amendment to Energinet.dk's ancillary services strategy*).

Assessment of the properties required to maintain power system stability (provided by different sources)
++ "Large contribution", + "Some contribution", (+) "Conversion possible", ÷ "Unsuitable" Table 6

	Power station >100 kV	Power station <100 kV	Wind turbine >100 kV	Wind turbine <100 kV	Classic HVDC	New HVDC	SVC/STATCOM	Synch. cond.
Inertia	++	+	(+)	-	(+)	(+)	-	++
Short-circuit power	++	+	(+)	-	-	(+)	-	++
Black start	(++)	(+)	-	-	-	(++)	-/+	-
Continuous voltage control	++	(+)	(+)	-	-	++	++	++
Voltage support during fault	++	-	++	-	-	++	++	++
Power system stabilisation (PSS)	+	-	(+)	-	(++)	(++)	(+)	-

Energinet 2011: Energinet.dk's ancillary services strategy

5.4 Demand side flexibility options

Aside from the installation of interconnectors and other measures implemented on the supply side, the introduction of flexible demand constitutes an important option for enhancing the dynamic capabilities of the power system. To date, demand response has not been important to the integration of wind power in Denmark, but there are expectations – and hopes – this will change.

Smart grid strategy

In 2013, the Danish government set forth a "Smart Grid Strategy" for the future development of the power grid (KEBMIN, 2013). The strategy was developed in cooperation with relevant Danish stakeholders, including Energinet.dk and the Danish Energy Association. It details a broad range of initiatives to be implemented by the government and power sector (see text box).

The "Smart Grid Strategy" sets forth a broad range of initiatives to be implemented by the government and energy sector, including for example:
→ Changes to the economic regulation of grid companies to promote investment in smart grid technologies
→ Improving access for small consumers to the market for ancillary services
→ Changes to the electricity tariff system to reflect the benefits of flexible load
→ Changes to building regulations to promote flexible heat pumps in new buildings
→ The promotion of "smart" appliances through EU regulation (Eco design directive)
→ Funds for showcase activities
→ Analysis of the interplay between electricity, heating and gas sectors

Source: KEBMIN, 2013

According to the strategy, two important preconditions need to be met in order to develop the potential for demand response:
→ Consumers should have hourly meters installed that can be accessed remotely, and
→ The electricity market should allow consumers to be settled on an hourly basis instead of the fixed-price settlement (known as template settlement) used today.

In the following sections we will look into the Danish plans for a smart meter roll out as well as the envisioned changes to regulations and the structure of the electricity market. However, before doing so we briefly describe the potential for demand response.

The potential for demand response

Status quo and future trend

In 2014, Danish electricity demand (including net losses) amounted to 33.5 TWh. In general, between 1990 and 2014 Danish electricity consumption increased by approximately 13 percent. It reached a peak of 36.1 TWh in 2008 and has been decreasing since then, falling seven per cent since that year. This decline can be attributed in particular to a reduction in electricity consumption in the manufacturing sector (Energinet.dk, 2015d).

Looking to the future, the Danish Energy Agency distinguishes between two types of electricity demand (Danish Energy Agency, 2014b):
→ "Classical electricity consumption" – i.e. by appliances, machines, lighting, and cooling.
→ "New electricity consumption" – i.e. electric vehicles, heat pumps, electric boilers, and fuel factories (e.g. for production of hydrogen).

Estimates for the future development of Danish electricity demand depend both on efficiency measures affecting the overall level of classical power consumption as well as the electrification of other energy sectors, the so-called "new electricity consumption". Energy consumption in households depends primarily on heat and the utilisation of electric appliances. The effect of an increased deployment of electric appliances may be partially offset by higher efficiency of new appliances in use. While electrification may contribute to enhance system flexibility, it may simultaneously induce an increase in total electricity demand.

According to forecasts developed by Energinet.dk (2015d), electricity consumption is expected to increase by 3.7 TWh from 2015 to 2024, which corresponds to eleven per cent growth. This rise in demand is partially attributed to the charging of electric vehicles (which will be responsible for 0.9 per cent of electricity consumption in 2024), as well as to electric boilers and heat pumps (estimated to account combined for 4.1 per cent of annual electricity consumption of 38 TWh in 2024).

