CITY OF AARHUS

THE FUTURE REQUIREMENTS FOR FLEXIBILITY IN THE ENERGY SYSTEM

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Aarhus Kommune

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Klimasekretariatet
Valdemarsgade 18
8000 Aarhus C

Sagsnr.: NM/11/00860
Sagsbeh.: Mette Behrmann

Telefon: 8940 2000
Direkte: 8940 4966
Telefax: 8940 2768

E-post:
Direkte: mbeh@aarhus.dk
www.aarhus.dk

The future requirements for flexibility in the energy system

Climate and energy challenges are a unique opportunity for creating growth in Denmark. The challenges require solutions that are to be developed in close collaboration between companies, knowledge institutions and energy suppliers.

One of the challenges is integrating increasing amounts of fluctuating energy production, e.g. wind and solar, into the energy system – this requires an intelligent energy system. An intelligent energy system is precisely one of the focal points for climate efforts identified in Aarhus Municipality's Climate Plan 2012-2015. As a foundation for the climate effort, Ea Energy Analyses has prepared a report for Aarhus Municipality describing the future requirements for flexibility in the energy system.

The report was discussed on June 6th, 2012 with representatives from Aarhus University, Energinet.dk, The Danish District Energy Development Center, NRGi, Ea Energy Analyses, and Aarhus Municipality's Climate Department.

At the meeting the conclusions in the report were met with wide support from the representatives. Discussions gave rise to undertaking a few adjustments to the report, which are incorporated in the present version.

Furthermore, a number of topics that could prove interesting to work with further were identified:

- With regard to heat pumps and heat storages: How are these technologies best implemented? A demonstration project in Aarhus could be used as a case study for similar actions elsewhere.
- The role of solar energy could be further investigated – with regards to both electricity and heat: What is the potential, and what specific challenges does it present, e.g. in the distribution net?
- Correlation between integration of solar energy and integration of wind energy.
- An assessment of what an increase in the proportion of decentralised technologies means in relation to the overall system.
- What synergies and complications can arise due to the use of different technologies in combination (when assessed according to their ability to integrate renewable energy)?
- Seasonal and hourly varying district heating prices that reflect variable costs in the production price.
- What are the opportunities for flexible heat consumption, e.g. low cost district heating for the dishwasher during summer?
- Further work with business clusters and collaboration between municipalities (strategic energy planning).
- Reliable market solutions for the purchase of green electricity and heat.
- Challenges related to the discrepancy between municipal and national accounting, for example, electricity production from wind turbines is calculated differently.
- An assessment of what will happen in the time period between 2020, 2035 and 2050 – when will the problems occur? Which measures should be demonstrated and tested now in order for them to play a crucial role after 2020 and 2035?
- Possibility to commission reserve capacity from mothballed plants if there has been a month with little wind (Aarhus University is conducting such an analysis)

The next step will be getting an overview of which topics are already being worked with in other forums, and which are of interest for further research within this participant group.

Ea Energianalyse

The future requirements for flexibility in the energy system

With focus on the integration of wind power

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Produced by:

Ea Energianalyse
Frederiksholms Kanal 4, 3. th.
1220 København K
Denmark
T: +45 88 70 70 83
F: +45 33 32 16 61
E-mail: info@eaea.dk
Homepage: www.eaea.dk

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1 Summary and conclusion

The realisation of a fossil-free Danish energy system demands a much greater share of renewable energy than utilised today. In Denmark there is particular focus on further wind power development and increased biomass usage, with other renewable technologies such as solar, wave and tidal also playing a role. Whereas increased use of biomass can easily be accommodated into the current system, integrating large amounts of fluctuating electricity production from wind and solar power poses one of the greatest challenges to the future system. For this reason it is one of the primary driving forces behind the development of a dynamic energy system in Denmark. This report focuses on the challenges involved in integrating wind power.

A major expansion of wind energy in Denmark will be accompanied by a number of challenges, and these challenges must be dealt with in parallel to the expansion. In contrast to conventional power stations and combined heat and power plants (CHPs), where supply can to a large extent be adjusted to match demand, power production from wind is both highly variable and relatively difficult to predict. The three greatest challenges associated with integrating wind are:

1. To ensure the value of wind on windy days, thus avoiding the sale of large amounts of wind power at low or negative prices.
2. To ensure sufficient production capacity when it is not windy. An expansion of wind power capacity will make it less attractive to build base load plants.
3. The balancing of wind power production, i.e. managing wind's unpredictable and fluctuating production patterns.

Technical solutions currently exist to deal with all three of these challenges; however, at this point in time many of them are not yet economically viable.

The challenge of integrating wind is not yet critical. Most analyses indicate that it will not be urgently necessary to introduce new and more advanced solutions until after 2020. The on-going development of the energy system has led to it becoming increasingly flexible. In addition, existing plans for system development, including expansion of the transmission network that allow for exchange with neighbouring countries, creates a solid foundation for accommodating increasing amounts of wind power through to 2020.

Of the outlined options, up till 2020, the district heating sector is expected to deliver the most significant contribution to wind power integration. Among other things, this will be realised by increased utilisation of heat storages, heat pumps, and electric boilers. In addition, centralised and decentralised power plants can be expected to increase their ability to deliver balancing services.

The most important means after 2020 will most likely be continued expansion of transmission capacity, and a further utilisation of electricity for heat production in the district heating sector. In addition to this, increases in electric vehicle and individual heat pump deployment will also contribute to integrating wind power.

The main argument for delaying the introduction of certain technologies is the current high market price of the technology. This is for example the case for electric vehicles, which are quite expensive, primarily due to the cost of their batteries. For other technologies the problem is the lack of low prices (i.e. insufficient demand), which makes them economically uninteresting to introduce before 2020. An example of this is the installation of electric boilers in industry. In addition to this, some measures may have a negative environmental impact if they are introduced in the short term before the majority of the electricity supply is converted to renewable sources.

The various measures outlined contribute to different aspects of wind power integration. Many of the outlined means are well-suited to the balancing of wind power, while there are fewer measures that are able to cope with periods with either too much or too little wind power production. Transmission connections are particularly useful as they can contribute to solving all three problems. In terms of ensuring the value of wind, the possibilities for integrating wind via the district heating sector are particularly interesting. With respect to ensuring sufficient capacity when there is little or no wind, it is necessary to have sufficient production capacity (e.g. peak load plants), and the ability to import electricity via interconnectors. Existing and new electricity consumption (heat pumps, electric vehicles, etc.) can also assist by not drawing electricity during periods of the day when the electricity system is most hard-pressed.

On the whole, it is important to consider the various measures in combination with the overall energy system. There is not one single measure that can manage all the challenges, and many of the measures supplement one another. It is therefore not possible to consider the relationship between wind power production and the individual measure as a direct relationship between problem and solution. The various measures should instead be thought of as elements that each contribute to the overall energy system, and thereby contribute to strengthening the flexibility and adaptability of the system.

2 Introduction

Ea Energy Analyses has carried out an analysis for Aarhus Municipality regarding the future requirements for flexibility in the energy system, and the potential means for meeting these requirements. The background for this request is the Danish Government's ambition to increase wind powers proportion of electricity consumption to 50% by 2020, convert electricity and heat supply to 100% renewable energy by 2035, and make the energy system, including the transport sector, fossil-free by 2050.

Aarhus Municipality has a vision of being CO_2 neutral as a society by 2030. The municipality therefore has a number of challenges to address in terms of converting the existing energy system. At the same time, these challenges also provide an opportunity to bring new solutions and technologies into use which will benefit both businesses and citizens in Aarhus. To concretise the Municipality's vision, the City Council unanimously passed Aarhus Municipality's Climate Plan for 2012-2015 in October of 2011. The Climate Plan focuses on five strategic main tracks: fossil-free energy, increasing energy efficiency in buildings and homes, energy-efficient transport, the intelligent energy system and export. With this plan, the municipality aims to generate progress and innovation by building up new systems and infrastructure, both technically and organisationally.

Wind power development – and in the long term other fluctuating energy production[1] – creates a number of challenges for the energy system. The aim of this report is to shed light upon the needs for, and effects of, various strategies to integrate wind power and clarify when it would be appropriate to introduce these measures. The analysis starts by looking at the technical solutions and focuses hereafter on the socioeconomic and corporate sector economic possibilities for implementing the various strategies. It must be noted that the framework conditions in the form of taxes and subsidies have a significant impact with respect to which technological solutions both businesses and private individuals will find most attractive to implement.

