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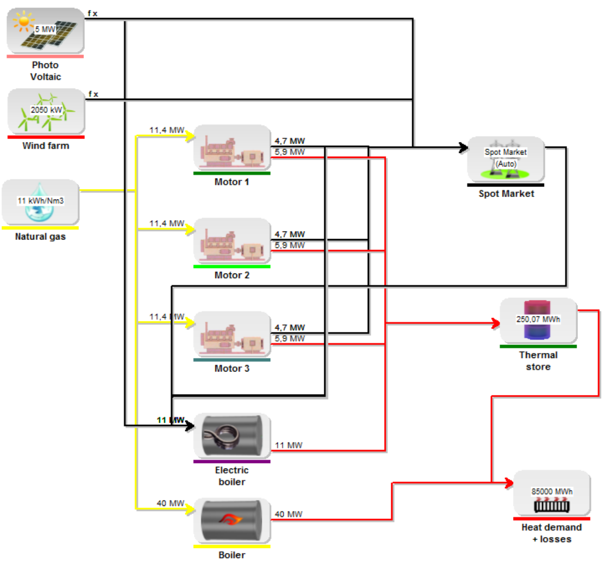
Facilitating energy storage to allow high penetration of intermittent renewable energy

Overview of current status and future development scenarios of the electricity system in Denmark – allowing integration of large quantities of wind power

Delivery 5.1 in stoRE



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Acknowledgements

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Executive Summary

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu). stoRE aims to facilitate the realization of the ambitious objectives for high penetration of variable renewable energies in the European grid by 2020 and beyond, by unblocking the potential for energy storage technology implementation. In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies (EST), namely pumped hydro energy storage (PHES) and compressed air energy storage (CAES).
Bulk EST are expected to be one of the key enabling technologies for the integration of large amounts of variable electricity generation from renewable energy sources (RES-E). In particular, the ability to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (i.e. output smoothing) can mitigate many challenges that arise from high shares of variable RES-E generation in the electricity system.

This Executive Summary, besides highlighting results from Delivery 5.1 in stoRE about the current status and future development scenarios of the electricity system in Denmark, are to be used as a basis in a wide consultation process with key actors from Denmark and Scandinavia, concerning the unblocking of the potential for energy storage technologies in Denmark and Scandinavia.

There are reasons for that Denmark in the near future has to promote bulk EST in either Denmark or e.g. Norway.

One important reason for promoting bulk EST is the ambitious goals set up by the Danish government and the Danish parliament.

Goals set up by the Danish government	**Goals set up by the Danish parliament.**
100 % renewable energy in 2050	25% reduction of fossil fuels from 2010 to 2020.
100 % renewable energy for electricity and heat in 2035	50% reduction of fossil fuels for electricity and heat from 2010 to 2020.
All oil boilers removed in 2030 (mainly to be substituted by heat pumps)	No oil boilers allowed in new buildings from 2013.
Wind turbine shall produce 50% of electricity consumption in 2020	Wind turbine shall produce 50% of electricity consumption in 2020

These goals are to be reached amongst others with a major development of wind energy.