Types of demand response

There are different ways of increasing demand flexibility (Ea Energy Analyses, 2011a):

→ Load shifting: This refers to the shifting of demand by household consumers (e.g. for cooling) and industrial customers from a period with high electricity prices to a period with low electricity wholesale prices.

→ Peak shaving: Refers to a reduction in peak demand during times of high prices. This may comprise consumption that is simply reduced, but not shifted to another period (e.g. lighting in shop windows when the shops are closed).

→ Fuel shift in industries: Substitution of currently utilised fuel (oil or gas) to electricity based process heat when electricity prices are low.

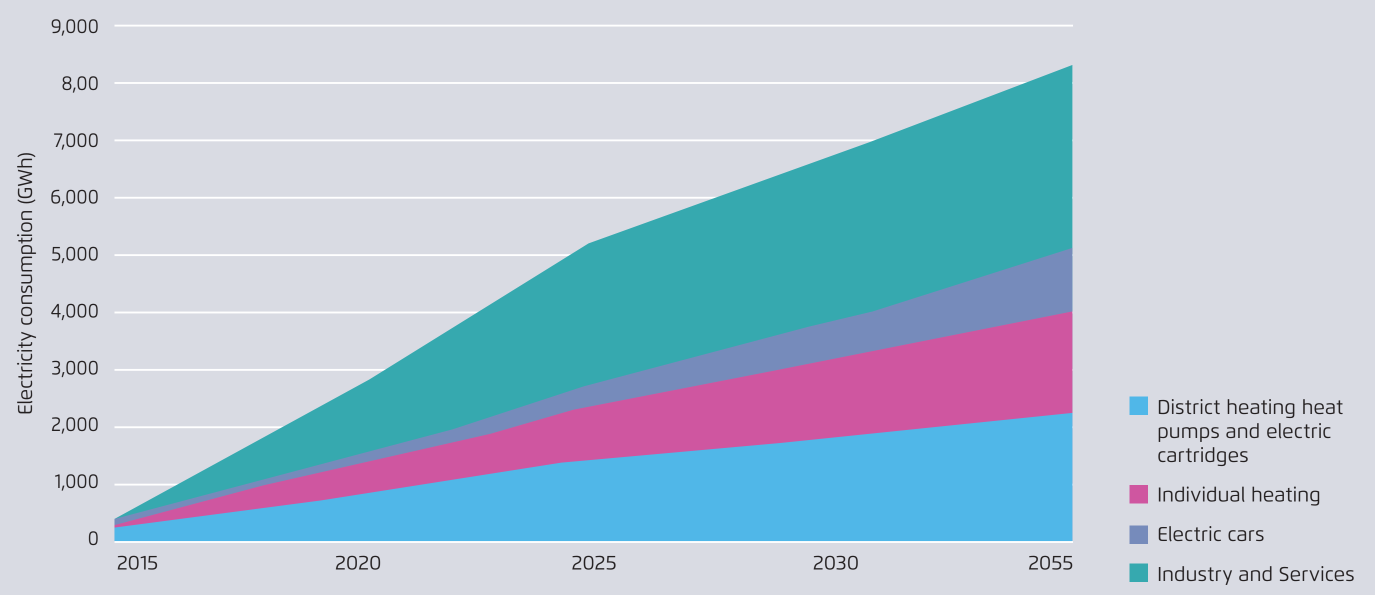
→ Indirect usage of electricity by means of hydrogen: electricity used for local or central production of hydrogen in order to replace natural gas. This solution is not likely to play a role in the short to medium terms as it requires reductions in investment costs for electrolysers as well as many hours with low wholesale electricity prices.

Smart grid strategy

The government's "Smart Grid Strategy – The intelligent energy system of the future" from 2013 (KEBMIN, 2013) describes a scenario for development in the theoretical potential for flexible electricity consumption for a number of technologies up to 2035 (see Figure 29). The potential identified for 2035 is just above 8 TWh.

Until now, however, it has proven difficult to realise the potential for demand response.

Electricity consumption – example of development of flexible consumption Figure 29



Danish Ministry of Climate, Energy and Building, Smart Grid Strategy The intelligent energy system of the future (KEBMIN, 2013), p. 11

Fuel-shift in industries

Even though the manufacturing sector in Denmark is relatively small there is a significant potential for flexible electricity consumption in the industry sector. This particularly involves a "fuel shift", i.e. substituting the fossil fuels that are currently used with electricity based process heat, either from electric boilers or potentially high temperature heat pumps, when electricity prices are low. Since the industry sector utilises much shorter payback periods than those used, for example, in the district heating sector, this can however pose a significant barrier for exploiting fuel-shift opportunities.