The Integration of wind power is one of the primary driving forces behind the development of a dynamic energy system in Denmark, but it is not the only one. Other technologies, such as photovoltaics (PV), electric vehicles (EV) and

[1] Other fluctuating energy sources include solar power and hydroelectricity, which in the long run are expected to play a role in Danish energy production.

electrical heat pumps, can also pose challenges for the existing energy system as they can cause either very high electricity production (PVs), or consumption (EVs and heat pumps), in the distribution network. These challenges are of a different nature than the challenges involved in the integration of wind[2] and are therefore not the focus of a detailed analysis in this report[3].

Background notes – focus on the individual strategy

As a supplement to this report a number of background reports have been compiled, where selected strategies are described in further detail. Each appendix includes an evaluation of the strategy with focus on which elements of the above-mentioned challenges it can help to solve. In addition, potential problems associated with utilising the particular technology and its potential for use is also described. Lastly, the economic value of the solution is assessed.

Appendices have been compiled for the following strategies:

- Electric vehicles
- Individual heat pumps
- Central heat pumps and electric boilers in the district heating system
- Storage technologies
- Heat storages
- Flexible demand

[2] E.g. a high prevalence of electric cars would create problems for the low voltage grid, which can either be dealt with by expanding the network, or by developing an intelligent management of the existing network.

[3] It is worth noting however, that during the past year there has been an extremely rapid increase of photovoltaic systems in Denmark. In May of last year there was roughly 1,000 PV systems installed in Denmark, while at the beginning of June 2012 there was nearly 9,000 systems in operation. By the end of 2012 it is expected that over 25,000 PV systems will be installed (Politiken, June 9th, 2012 ''Solceller leverer mindre end lovet'' (PVs deliver less than promised), with a total capacity of over 150 MW (Assumes an average capacity of 6 kW per system, which is likely on the high end). In comparison with the installed wind capacity of roughly 4,000 MW, PVs are still of much less importance to the overall system. However, the installed capacity will likely increase rapidly going forward if PV systems continue to be billed according to the favourable 'nettoafregning' (net settlement) system, and along with this growth will come increased challenges related to PV integration, particularly in the distribution grids.

3 Challenges with integrating wind

The Danish Government has set a target that more than half of the traditional electricity consumption[4] in 2020 be supplied by wind. In the longer term, up till 2030, this wind expansion can be expected to increase even further as part of the Government's objective to achieve a 100% renewable-based electricity and heating supply in 2035. The Government proposal "Our Energy" indicates that wind power could supply 2/3 of electricity consumption in 2030. In the more distant future, the Danish Climate Commission expects that by 2050 the fluctuating share of electricity production could reach 80-90%. By far the largest portion of this fluctuating electricity production is expected to come from wind power.

The extent of development in the wind sector undertaken in order to achieve the ultimate aim of reaching fossil-fuel independency in the long term will, among other things, depend on the amount of biomass that is available at a reasonable price, and whether carbon capture and storage (CCS) becomes economically attractive and politically acceptable. The distribution between different energy sources for electricity production in the Government's proposal "Our Energy" is illustrated in the figure below.

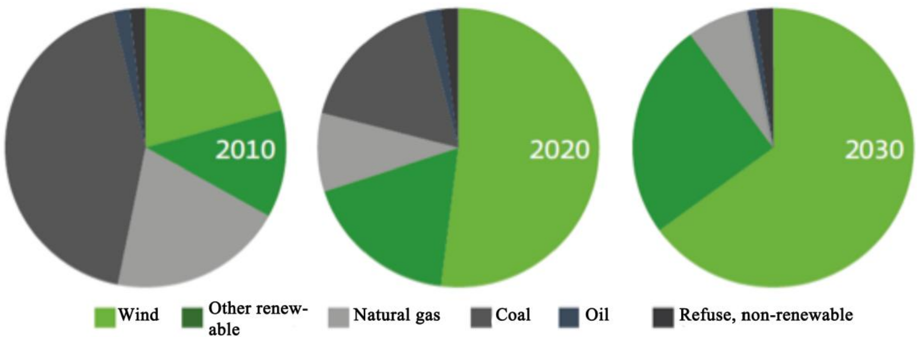

Figure 1: Electricity production grouped by energy source according to the Government's energy proposal "Our Energy" (corrected for import and export)[5]. (Regeringen, 2011)

3.1 Three challenges

In looking at the various types of production capacity, there are vast differences in their characteristics. Contrary to conventional power plants and

[4] The traditional electricity consumption encompasses the kinds of electricity consumption that exist today, such as electricity use for lighting and household appliances. Non-traditional electricity consumption is the anticipated electricity consumption for heat pumps and electric vehicles, which will cause the total electricity demand to rise.

[5] The term "refuse, non-renewable" encompasses the fossil-based share of the total amount of waste sent to incineration and is also termed as non-biodegradable waste. In the Energy Agency's "Energy Statistics 2010" it is assumed that 58.8% of the waste used in the production of electricity and district heating is biodegradable.

CHPs where production can, to a large extent, be adjusted to match demand, the production of electricity from wind varies and can be relatively difficult to predict.[6]

In addition to this, wind turbines also have relatively low capacity factors (ratio of the actual output of a production unit to its potential output if it had operated at full nameplate capacity). Land-based wind turbines have capacity factors around 30%, while off shore wind turbines, with their more stable wind conditions, have capacity factors of nearly 50%. This means that there are periods in which large amounts of wind energy are available, while at other times there are long periods without any wind power production at all. In order to maintain the balance between electricity supply and demand, these large fluctuations in production require that the rest of the overall energy system be quite dynamic.

Three main challenges

Generally speaking, due to the fluctuating and intermittent nature of wind, there are three main challenges associated with integrating wind power:

1. To ensure the value of wind when it is very windy.
2. To ensure sufficient production capacity when there is no wind. Wind power expansion results in it being less attractive to build base load plants.
3. To balance wind power production, i.e. managing wind's both unpredictable and fluctuating production patterns.

All three of these main challenges associated with integrating wind power are fundamentally economic challenges, as technical solutions to cope with these issues already exist today. Other than the three above-mentioned challenges, a widespread move away from conventional power plants would create a need for so-called system-supporting properties (ancillary services) such as short circuit power, voltage control and reactive reserves from other units. This challenge is however deemed to be less significant as the System Operator, Energinet.dk, already has concrete plans and initiatives to cope with the challenge of sourcing ancillary services. This challenge is therefore not addressed in detail within this report.[7]

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[6] Despite systems becoming better and better at predicting wind patterns, there is still a challenge in predicting electricity production, especially in 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 of wind prognoses in Denmark is approximately 6% (12-36 hours forecast). Overview of wind resources in Denmark: http://www.emd.dk/files/windres/WinResDK.pdf

[7] In relation to delivering system-supporting properties (ancillary services), it is expected that inverter-based production such as wind power, fuel cells, solar cells, as well as converter-based consumption such as electric cars and heat pumps will be able meet the majority of these demands. Synchronous compensators without a power plant will also be able to deliver ancillary services in the form of short circuit power and

Challenge 1. Ensuring the value of wind when it is very windy

If a large part of the produced wind power electricity is sold at low or negative prices it damages the wind turbine's economy and thereby reduces the incentive to invest in new wind turbines. For this reason it is crucial to ensure the value of wind, both to maintain its socioeconomic value, and in order to preserve the economic foundation for continued wind power development. The initial solution is to reduce production at other power production units, export to neighbouring countries, or to increase electricity consumption where this is economically attractive. When these alternatives have been exhausted it would be possible to halt or reduce production from some of the wind turbines, both for shorter periods consisting of a few minutes, or for longer periods extending several hours. This is possible 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 is dynamic. In a future with a large share of wind power, it will likely be economically beneficial to stop some wind turbines every now and then.

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

The challenge of ensuring sufficient production capacity can be dealt with in several ways: establishing peak load production capacity such as gas turbines, or via a closer integration of the Danish electrical grid with neighbouring countries. Flexible electricity consumption and the activation of emergency power generators are also interesting possibilities that are, to a certain extent, already in use. The value of the various alternatives depends in particular upon the length of the duration that the strategy can be used. While certain types of flexible electricity consumption can only provide a solution for a number of hours with lacking capacity, other possibilities such as peak load plants or international grid connections can be used over longer periods of time with no wind power production, which potentially could last for a number of weeks.

Challenge 3. Balancing wind power

There is a need for balancing if e.g. the production from wind power falls unpredictably, either as a result of altered wind conditions, or due to production issues caused by technical problems or damage to the turbines. The latter also applies for fallouts from other production units or transmission connections. Balancing can be achieved either by production units or

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voltage regulation. Energinet.dk has signed a contract with Siemens for an order of synchronous compensators to be used to support the electric voltage in the electricity grid. In addition, Energinet.dk, is also working on alternative solutions to ensure the stability of the grid.

consumers being prepared to change their production/consumption patterns with relatively short notice (see the text box below). Gas turbines can be well suited to meet this need, but also other productions units, electric boilers, or electrical heat pumps, and other consumption units can provide balancing services. Increased integration with neighbouring countries' energy systems can also provide access to more sources capable of providing balancing. The difference between the first two challenges, and the challenge related to balancing, is that with balancing the problem relates mainly to the unpredictability in wind energy production.

In the first two challenges the problem is typically known in advance, while in the third challenge, problems can occur with a moment's notice.

The greatest challenges
It is difficult to measure the challenges against each other, however the first two challenges are likely more problematic than the third challenge, which entails the balancing of wind power.

Balancing

One condition for a well-functioning energy system is a constant balance of production and consumption, right down to the second. To ensure this balance all large electricity markets are comprised of two phases, a planning phase (typically the day before), and a real-time phase, where corrections are made in cases where previous planning proves to be incorrect. In addition to this, the system requires access to reserves in case of accidents or larger system failures. There are different kinds of reserves that the system operator (Energinet.dk) draws upon to maintain balance in the system. The various types can be divided into primary, secondary and tertiary reserves. Primary reserves are automatic reserves that can be activated within a second to counteract frequency deviations. Secondary reserves are also automatic and can be used to re-establish the primary reserves. Their reaction time is almost as quick as that of the primary reserves. The tertiary reserves are manual reserves, also referred to as regulating power, and can be brought into use within 15 minutes to provide either up or down regulation for the system. Balancing can last for just a few seconds, or up to a number of hours.

Until an hour before the hour of operation, actors in the electricity market have the possibility of trading so as to avoid imbalances. This trade takes place in the intraday Elbas market.

3.2 Electricity prices as indicators of challenges

The number of kWh with very low electricity prices can be used as an indicator of the challenges related to integrating wind power.

In the electricity market the market price is established every hour by the marginal power plant, that is to say the power plant that has bid in at the highest price. In hours with low consumption, for example at night or in the summer, today it will typically be the traditional base load plants that determine the market price. However, in hours of high consumption it is the peak load plants, which are often less efficient and use more expensive fuels, that decide the price. As a result, electricity prices are generally higher during the winter than in the summer, and likewise higher during the day than during the night.

Electricity producers' revenue thus depends upon what possibilities they have to organise their production in relation to when there is a need for electricity production.

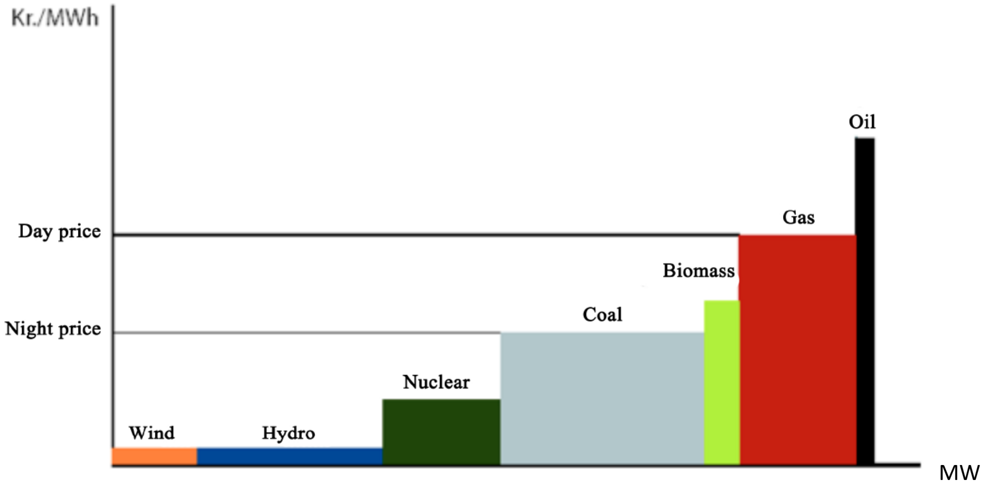

Figure 2: Stylised demand/supply curve for the Scandinavian and German electricity market. Wind power farms would most likely bid in at the lowest costs in the electricity market, as they don't have any fuel costs to cover. The same applies in principal to hydroelectricity – however hydroelectric plants with a storage capacity have the possibility of holding back production and thereby optimising their production in accordance with the expected market prices for electricity. Hereafter follows nuclear energy, coal and biomass plants, which are more expensive than hydro and wind, but also have relatively low fuel costs, and finally gas and oil fired plants.

Wind turbines would typically bid in at the lowest cost on the electricity market. This is due to the fact that wind power production does not involve any fuels costs. When the turbines are producing, they force the expensive power plants out of the electricity market, which thereby lowers the market price of electricity. In this way wind power has a price lowering effect on the electricity market during periods of high wind levels. Large amounts of wind power production can also lead to hydroelectric plants withholding their production till a later time when electricity price levels are higher. This means that wind power can indirectly exert a price deflating effect even during periods when wind power production is low.

The value of wind power will in a market-based system be expressed as the value that the market ascribes the production, directly expressed through the price of electricity. The price that the wind turbine can sell its production for in the market can be regarded as the socioeconomic value of wind turbine power production.[8]

[8] 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.

The figure below shows the correlation between wind power production in West Denmark and the market price of electricity in the same area in 2011. The figure shows that electricity prices generally are lower when it is windy, which is due to the most expensive power plants being pushed out of the market. When wind power production is zero, the price of electricity is on average 39 øre/kWh (50 €/MWh) and at maximum wind production of 2,500MW the price of electricity is on average around 30 øre/kWh (40 €/MWh).

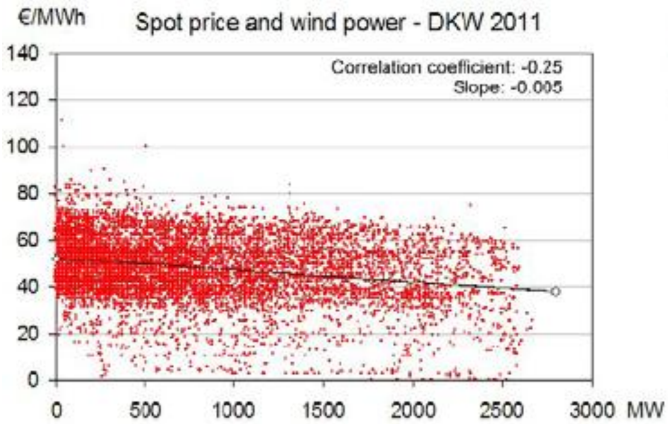

Figure 3: Correlation between wind power production in West Denmark and the market price of electricity in Euro per MW. (Bach, 2012)

The number of hours with very low electricity market prices can be used as an indicator of the challenges related to integrating wind power.[9,10]

Prices with a value of zero today

Prices with a value of zero (or even negative prices[11]) can occur in the electricity market when a quantity of electricity greater than the sum of consumption and export is offered at prices equal to zero. These extremely low prices already occur today, although only to a limited extent. This usually

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[9] A more precise, yet more complicated indicator is to compare the average market price of electricity that wind turbines can sell their production to over the year with the average price that a consumer can purchase electricity for from the market. This indicator gives a precise picture of wind power's utility for the electricity system.

[10] To the extent of the authors' knowledge, there is no definition of low or high electricity prices. If such a definition were to be made it could take the marginal production costs for key technologies in the electricity market into account. The precise level would depend on fuel prices and CO_2 prices amongst other things:

- High electricity prices: Electricity price is higher than the marginal cost of producing electricity at a central condensing power plant.
- Low electricity prices: Electricity price is lower than the marginal cost of producing electricity at a CHP.
- Very low electricity prices: Electricity prices are lower than the marginal cost of producing heat with a heating boiler. This means that the price of electricity is so low that it is cost-effective to use electricity directly to produce heat.

[11] Negative electricity prices can occur due to, among other things, the majority of renewable energy producers receiving a production subsidy on top of the price they receive for selling electricity on the market. For example all wind turbines connected to the national grid in 2000 or later received an extra payment, which means that these producers have an incentive to sell their electricity at a negative price to be sure to receive this subsidy.

happens when electricity production is high in comparison to consumption, and there simultaneously is a limited capacity for transfer of electricity on the foreign connections. Most of these low prices occur during the night in the winter (Ea 2009a).

Year	West Denmark	East Denmark	Wind power share
2002	30	0	12%
2003	83	1	12%
2004	1	4	16%
2005	16	7	18%
2006	28	5	13%
2007	85	30	18%
2008	28	9	19%
2009	55 (9)	4 (0)	18%
2010	12 (11)	6 (5)	20%
2011	18 (15)	17 (14)	28%
2012 (til 21st sep)	7 (7)	6 (6)	28%

Table 1: The number of hours with prices with a value of zero in the period 2002-2010, along with the share of wind power as a portion of the total electricity production. For 2009 and 2010 the share of hours with negative prices are given in parentheses[12] (Energistyrelsen, 2011).