Storing electricity

A number of technologies have been discussed with a view to storing electricity locally in Denmark, including compressed air storage, batteries, flywheels, hydro reservoirs, and hydrogen production in combination with fuel cells. All of these technologies are technologically possible, but they require large investments. Also, the majority of these technologies are associated with significant energy losses.

In 2014, the Danish Energy Agency published four different scenarios showing how Denmark could meet the vision of a fossil fuel independent energy system by 2050 (Danish Energy Agency, 2014b). **Direct electricity storage in Denmark is not included in any of the scenarios. The preliminary assessment from the Danish Energy is that use of the electricity market (including hydropower storage facilities abroad) and flexible electricity consumption are cheaper solutions.**

Power to hydrogen/gas

However, two of the scenarios – including the so-called wind scenario, which was the scenario favoured by the former minister of climate and energy – foresee large-scale hydrogen production. The hydrogen is used to replace biomass and biogas to make it last longer, as biomass may become a scarce resource in the future. At the same time, the electrolyser factories provide a source of relatively flexible electricity demand, improving the integration of wind power.

Smart meter roll-out

In 2013, legislation was passed for a roll-out of smart meters to consumers nationwide by 2020. The deployment of 200,000 to 300,000 smart meters per year is foreseen

Savings for consumers with adoption of smart meters
(Calculated with exchange rate: 7.4615 DKK = 1 euro, as of 26 June 2015, to provide a general indication) Table 7

	Example of annual electricity consumption			
Expenditures (in euro)	1,500 kWh	4,000 kWh	5,000 kWh	10,000 kWh
Investment in meters	-17.15	-17.15	-17.15	-17.15
Saved reinvestment	7.64	7.64	7.64	7.64
Operating expenditures	-1.34	-1.34	-1.34	-1.34
Dissemination costs (feed-back)	-0.54	-0.54	-0.54	-0.54
Total costs	-11.39	-11.39	-11.39	-11.39
Savings (in euro)				
Energy savings (2 %)	9.11	24.39	30.56	60.98
Improved competition	5.63	15.01	18.90	37.66
Consumer shifting	2.01	5.23	6.43	13.00
Total savings	16.75	44.63	55.89	111.64
Net result with all savings	5.36	33.24	44.50	100.25

Danish Energy Agency (2013)

(Danish Energy Agency, 2013). More than half of all consumers **already have remotely read hourly meters installed.**

The economic attractiveness for shifting consumption from hours with high electricity wholesale market prices to hours with high wind energy feed-in and low prices depends

→ on potential savings based on the difference in electricity wholesale prices, and
→ on installed profiling/metering systems that reflect these differences.

According to the Danish Energy Agency, consumers are expected to benefit from the roll-out of smart-meters in spite of the additional cost of the meter itself (see Table 7). Consumers opting for an electricity tariff with variable electricity prices (based on hourly metering) are expected to benefit the most. However, consumers with a fixed tariff may also gain by becoming more aware of their actual electricity consumption.

Demand response in the electricity market

For customers in, for example Denmark, with a large electricity demand, it is easy to be active with demand-side flexibility. The electricity used by the company is accounted for based on hourly consumption, and the company may choose to buy electricity at the spot price with free volume. The term "free volume" means that the company does not have to report the amount of electricity it will use the next day. The retailer will predict the demand for all its customers, based on historic demand. With many customers, demand is relatively easy to predict (based on information about the type of day and outdoor temperature).

The company receives the next day's prices around 1 p.m. the day before. If the company has processes that can be performed at alternate times, then this can be done to minimise demand during expensive hours, and maximise demand during the cheapest hours. The company can develop its own strategy (e.g. if it will react to price data every day, or only when the price difference is high).

With this set-up, demand-side flexibility is straightforward for the end-user, and the flexibility will enter the market as price-dependent bids, thus influencing price formation.