In looking at the development in the number of hours with prices of zero value or less over the last 10 years, there has not been a significant rise, despite the fact that the share of wind power has increased during the same period. This is presumably due to the improvements in the market that have been made over the same period that have allowed for a more flexible interplay between wind and CHPs, expanded transmission capacity, and improved conditions for using electricity in heat production. It should be noted that in 2003 and 2007 there were more hours with zero value prices than in other years. This could be a result of coincidences (many hours with low electricity consumption in combination with a high level of wind power production), or the result of transmission cable outages. As it does not reflect a general tendency, the underlying cause is not examined further in this report.

[12] Negative electricity prices were introduced to the power market Nord Pool Spot on the 30th November 2009.

4 Expectation for electricity price development

In connection with Ea Energy Analyses' work for, amongst others, The Climate Commission, a number of model calculations have been generated using the electricity market model Balmorel. The objective was to demonstrate what electricity prices might look like in 2020 and 2050, as well as to determine how significant the problems related to low and negative electricity prices may be in the future.

The Climate Commission's various future scenarios are very similar to the current government's visions for development, and as such the Commission's prognoses are utilised to provide an illustration of the expected electricity price development.

4.1 Projection of electricity prices in 2020

The model calculations for The Climate Commission are based on a projection of the Danish energy system where a substantial wind power expansion (corresponding to the criteria for The Climate Commission's Scenario A) occurs up to 2020. In this scenario wind production increases from just under 7 TWh in 2009 to approximately 17 TWh in 2020 – primarily through the establishment of new offshore wind farms.[13] In addition to this, a significant number of Danish coal-fired power stations will be converted to biomass, while biogas is assumed to play an important role in non-central CHPs. It is presumed that Denmark's neighbouring countries will also fulfil their 2020 EU goals, with wind development playing a significant role therein.

Large-scale wind power expansion in Denmark and its neighbouring countries is expected to lead to greater fluctuation in electricity prices. This being said, it should also be noted that initiatives that could suppress these fluctuations, for example expanding the transmission capacity between Denmark and neighbouring countries, have been included in these projections.[14] In addition, a conversion to heat pumps/electric boilers in the district heating sector is

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[13] For the sake of comparison, production from wind power in "Our Energy" is expected to be around 22TWh in 2020

[14] These include the Skagerrak connection to Norway, strengthening connections between West Denmark and Germany, and establishing the Cobra cable between West Denmark and the Netherlands.

incorporated, and an increase of electricity consumption for electric vehicles and individual heat pumps is also expected.[15,16]

The projections displayed in Figure 4 will thus look slightly different if it is instead assumed that no further wind integration initiatives are implemented.

The figure below shows a comparison of the actual electricity prices in 2009 with the prices for 2010 and 2020 that were calculated using the model. The prices derived from the model are calculated based on a normal precipitation year and with an assumption of "perfect" knowledge of the future. There are no unforeseen occurrences included in the model, such as power stations outages for example, which do occur in the real electricity market and can cause higher prices. The model's electricity prices are therefore most comparable with the Nord Pool spot price. When looking at the operational day, electricity price variation will therefore be higher than what the model displays.

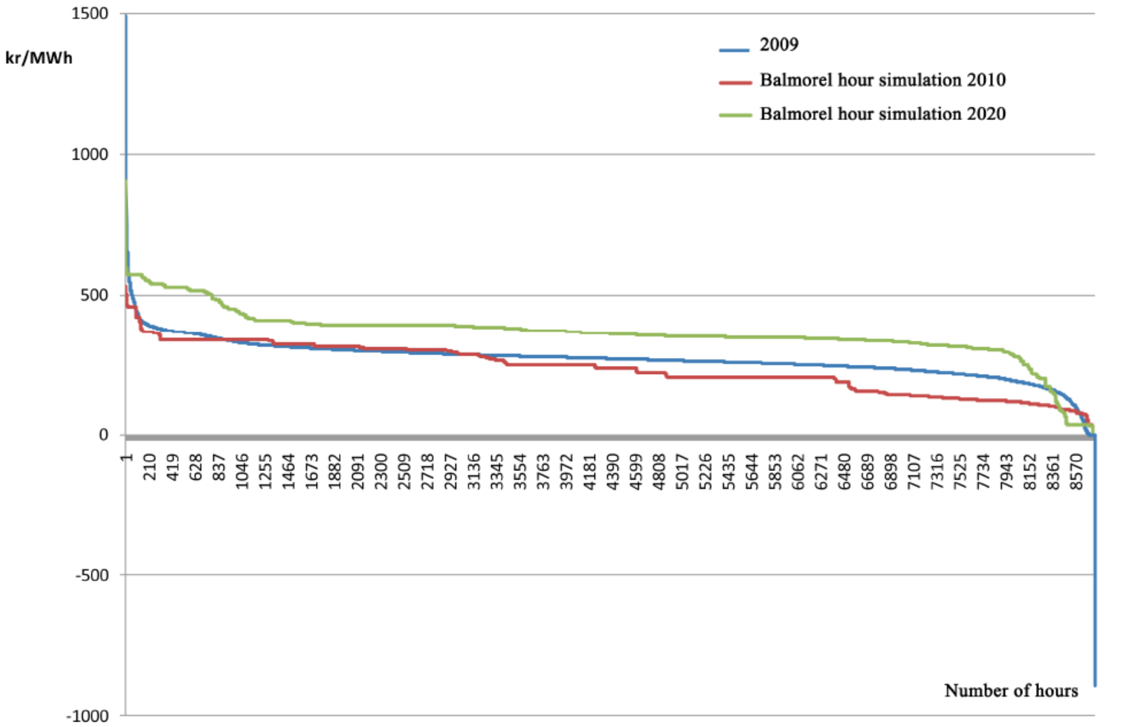

Figure 4: Comparison of actual electricity prices in 2009 with the model calculated prices for 2010 and 2020.

[15] Central heat pumps with an electrical capacity of approximately 90 MW and electric boilers with a capacity of 290 MW. Energinet.dk estimates that there are currently 250 MW electric boilers in Denmark (Energinet.dk, 2011a)

[16] For electric vehicles and individual heat pumps the electricity consumption is estimated to be just over 1 TWh in 2020 (The total electricity consumption in 2020 is expected to be 37 TWh in 2020, while in 2010 it was just over 35 TWh).

As can be seen in the graph, electricity prices in 2020 will generally be at a higher level than they are today. This is because the conventional coal and gas-fired power stations typically set the price level for electricity, and as fuel and CO_2 costs rise, so too will the marginal production costs of these plants. The number of hours with very low price levels will also rise slightly. In general however, the price patterns in 2020 will not be radically different from those we see today. In total there will be approximately 309 hours in 2020 where electricity prices will be lower than 10 øre/kWh (there were 181 hours in 2009).

The calculations indicate that generally speaking there will not be significantly larger price variations than we experience today.

4.2 Projection of electricity prices in 2050

In conjunction with the aforementioned Climate Commission work, a similar modelling exercise for the expected development of electricity prices in a system with a large share of wind power has also been calculated for 2050. The calculations show substantial price variations both in comparison to the current electricity system, and in comparison to the calculations made for 2020.

A large number of initiatives have been incorporated in the 2050 analysis, which, amongst other things, assist in the integration of wind:

- Doubling the exchange capacity with foreign countries
- Establishing heat pumps and electric boilers in the district heating system on a large scale (approx. 18 PJ /5 TWh electricity consumption)
- Individual heat pumps (approx. 18 PJ /5 TWh electricity consumption)
- Expanding heat storage in the district heating system (30 GWh extra, approximately double the current capacity)
- Flexible electric cars and other electrically powered vehicles (83 PJ /23 TWh electricity consumption)
- Production of biomass-based transport fuels with a certain flexibility (43 PJ/12 TWh)
- Dynamic production units (e.g. gas turbines and motors running on biogas). In total roughly 6,000 MW thermal capacity where just over 5,000 MW is from gas turbines or gas motors
- Increased flexibility in industrial electricity consumption (approx. 90 PJ/25 TWh). There is also a possibility of converting boilers to run on biomass.

The combination of these initiatives contributes to a massive increase in the total electricity consumption, which is expected to be two and half times as large as it is today. If these initiatives are not incorporated the price pattern will fluctuate more than that illustrated in Figure 5 below, and the value of wind power will be lower. Without these initiatives the electricity system as a whole in 2050 will be different from the modelled one above, as the total electricity consumption will be significantly lower. This lower consumption would also influence the amount of wind capacity it would be financially viable to establish.