Currently, other end users (<100,000 kWh/year) cannot receive economic benefit from demand-side flexibility as the profiling system[28] does not allow for this. For ancillary services, demand-side flexibility is not practical, as the procedures and rules in place were designed for generators. Both areas (the profiling system and procedures for ancillary services) are under development. According to Energinet.dk, a new hourly settling system should be ready by July 2016 (Energinet.dk, 2015e).

28 The profiling system helps convert long-term meter readings (avoid abbreviation over one year) into hourly values. In this way, demand from users without smart meters can be part of the planning and settlement of the market. In the Danish profiling system, the profile is computed based on the residual demand in each grid company. That is the total electricity delivered to the grid area minus the demand from users with hourly settlement and minus grid losses. Therefore, all small end users in a specific grid area have the same profile. In other countries, like Finland and the Netherlands, the profile is defined for different types of consumers.

Appendix: List of wind integration measures

Important wind integration measures in Denmark

Measure	When?
Denmark joins Nordic spot market	1999/2000
Joint Nordic market for regulating power	2002
More flexible power plants	Continually
Changed taxation of CHP plants, boilers and electric boilers	2005
Decentralised CHP plants in the spot market	2006
Market coupling with Germany	2009
Negative prices in spot market	2009
Great Belt Interconnection	2010
New strategy for procurement of ancillary services	2011
Lower tax on electricity for heat	2012
Smart grid strategy including decision on smart meter roll out and hour settlement of small consumers	2013
Incentive for system-friendly wind power	2014
Market coupling with Western Europe	2014
Additional interconnector to Norway (Skagerrak 4)	2014

Own elaboration

6 References

Blum, R., Christensen, T. (2013). *High Flexibility Power Plants – 25 Years of Danish Experience.* Presentation at ENS-China workshop meeting on Future Flexible Power System for Renewable Energy Grid Integration, Beijing, 4 December 2013

Danish Energy Agency. (2012). Energistyrelsen. Hentet fra *Skrotningsordningen - udløb den 15. december 2011:* http://www.ens.dk/undergrund-forsyning/vedvarende-energi/vindkraft-vindmoller/vindmoller-paland/skrotningsordningen

Danish Energy Agency (2013). *Faktaark smarte elmålere (Fact sheet on smart meters).* 17 September 2013. http://www.kebmin.dk/files/dokumenter/side/faktaark_maalere_17092013_2.docx.pdf

Danish Energy Agency. (2014). Energistyrelsen. Hentet fra *Afregning og tilskud til vindmøller:* http://www.ens.dk/undergrund-forsyning/el-naturgas-varmeforsyning/elforsyning/elproduktion/stotte-vedvarende-energi-2

Danish Energy Agency (2014a). *Energy Statistics 2013.*

Danish Energy Agency (2014b). *Energiscenarier frem mod 2020, 2035 og 2050.*

Danish Energy Agency. (25 February 2015). Energistyrelsen. Hentet fra *Procedures and permits for offshore wind parks* http://www.ens.dk/en/supply/renewable-energy/wind-power/offshore-wind-power/procedures-permits-offshore-wind-parks

Danish Wind Turbine Owners' Association (2012). *Status for vindkraftudbygningen i Danmark.* Aarhus: Danmarks Vindmølleforening. Hentet fra http://www.dkvind.dk/html/nogletal/pdf/statusnotat_0112.pdf

Ea Energy Analyses (2009). *Placing increasing amounts of renewable energy into the electricity system.* Report part 2: Catalogue of solutions.

Ea Energy Analyses (2011). *Forslag til ny struktur for CO_2- og energiafgifter i Danmark - med fokus på fjernvarme.*

Ea Energy Analyses (2011a). *Kortlægning af potentialet for fleksibelt elforbrug i industri, handel og service.* (Survey of the potential for flexible demand within industries and the trade and service sectors) Prepared by Ea Energianalyse for Energinet.dk. 8 June 2011.