The figure below shows the distribution of electricity prices in West Denmark in 2009 (blue line) and the projection for 2050 (red line). The price in 2050 is expected to fluctuate between roughly 100kr./MWh (close to 0[17]) and 1000 kr./MWh. When prices are occasionally very high, it is usually caused by two factors: partly due to increased fuel prices (including biomass), and partly due to the fact that wind turbines erode the financial viability of base load production, thus resulting in more expensive medium and peak load units producing when production from wind power is low.

Even with all the above measures in place to assist in the integration of wind, in West Denmark the model indicates that there will be approximately 1,400 hours where a portion of the electricity production from wind turbines cannot be used. It is thus necessary to trim roughly 5% of the potential wind production in Denmark, corresponding to approximately 14 PJ.

[17] There are variable running and maintenance costs on wind turbines, which means that the electricity price doesn’t quite reach zero.

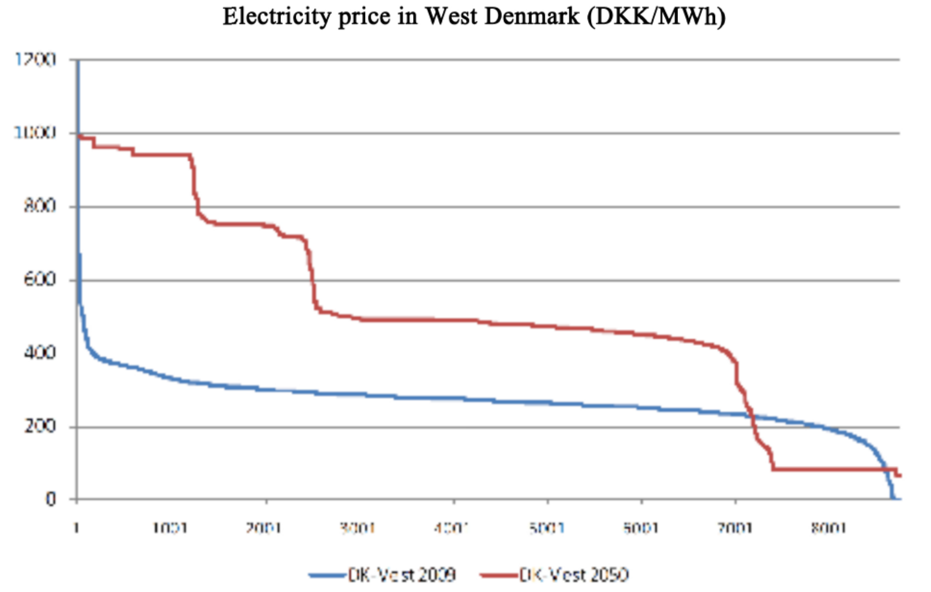

Figure 5: Duration curve for electricity prices in West Denmark calculated using Balmorel in 2050 compared with the electricity prices in 2009 (Ea 2010).

4.3 Electricity sales and purchase prices

The price that production technologies can sell their electricity for expresses their value for the electricity system. By comparing the average income for each sold kWh with the technology's corresponding production costs, it is possible to judge whether it is economically viable to invest in the technology.

In conjunction with the work for The Climate Commission an analysis was made regarding what prices various electricity production technologies and consumers respectively are paid, or pay, for electricity on the Northern European market. These prices are displayed in the table below.

Production	West Denmark
Offshore wind	35-37
Onshore wind	45
Solar panels	53*
Wave power	37
Centralised biogas plant	60
Biogas turbines	97
Biogas CC	83
Wood chip-fired CHP-plants	96
Consumption	**West Denmark**
Classic consumption	52
Centralised electric boilers	33
Centralised heat pumps	35-46
Individual heat pumps	54
Electric vehicles	35-46
Biofuel production	35

*Table 2: The average market prices for electricity in øre/kWh in 2050, calculated using hourly simulations for the ambitious future Scenario A, with the electricity and heating model Balmorel. When intervals are given this reflects differences caused by variations in efficiency, production/consumer profiles and variable running and maintenance costs. *Due to a fault in the model it has not been possible to calculate prices for solar production in West Denmark so the price has therefore been estimated using prices from East Denmark.*

With regards to the production technologies, the table clearly shows that the fluctuating electricity production from renewable sources receive a lower payment per unit of electricity than biomass-based adjustable electricity production technologies. Biogas turbines are the most expensive, which is due to the high production costs involved and the limited annual fuel supply, thus resulting in biogas turbines only successfully bidding into the electricity market during the most expensive hours. The average payment for biogas is therefore very close to the highest electricity prices. Offshore wind production, which is the greatest source of fluctuating electricity production, receives the lowest average payment of 35 øre/kWh. Onshore wind production has a slightly different production profile in West Denmark, and it therefore receives a somewhat higher payment.

Similar patterns can been seen on the consumption side where new forms of electricity consumption are able to exploit hours with low prices and are therefore able to reach a lower average price in comparison to the less flexible classic consumption. The price of classic consumption (52 øre/kWh) is slightly higher than the simple time-weighted average of 51 øre/kWh. Central electric boilers and heat pumps, electric vehicles and electricity consumption used in biofuel production are to a high degree able to adapt their consumption to the fluctuating wind production from offshore wind. As a result their average electricity prices are very similar to the payment that offshore wind turbines receive.

When comparing the electricity price that centralised and individual heat pumps respectively pay for their electricity consumption we can observe a difference of up to 19 øre/kWh in favour of the centralised heat pumps. This is an indicator of the value of being able to adapt heat production to the current electricity price. Depending on their location, centralised heat pumps have the possibility of exploiting heat stores or alternative heat production to avoid consuming electricity during peak price periods.

5 Strategies to integrate wind

As was revealed in the previous chapter, the challenges of integrating wind are not urgent in the short term. This is due to the fact that options for incorporating more wind in the current system are good, and because a number of measures have already been initiated to integrate wind, e.g. concrete plans to expand the transmission capacity to neighbouring countries (see footnote in section 4.1). In the years up to 2020 it is expected that the district heating sector will be able to contribute significantly to accommodating more wind power by increasing the use of turbine bypass, heat storage, and heat pumps and electrical boilers. Looking towards 2050 however, the challenges are expected to grow, which will necessitate the utilisation of other wind integration measures.

The following section will discuss various solutions for dealing with the three main challenges associated with integrating wind power. These strategies will then be put into chronological order according to when it is deemed that they will be economically viable to be introduced.

5.1 Strategies to ensure the value of wind when it is windy – challenge 1

Periods with high wind levels, and therefore a high level of wind power production, can both occur for shorter periods of time lasting just a few hours, or can last for a number of days. Typically the latter will be the case though, as periods of high production will have longer durations.

Exchange with neighbouring countries, hydropower as storage for wind

The market-based exchange with Denmark's neighbouring countries has historically been one of the most important means of integrating wind power production. Trade between Denmark and Norway/Sweden has been one of the most effective ways of ensuring the value of wind. Trading in electricity contributes to the evening out of fluctuations in electricity consumption and production between countries, and ensures that it is the cheapest power stations that are producing. Via the electricity market, the Nordic hydropower stations function as a 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. Meanwhile, when electricity prices are high they increase their production.

In the Nordic context wind power still holds a fairly limited share of the total electricity supply, so there are great opportunities to integrate wind via hydropower storage. The exchange capacity between the Nordic countries and internally within Norway and Sweden will most likely be the initial barrier to exploiting the full potential for trading wind and hydro-based electricity between countries. West Denmark is currently connected to Norway and Sweden via the Skagerrak and the Kattegat cables respectively, and East Denmark is connected to Sweden via a cable across Øresund.

Expansion of the electricity transmissions capacity will therefore also be an important means of integrating wind power in the future.

Energinet.dk is currently in the process of increasing the capacity of the Skagerrak connection so that by 2014 it will be 1,700 MW, up from its current 1,000 MW. In addition to this, Energinet.dk is investigating: the possibility of expanding the transmission network between Jutland and Germany, the so-called "COBRA cable" between Jutland and the Netherlands, as well as establishing a new connection between Zealand and Germany to link up the wind farm, Kriegers Flak. Energinet.dk has also investigated the possibility of yet another Great Belt connection, but current analyses suggests that it is not yet socioeconomically cost-effective to make such an investment.[18]

Improving interplay between the electricity and heating systems and reducing heat-based production

A very large portion of Danish electricity production is connected to the district heating system. With the exception of a few plants, all power stations in Denmark have the possibility of co-generating electricity and district heat. This results in restrictions with respect to the ability to integrate wind, as electricity production is to a certain extent dictated by the heat demand.