Ea Energy Analyses et al. (2013). Activating electricity demand as regulating power. *Flexpower – testing a market design proposal.* http://www.ea-energianalyse.dk/reports/1027_flexpower_activating_electricity_demand_as_regulating_power.pdf

Ea Energy Analyses (2014). *Fjernvarmeanalyse – bilagsrapport MODELBEREG-NINGER AF SCENARIER FOR FJERNVARMENS UDVIKLING I FREMTIDENS ENER-GISYSTEM.* (Model analyses of the future development of district heating) http://ea-energianalyse.dk/reports/1307_fjernvarmeanalyse_modelberegninger.pdf

Energinet.dk (2011). *Energinet.dk's ancillary services strategy.* https://www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/El/77566-11%20v1%20Energinet%20dk's%20ancillary%20services%20strategy.pdf

Energinet.dk (2013). *Amendment to Energinet.dk's ancillary services strategy.* http://energinet.dk/SiteCollection-Documents/Engelske%20dokumenter/El/14-02812-79%20Amendment%20to%20Energinet.dk%27s%20ancillary%20services%20strategy%202011-2015.pdf

Energinet.dk (2015a). *Energinet.dk's strategi for systemydelser 2015-2017. (Energinet.dk's strategy for ancillary service 2015-2017)*

Energinet.dk (2015b). Market data downloaded from Energinet.dk's website in May 2015. http://www.energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx .

Energinet.dk (2015c). (25 February 2015). Energinet.dk. http://www.energinet.dk/DA/El/Vindmoeller/Afregning/Sider/Afregning.aspx

Energinet.dk (2015d). *Forbrug i Danmark.* (Demand in Denmark) http://www.energinet.dk/DA/KLIMA-OG-MILJOE/Miljoerapportering/Sider/Forbrug-i-Danmark.aspx

Energinet.dk (2015e). *Koordinerende Styregruppe for Engrosmodellen og DataHub drift,* møde 8. (Meeting note) http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Referat,%20Koordinerende%20Styregruppe%20for%20Engrosmodellen%20og%20DataHub%20drift,%2022-04-2015.pdf

ENTSO-E WGAS, (January 2015), *Survey on Ancillary services procurement, Balancing market design 2014.*

Feldmüller, A. (2013). Siemens AG (Siemens Energy, Service Fossil). *Wie flexibel ist der heutige konventionelle Kraftwerkspark aus Herstellersicht?* See: http://www.effiziente-energiesysteme.de/fileadmin/user_upload/PDF-Dokumente/Veranstaltungen/Workshop_Retrofit/3_SIEMENS_Feldmueller.pdf

KEBMIN - Klima-, Energi- og Bygningsministeriet - Danish Ministry of Climate, Energy and Building (2013). *Smart Grid Strategy. The intelligent energy system of the future.* See: http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Forskning/Smart%20Grid%20Strategy.pdf

KEBMIN - Klima-, Energi- og Bygningsministeriet - Danish Ministry of Climate, Energy and Building (2013a). *Faktaark Smarte elmålere.* (Fact sheet on smart meters) See: http://www.ens.dk/sites/ens.dk/files/undergrund-forsyning/faktaark_maalere_17092013_2.docx.pdf

NEAS Energy, Aalborg Universitet, Aarhus Universitet, Neogrid, PlanEnergi og Ea Energianalyse (2014). *READY Smart Grid Ready VPP Controller for Heat Pumps.* See: http://www.ea-energianalyse.dk/projects-english/1236_READY_heat_pumps.html

Skatteministeriet (9 September 2014). Retsinformation. Hentet fra *Bekendtgørelse af lov om skattemæssige afskrivninger* (afskrivningsloven) (legal information): https://www.retsinformation.dk/Forms/R0710.aspx?id=164300#P5

TenneT (2012). *Determination of Transfer Capacity at trade relevant Cross-Border Interconnections of TenneT TSO GmbH.* http://www.tennet.eu/de/fileadmin/downloads/Kunden/bestimmungenubertragungskapazitat20120924_fin_en.pdf

The Danish Commission on Climate Change Policy (2010). *Green Energy - the road to a Danish energy system without fossil fuels.*

Togeby, M., Werling, J., Hethey, J. *Improving Taxes, Electricity Markets and Framework Conditions to Help Integrate Wind Power* (2009). http://www.ea-energianalyse.dk/papers/916_improving_taxes_electricity_markets_and_framework_conditions_to_help_integrate_wind_power_310809.pdf

Xu, Z., Østergaard, J., Togeby, M. (2011). *Demand as Frequency Controlled Reserve.* IEEE Transactions on Power Systems — 2011, Volume 26, Issue 3, pp. 1062-1071