Most central plants are CHP plants, which can switch between producing only electricity (referred to as condensation mode), and producing both district heat and electricity. The smaller decentralised power plants are mainly so-called backpressure steam plants, which produce electricity and heat at a particular ratio. They can normally only produce electricity when they also have the possibility of selling produced heat.

Heat stores have been established in conjunction with the majority of the Danish CHP plants. These heat accumulators are usually designed to store roughly 8 hours worth of heat production. Heat stores increase the flexibility

[18] http://www.energinet.dk/DA/El/Nyheder/Sider/Ny-%C3%B8st-vest-elforbindelse-ikke-rentabel-p-%C3%A5nuv%C3%A6rende-tidspunkt.aspx . For a description of the other planned infrastructure projects, please refer to Energinet.dk's system plan 2011 http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Om%20os/Systemplan_2011.pdf

of the electricity system as the CHPs can reduce or stop production of heat and electricity during windy periods, and instead supply their heating customers with heat from the heat accumulators.

Larger heat stores are one 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.

In other situations it can be necessary to stop cogeneration of electricity and heat all together. The production of cogenerated heat is environmentally and economically sensible as long as the alternative is letting the heat produced go to waste. However, in order to fully utilise the electricity produced by wind, it will become increasingly environmentally and socioeconomically attractive to decouple this link between heat and electricity production. In cold periods where wind turbines can cover electricity consumption, CHPs can for example let the steam bypass the turbines and use it directly to produce heat if they have installed a **'steam bypass'** system.[19] As such, when CHPs use steam bypass they effectively function like a boiler. Steam bypass systems can be installed relatively inexpensively (approximately 0.1 million DKK per MW), and have the advantage that the CHP's boiler is kept warm so that the plant can quickly be returned to electricity production mode when the winds subside.[20]

An alternative or additional possibility is using electricity to produce 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 4 times as much heat compared to the electricity they use, and can thereby contribute to a highly efficient overall energy usage. On the other hand, heat pump systems involve significant investments. An alternative to heat pumps with a substantially lower investment cost is electric boilers. 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,

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

[20] 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 investment necessary 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, 2009b: Placing increasing amounts of renewable energy into the electricity system, Report part 2: Catalogue of solutions)

whereas electric boilers are more cost-effective for applications involving fewer operating hours.

As both electric boilers and heat pumps involve an increase in electricity consumption, these solutions will contribute more to ensuring the value of wind than steam bypass, which merely stops or reduces electricity production.

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

There is also a great potential for flexible electricity consumption in industry. This involves replacing the current utilised fuel (oil or gas) to electricity based process heat, either from **electric boilers or potentially, high temperature heat pumps**, when electricity prices are low. Industry utilises much shorter payback periods than those used in the district heating sector, and in the short term this can pose a significant barrier for exploiting the potential from electric boilers and heat pumps in the industrial sector.

Storing electricity

A number of technologies have been discussed for the purpose of **storing electricity locally** in Denmark, including compressed air storage, batteries, flywheels, hydro reservoirs, and hydrogen production in combination with fuel cells. All these technologies are technologically possible, but they require large investments, and the majority are also associated with not insignificant energy losses related to storing large amounts of energy. With large-scale wind power integration it might become relevant to establish electricity storage in the local grid, especially if the economics involved in storage technologies become more favourable.

Overall it can prove most economical to design a system with a very large share of wind power such that a small proportion of the wind power production is anticipated to be lost each year[21], as the alternative can entail very large investments in the surrounding system. There is no direct cost associated with stopping wind turbine production. If the wind turbine's average production costs are 40 øre/kWh and it sells electricity for 0 øre/kWh, the loss involved in the inactive hour will be 40 øre/kWh.

[21] Even investing in cheaper integration measures such as electric boilers or steam bypass requires a certain number of low electricity prices to make them economically viable. It would therefore be economically sensible to allow a certain "waste" of electricity.

5.2 Strategies to ensure sufficient production capacity when it is not windy – challenge 2

Just as periods of high wind levels can last for several days, there are also times when low wind speeds can last for longer periods of time (days and even weeks). It is therefore necessary to have solutions that can be used in situations where wind power production is low for several days in a row.[22]

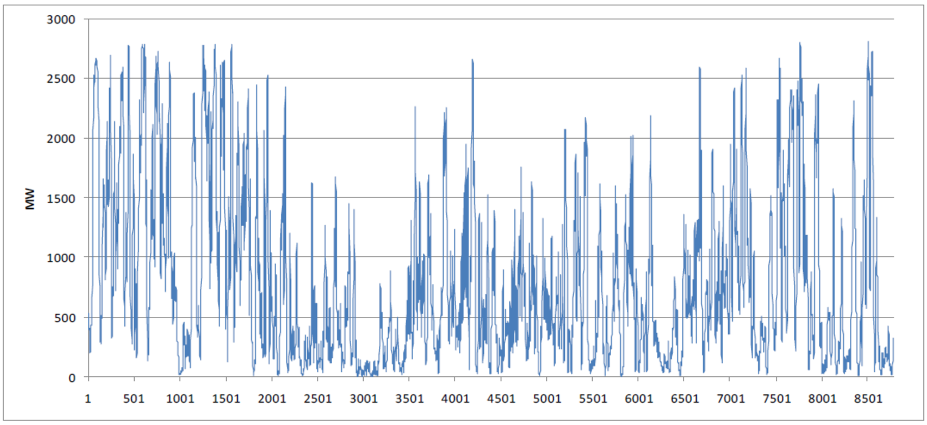

Figure 6: Electricity production from wind power. Hourly values, Denmark 2008.

The question of ensuring sufficient production capacity is an issue in all electricity markets, but the challenge is greater in a system with a large share of wind power as wind power reduces the revenue of conventional power plants and CHPs. The market prices of electricity must therefore be higher than normal in periods where the wind isn't blowing for it to be attractive to invest in power plant capacity. This represents a challenge for the functioning of the electricity market.

From a technical perspective, the issue of ensuring a sufficient production capacity can be dealt with in a number of ways: establishing peak-load production capacity, for example using gas turbines, exploiting existing capacity more extensively, for example by establishing cooling towers at de-centralised CHPs so that can produce electricity when there is no demand for district heating, or by more closely integrating the electricity system with neighbouring countries (importing hydropower).

Flexible electricity consumption from, for example, electric vehicles or individual heat pumps, could also be interesting options in the longer term. However, they will only be used for shorter periods of time lasting a couple of

[22] As shown in Figure 6, there was a period of roughly 10 days in a row in the year 2008 (randomly selected year) with very little wind power production (under 100 MW on average).

hours. If electric vehicles and heat pumps can avoid consuming electricity when the system is experiencing high demand, for instance around dinnertime in the evening, it would be possible to reduce the need for investments in peak load capacity.

It is the system operator Energinet.dk's task to ensure the security of supply. Energinet.dk monitors the energy security via, amongst other things, the power balance, which measures the expected peak consumption against the available production capacity.

Several of the Danish coal-fired power plant units have environmental operational limits, and within the last few years some units have been temporarily or permanently removed from operation. If only confirmed contracts for new power plants are taken into consideration, Energinet.dk therefore expects the power balance to be negative in Denmark from 2016 to 2020. Norway, Sweden and the Netherlands are, however, expected to have a power surplus, which means that Northern Europe as a whole is expected to have a surplus (Energinet.dk 2011b).

There is however a good deal of uncertainty regarding the situation in Germany where it is unknown which production plants will replace the 20,000 MW of nuclear power that is planned to be removed from operation before 2022. Energinet.dk therefore writes that *"it is necessary for Energinet.dk to keep a close eye on the power situation in neighbouring countries to ascertain the availability of imports".*

Energinet.dk further notes that they will *"continue to develop methods and indicators to judge the power balance and energy balance as well as to prepare action plans if developments in capacity are deemed to be critical for supply security"* (Energinet.dk 2011b). Important questions in this respect are the possibilities to factor wind power production into the power balance and the management of price-flexible electricity consumption.

If Energinet.dk considers the power balance to be critical it has the option of implementing a bidding system to procure new capacity to secure the power balance, or to enter into agreements with actors in the electricity market to keep certain power plants in a state of readiness that would otherwise have been removed from operation.

5.3 Strategies to balance wind power – challenge 3

The solutions for balancing wind power are to a certain extent the same as those to ensure the value of wind in periods with high levels of wind power production. Whereas periods of high wind can last for several days, the challenge of balancing wind power is limited to shorter periods of up to a few hours.