Publications of Agora Energiewende

In English

12 Insights on Germany's Energiewende
An Discussion Paper Exploring Key Challenges for the Power Sector)

A radically simplified EEG 2.0 in 2014
Concept for a two-step process 2014-2017

Comparing Electricity Prices for Industry
An elusive task – illustrated by the German case

Comparing the Cost of Low-Carbon Technologies: What is the Cheapest Option?
An analysis of new wind, solar, nuclear and CCS based on current support schemes in the UK and Germany

Cost Optimal Expansion of Renewables in Germany
A comparison of strategies for expanding wind and solar power in Germany)

Power Market Operations and System Reliability
A contribution to the market design debate in the Pentalateral Energy Forum

In German

12 Thesen zur Energiewende
Ein Diskussionsbeitrag zu den wichtigsten Herausforderungen im Strommarkt (Lang- und Kurzfassung)

Aktionsplan Lastmanagement
Endbericht einer Studie von Connect Energy Economics

Auf dem Weg zum neuen Strommarktdesign: Kann der Energy-only-Markt 2.0 auf Kapazitätsmechanismen verzichten?
Dokumentation der Stellungnahmen der Referenten für die Diskussionsveranstaltung am 17. September 2014

Ausschreibungen für Erneuerbare Energien
Welche Fragen sind zu prüfen?

Das deutsche Energiewende-Paradox. Ursachen und Herausforderungen
Eine Analyse des Stromsystems von 2010 bis 2030 in Bezug auf Erneuerbare Energien, Kohle, Gas, Kernkraft und CO_2-Emissionen

Publications of Agora Energiewende

Die Energiewende im Stromsektor: Stand der Dinge 2014
Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2015

Die Entwicklung der EEG-Kosten bis 2035
Wie der Erneuerbaren-Ausbau entlang der langfristigen Ziele der Energiewende wirkt

Die Rolle des Emissionshandels in der Energiewende
Perspektiven und Grenzen der aktuellen Reformvorschläge

Die Rolle der Kraft-Wärme-Kopplung in der Energiewende
Status quo, Perspektiven und Weichenstellungen für einen sich wandelnden Strom- und Wärmemarkt

Der Spotmarktpreis als Index für eine dynamische EEG-Umlage
Vorschlag für eine verbesserte Integration Erneuerbarer Energien
durch Flexibilisierung der Nachfrage

Erneuerbare-Energien-Gesetz 3.0
Konzept einer strukturellen EEG-Reform auf dem Weg zu einem neuen Strommarktdesign

Energieeffizienz als Geschäftsmodell
Ein marktorientiertes Integrationsmodell für Artikel 7 der europäischen Energieeffizienzrichtlinie

Kostenoptimaler Ausbau der Erneuerbaren Energien in Deutschland
Ein Vergleich möglicher Strategien für den Ausbau von Wind- und Solarenergie in Deutschland bis 2033

Negative Strompreise: Ursache und Wirkungen
Eine Analyse der aktuellen Entwicklungen – und ein Vorschlag für ein Flexibilitätsgesetz

Netzentgelte in Deutschland
Herausforderungen und Handlungsoptionen

Positive Effekte von Energieeffizienz auf den deutschen Stromsektor
Endbericht einer Studie von der Prognos AG und dem Institut für Elektrische Anlagen
und Energiewirtschaft (IAEW)

Power-to-Heat zur Integration von ansonsten abgeregeltem Strom aus Erneuerbaren Energien
Handlungsvorschläge basierend auf einer Analyse von Potenzialen und energiewirtschaftlichen Effekten

Stromspeicher für die Energiewende
Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich,
Systemdienstleistungen und im Verteilnetz

All publications are available on our website: www.agora-energiewende.de

082/16-S-2015/EN

How do we accomplish the *Energiewende*? Which legislation, initiatives, and measures do we need to make it a success? Agora Energiewende helps to prepare the ground to ensure that Germany sets the course towards a fully decarbonised power sector. As a think-&-do-tank, we work with key stakeholders to enhance the knowledge basis and facilitate convergence of views.

Agora Energiewende
Rosenstraße 2 | 10178 Berlin
T +49 (0)30 284 49 01-00
F +49 (0)30 284 49 01-29
www.agora-energiewende.de
info@agora-energiewende.de

Agora Energiewende is a joint initiative of the Mercator Foundation and the European Climate Foundation.