Gas turbines and gas motors are particularly well-suited to supply this balancing. Even though they are less flexible than gas turbines or gas motors, conventional boiler-based power plants, which use solid fuels (coal or biomass), also have good potential for supplying balancing services. In addition, electric boilers or electrically driven heat pumps in the district heating system can also provide balancing services. Closer integration with neighbouring countries' energy systems would also provide access to more sources for balancing. Lastly, we can expect a contribution from electric vehicles and heat pumps as these technologies evolve, as well as from other flexible electricity use in households (for example fridges) and industry.

5.4 The contribution of the various strategies to integrate wind

The contributions made by the various strategies to solve the problems involved with integrating wind power are summarised in the table 3. The most important initiatives are described in more detail in the separate background reports. It should be noted that the table only refers to the strategies' properties and not to their potential (in TWh/MW).

It is evident that many of the elements are suited to balancing wind, whilst there are fewer strategies capable of coping with periods of too much or too little wind. Transmission connections stand out as being able to contribute to solve all three problems. When it comes to ensuring the value of wind power, the possibilities of integrating wind using the district heating sector are particularly interesting.

With respect to dealing with periods with low wind levels, the challenge is to secure a sufficient production capacity (e.g. using peak load plants) and to have the option of importing electricity through exchange connections. Electricity consumption with an appropriate consumer profile, or electricity consumption that can be moved in time, can facilitate adaption of the overall electricity consumption to fit fluctuating wind power production. This can be achieved for both new and existing electricity consumption (heat pumps, electric vehicles, etc.) by avoiding using electricity at the times of the day when the electricity system is under most pressure.

Strategy	Ensuring the value of wind, when it is windy	Ensuring sufficient capacity when wind levels are low	Balancing wind power
Electric vehicles	XX	XX	XXX
Individual heat pumps	XX	X	XXX
Flexible domestic electricity consumption	X	XX	XXX
Flexible industrial electricity consumption	X	XX	XXX
Fuel-shift in industry (electric boilers)	XXXX	X	XXX
Cooling towers at decentralised CHPs		XXX	XXX
Centralised heat pumps (for district heating production)	XXX	XX	XXX
Centralised electric boilers (for district heating production)	XXXX	X	XXXX
Bypass at power plants	XXX		XXX
Heat stores	XXX	XX	XXX
Activating emergency power stations		XX	XX
Improving exchange connections	XXXX	XXX	XXXX
New peak load plants		XXXX	XXXX
Stopping wind turbines	X		XXX
Production of fuels for transport	XXX	XX	XXX

Table 3: Summary of the various measures properties in terms of coping with the challenges associated with integrating wind power. X: Limited effect. XX: Some effect. XXX. Significant effect. XXXX: Very significant effect.

6 Assessment of potential

There are large differences between the various solutions' potential roles and functions, and when it would be appropriate to introduce them into the energy system. The following section will assess the potential of the various strategies, and then describe the financial aspects as well as the time perspectives involved in developing the initiatives.

The assessment of potential is summarised in Table 4.

Table 4 also indicates to what extent it is the challenges associated with integration of wind that is the driving force behind the development of the technology, or whether there are other factors that play a more important role. For a more detailed account of the various strategies, please refer to the relevant background material.

Measure	Potential and function	Is integration of wind the main goal?	Other goals
Electric vehicles	There is great potential for increasing the number of electric vehicles in the long term as electric vehicles can potentially replace all internal combustion engine vehicles. In the short term, the market penetration will be much lower and an increase of 100,000 electric vehicles by 2020 would probably be an optimistic prognosis. 100,000 electric vehicles with an annual electricity consumption of 2,000 kWh would represent an annual energy consumption of 0.2 TWh (0.7 PJ). Electric vehicles can contribute to balancing wind power and can also to a certain extent be used indirectly to cope with periods of low wind power production by avoiding charging during peak-load times. However, electric vehicles have a limited capacity to increase their charging during periods of high wind power production.	X	Reduce oil consumption in the transport sector
Individual heat pumps	The forecasts made by The Climate Commission have concluded that in the long term the potential consumption of individual heat pumps would total 18 PJ. In the absence of new initiatives, the Danish Energy Agency (Energistyrelsen) estimates that the electricity consumption from individual heat pumps will increase to around 6 PJ by 2020. In terms of integrating wind, individual heat pumps will likely serve a similar function as that of electric vehicles.	X	Reduce the use of oil and gas for individual heating
Flexible domestic electricity consumption (excluding electric vehicles and heat pumps)	The flexibility of existing electricity consumption could potentially comprise up to 12-13 PJ. Excluding the current consumption of electric heat, the potential is around 8 PJ. This potential could already be realised in the short term up to 2020, but will more realistically be realised in the longer term. The consumption would primarily be moveable during short time periods consisting of a few minutes or hours (e.g. fridges and freezers), and would therefore primarily be suited to the balancing of wind.	XXX	Reduce consumption of expensive electricity produced at peak load plants
Flexible industrial electricity consumption	Of the current total electricity consumption used by industry, 15 PJ could potentially become flexible to some degree. This flexibility could potentially be utilised in the short term if it is deemed to be cost-effective. The majority could be shifted for shorter periods of time of a few minutes or hours, and would therefore primarily be suited to the balancing of wind.	XXX	Reduce consumption of expensive electricity produced at peak load plants
Fuel-shift in industry (electric boilers)	The largest potential for improving the future flexibility of electricity consumption in industry could likely be achieved by replacing current process heat fuels (typically fossil fuels) with electricity when electricity prices are low. Approximately 50 PJ of fuel could be replaced with electricity using electric boilers or electric heaters. Over the long-term, if it is assumed that in ¼ of the hours within a year electricity prices will be sufficiently low for businesses to substitute an alternative fuel with electricity, it would result in an additional annual electricity consumption of 12.5 PJ (approximately 3.5 TWh). This electricity consumption would assist in supporting the price of wind when it is very windy. In addition to this, fuel-shift could also be used to balance wind power. Fuel-shift is deemed to be a less relevant solution in the short term, and will most likely become more relevant after 2035. If electricity is also used by industry (locally or centrally) to produce hydrogen as a replacement for natural gas, the potential would increase by a further 23 PJ.	XXX	Reduce the use of fuels for process heat
Cooling towers at CHPs	Electricity production at decentralised CHPs takes place primarily at backpressure steam plants, which are only able to produce electricity when they simultaneously can supply heat. By establishing cooling towers at these plants, this introduces the possibility of producing electricity independently of the heat demand. This is for example a relevant solution during the summer months when electricity demand is relatively high but wind production is rather low.	XX	Facilitates greater revenue generation in the electricity market
Centralised heat pumps (for district heating production)	Using The Climate Commission's report as a starting point it would be reasonable to assume that 40% or more of district heating could be produced with heat pumps. This equates to an electricity consumption of approximately 16 PJ and an electricity consumption capacity of at least 1,000 MW. The expansion by 2020 will not exceed more than 1/10 of this amount. Heat pumps will run when electricity prices are at a normal or low level and will thereby be able to increase the value of wind power. They will also be able to provide balancing services.	XX	Reduce the use of fuels in district heating production

Central electric boilers (for district heating production)	Once again using the Climate Commission's report as a starting point, it would be reasonable to assume that up to 10% of district heating production will be generated by electric boilers, corresponding to an electricity consumption of approximately 12 PJ. The utilisation rate will however be significantly lower than for heat pumps and the electric boilers' required effect is therefore correspondingly much greater, up to 7,000 MW. Only a moderate expansion of the technology is expected in the years up to 2020.	XXXX	Reduce the use of fuels in district heating production
Bypass at CHPs	Bypass systems could be installed at all large combined heat and power plants (CHPs). They could contribute to increasing the value of wind power and to balancing as the plants can quickly shift between cogeneration and bypass. However, bypass systems are not able to add additional capacity in periods where wind levels are low and can therefore not function as a stand-alone initiative. Bypass systems are expected to be introduced and used in the short term.	XXXX	
Heat storage	The potential for increasing utilisation of heat storage is large as the primary barrier to their use is the costs involved in establishing and running the storage. Heat stores can already be introduced as a solution in the short term, although a large-scale utilisation is not realistically relevant until after 2030 when the challenges with integrating wind increase.	XXX	Increase production at CHPs (reduce the need for peak load plants), integrate solar power
Activating emergency power plants	They can deliver production capacity in stressed situations with high electricity consumption and no wind, and are also able to provide balancing in critical situations. It has been assessed that Denmark has a potential of approximately 400 MW emergency power. Like many of the other strategies, this potential can already be exploited in the short term but is estimated only to become truly relevant in the longer term as wind integration challenges intensify.	XX	Test that the plants work
Improving exchange connections	The exchange capacity with neighbouring countries is currently around 5,500 MW. A further expansion with planned and analysed connections to Norway, Germany and the Netherlands could increase the capacity by nearly 3,000 MW to 8,300 MW. In the longer term it is highly possible that expansions beyond this could take place. Exchange connections can contribute to ensuring the value of wind, handling periods of low wind production, as well as balancing wind power production.	XX	Provide access to cheaper supply possibilities; improve competition in the electricity market; access to cheaper balancing services and improve security of supply
New peak load plants	Gas turbine plants (single cycle) are interesting as peak load plants as they offer both good balancing opportunities and, relative to coal-fired power plants for example, short start-up times. Their potential is financially limited and realising it will depend on the ability to utilise the other mentioned measures to maintain balance in the electricity system when wind speeds are low.	XX	There is a need for peak load plants in a thermal-based electricity system but the need is increased with the introduction of large amounts of wind power
Stopping wind turbines in very windy periods	"Last resort" measure to cope with situations where wind production exceeds the combined consumption and export capacity.	XXX	
Production of fuels for transport	Using electricity to produce alternative fuels such as hydrogen and methanol can prove to be an attractive solution in the long term. It can be presumed that the flexibility of electricity consumption at these plants is much greater than that of electric vehicles for example. Production can be stopped during periods with low wind levels and high electricity prices, and the plants could also be used to balance wind power. The long-term potential will, amongst other things, depend on to what extent cheaper and more energy-dense batteries for electric vehicles are developed.	XX	Production of transport fuels with a view to replacing oil-based fuels

Table 4: The assessment of potential for the various strategies to integrate wind power.
X: No or limited effect. XX: Some effect. XXX: Significant effect. XXXX: Very significant effect.

6.1 Economics of the various strategies

The table below presents a general assessment of the societal and corporate economics associated with the various measures in the period up until 2020.

	Economics today	
Measure	**Societal**	**Corporate**
Electric vehicles	X	XX
Individual heat pumps	XXX	XXX
Flexible domestic electricity consumption	X	X
Flexible industrial electricity consumption	XX	XX
Fuel-shift in industry (electric boilers)	XX	X
Cooling towers in decentralised CHPs	X	X
Centralised heat pumps (for district heating production)	XX	X
Central electric boilers (for district heating production)	XX	XX
Bypass at CHPs	XXX	XXX
Heat storage	XX	XX
Activating emergency power plants	XXX	XXX
Improving exchange connections	XXX	XXX
New peak load plants	X	X
Stopping wind turbines during very windy periods	X	XX
Production of fuels for transport	X	X
X: Not financially viable XX: Close to being financially viable XXX: Financially viable		

Table 5: Assessment of the societal and corporate finances of the measures to integrate wind

Improved economy in the short term

Most of the strategies will become more financially viable in the future as the electricity system evolves.

In the case of electric vehicles, the societal cost is significantly higher than the savings they would incur. This is primarily due to the high price of the battery. The largest savings relate to not having to purchase gasoline or diesel, while flexible charging and system services are less important. In 2030 the figures look more favourable for electric vehicles, mainly due to an expectation that battery prices will fall dramatically. The value of flexible charging and the value of system services are expected to rise but still constitute less than 20% of the total revenue for the electric vehicle. For further details regarding the electric vehicle financial calculations please refer to the corresponding background material.

Other examples of technologies whose economics become more favourable in the future are centralised heat pumps and electric boilers. In fact, a study from Aalborg University finds that there are already today large societal savings to be realised by investing in centralised heat pumps at existing power plants. The study found that if 450 MW of heat pump capacity is installed up to 2020, it is expected that they could realise societal savings of 1.7 billion DKK during this period.

Calculations that Ea Eneary Analyses has made using the electricity market model Balmorel indicate that from a socioeconomic perspective, the development of approximately 150-200 MW of heat pump capacity in the years up to 2020 would be cost-effective.

From at corporate perspective however, it is not yet financially viable to invest in heat pumps, a conclusion which has been shown in, amongst others, a study that investigated the potential for installing a heat pump to supply district heating in Aarhus.

6.2 Time perspective – the need for the various strategies

The requirement for flexibility in the short term

Most analyses show that new and more advanced solutions will first really become necessary in the longer term. For example, in The Climate Commission's background report "A note on the challenges involved in accelerating wind power expansion" it was concluded that a dedicated annual expansion of 400 MW additional wind power each year until 2020 would not require any fundamental changes to the electricity system. Existing plans for expanding the overall transmissions network would, in collaboration with neighbouring countries, create a solid foundation for incorporating large amounts of wind in the period up until 2020. In the longer term however, there is a need to introduce additional strategies as well. In the years up to 2020 the district heating sector is expected to provide the most significant contribution to integrating wind power, for example through increased use of heat stores and the use of heat pumps and electric boilers. Furthermore, the ability of centralised and decentralised power plants to provide balancing capacity can also be expected to increase.

An additional strategy that would be advantageous to implement already at the beginning of the period up to 2020 is, at the end of their product lifetime, the conversion of individual oil and natural gas furnaces to district heating and heat pumps. The abovementioned strategies are deemed to be socioeconomically attractive in the short term, and can therefore be implemented in the near future. Here the primary economic driving force is however not the integration of wind, but instead fuel substitution.

The requirements in the longer term

In the long-term, after 2020, the requirements for flexibility will increase if the goal in “Our Energy” of fossil-free electricity and heating production in 2035 is to be reached. The development of wind power production in Denmark’s neighbouring countries is an important factor. If Denmark’s neighbours also undertake a significant wind power expansion it might complicate the wind integration in Denmark. Despite the fact that there is a significant geographical smoothing effect between countries, there is a strong possibility that if it is windy in Denmark, it will also be windy in our neighbouring countries. As a result, the potential to export electricity can be limited during times with high wind levels.

Continued expansion of transmission connections and further utilisation of electricity for heat production in the district heating sector are likely to be important strategies after 2020. In addition, one would expect an increased prevalence of individual heat pumps, which will also contribute to wind power integration.

For some technologies, the primary argument for delaying a large-scale introduction is the costs involved. This is for example the case for electric vehicles, which have very high costs, primarily due to their expensive batteries. If this barrier was removed, and the vehicle range was improved, electric vehicles could play an important role in the transport sector after 2020 – as well as a role in integrating wind power.

In the case of some other technologies, there are not enough hours with low prices in the short term for the technologies to be economically interesting before 2020. An example of this is electric boilers in industry.

In addition, some measures can have a negative environmental impact if they are introduced in the short term. This e.g. applies to permanent conversion of industry’s process energy from fossil fuels to electricity. Over the next 5-10 years, when the share of wind power in the overall Northern European electricity system will still be minimal, the environmental effect of a conversion could be negative, as the extra electricity could, for example, be provided by coal-fired power plants. For this reason it is only sensible to support such conversions if electricity can be efficiently converted to heat via heat pumps, or if short-term conversions are made with low electricity prices as part of a broader long-term evolution towards an "intelligent" energy system.

It is evident that certain elements in a conversion should be prioritised at the beginning of the period and others at the end. It is also apparent that some decisions will depend on the technical and economic development of key technologies, and as such should perhaps be introduced at a later time.

Below is a summary of the timeframes involved for each strategy where the technology's economics and potential have been taken into account.

Measure	2012-2020	2020-2035	2035-2050
Electric vehicles	X	XX	XXX
Individual heat pumps	XXX	XXX	XXX
Flexible domestic electricity consumption	X	X	XX
Flexible industrial electricity consumption	X	XX	XXX
Fuel-shift in industry (electric boilers)	X	XX	XXX
Cooling towers at decentralised CHPs	X	XX	XX
Centralised heat pumps (for district heating production)	XX	XXX	XXX
Centralised electric boilers (for district heating production)	XX	XXX	XXX
Bypass at CHPs	XXX	XX	XX
Heat storage	XX	XXX	XXX
Activating emergency power plants	XX	XXX	XXX
Improving exchange connections	XX	XXX	XXX
New peak load plants	X	XX	XXX
Stopping wind turbines in very windy periods	X	X	XX
Production of fuels for transport	X	XX	XXX

X: Less relevant measure
XX: Relevant measure
XXX: Very relevant measure

Table 6: Timeframes for when the various strategies for integration of wind power could be relevant. The timeframe is described in further detail in the corresponding background notes.

It should be further noted that out of consideration for the business community, job creation, "first mover" effects, or where efforts are necessary to comply with renewable energy or CO_2 commitments, there may be areas or technologies that Denmark is particularly interested in promoting in the short term. As such, cost-effectiveness and timeframe aspects related to the technologies may be less prioritised, but these potential considerations have not been included in the table above. In cases where such conditions do apply, it is described in the corresponding background materials.

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NATURE AND ENVIRONMENT
Valdemarsgade 18
P.O. Box 79
DK-8100 Aarhus C
Phone + 45 8940 2000