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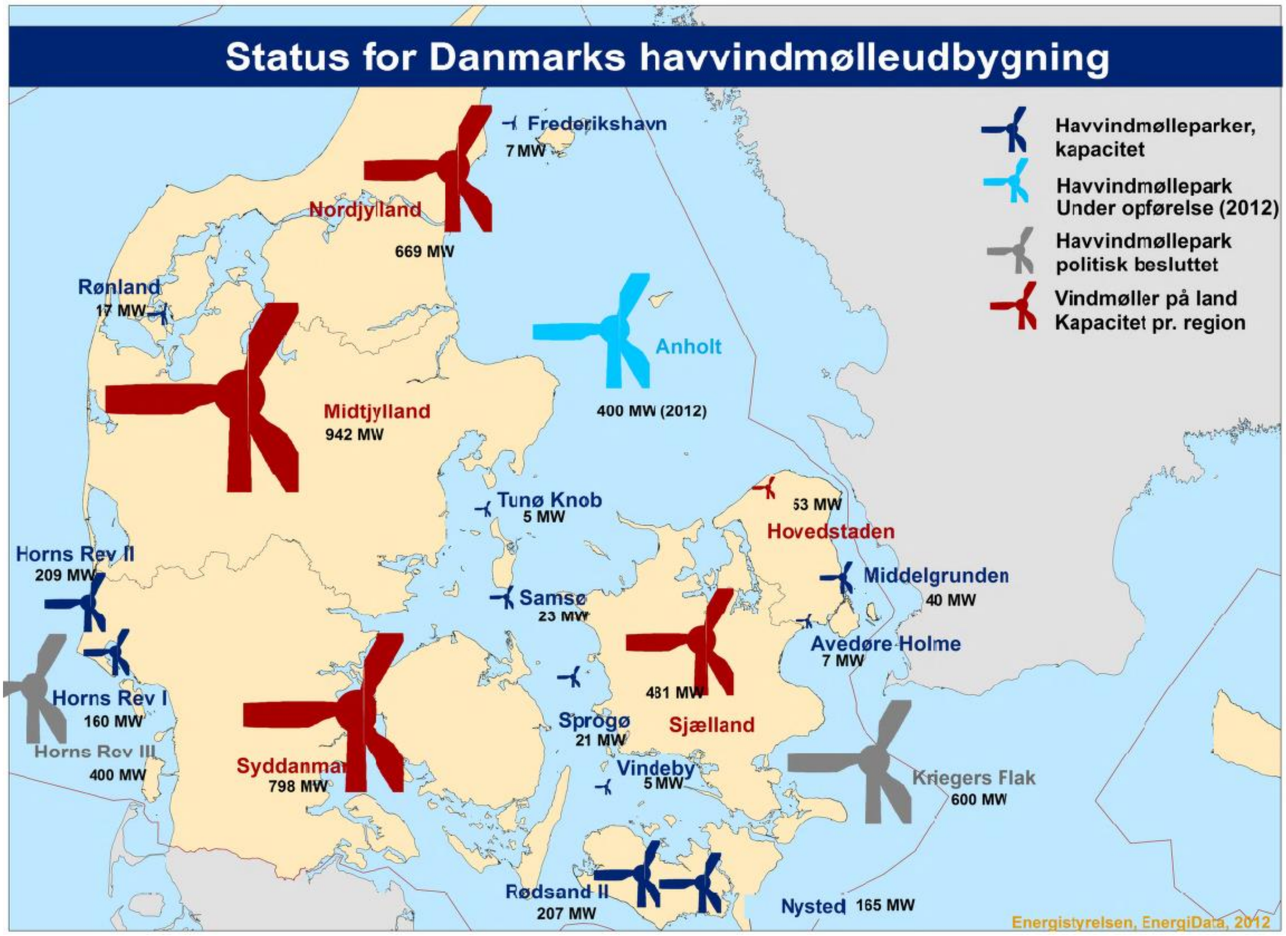
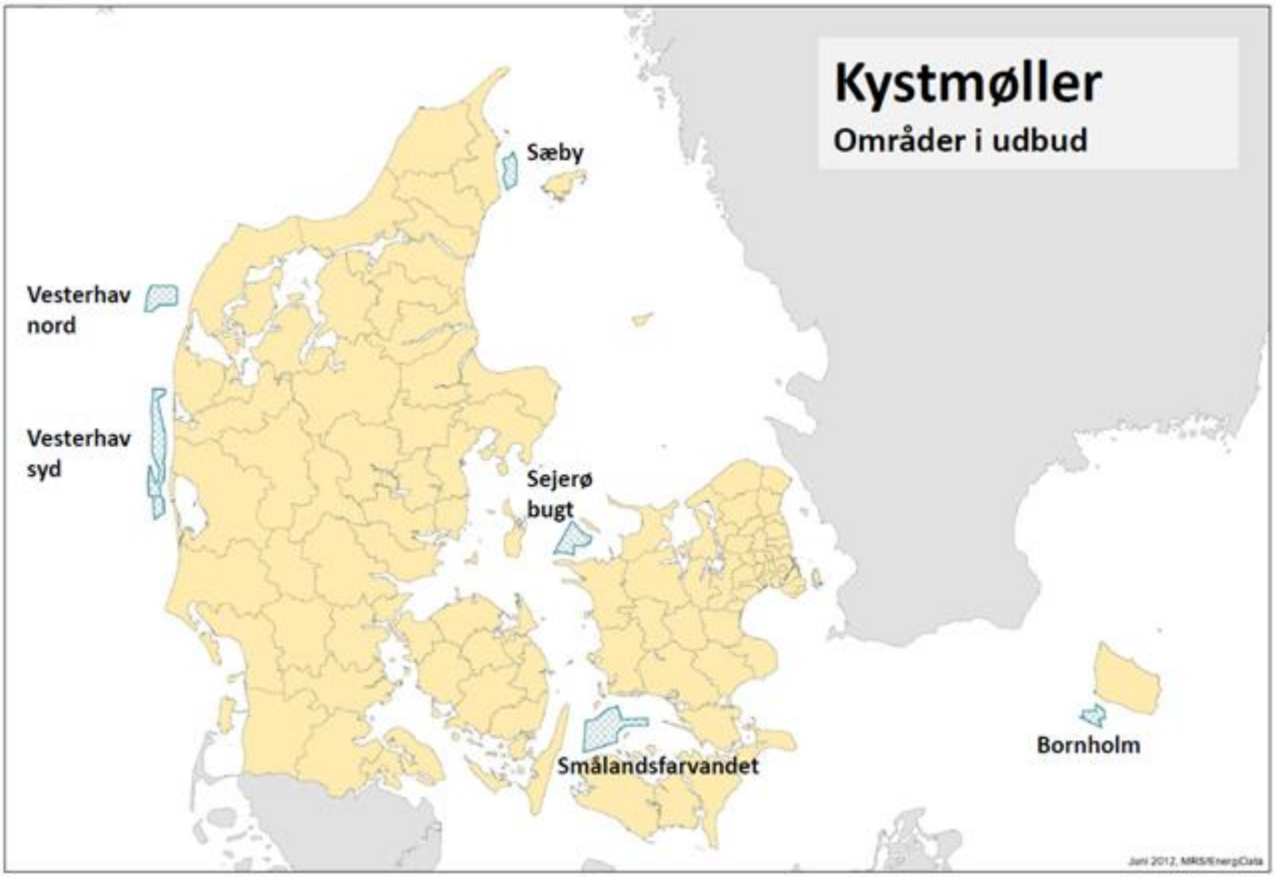


In this figure is shown the status for wind turbines in Denmark. Red: Inland turbines in operation. Dark blue Offshore farms in operation. Light blue: Offshore farms under construction: Grey: Offshore farms decided (source: Danish energy agency).

During the last year a planning process for near shore wind farms has taken place and six sites has been chosen. As this figure indicates a desired geographical distribution has been taken into account. These farms are not expected to be in operation not before 2020.



Near shore wind sites considered (source: Danish Energy Agency)

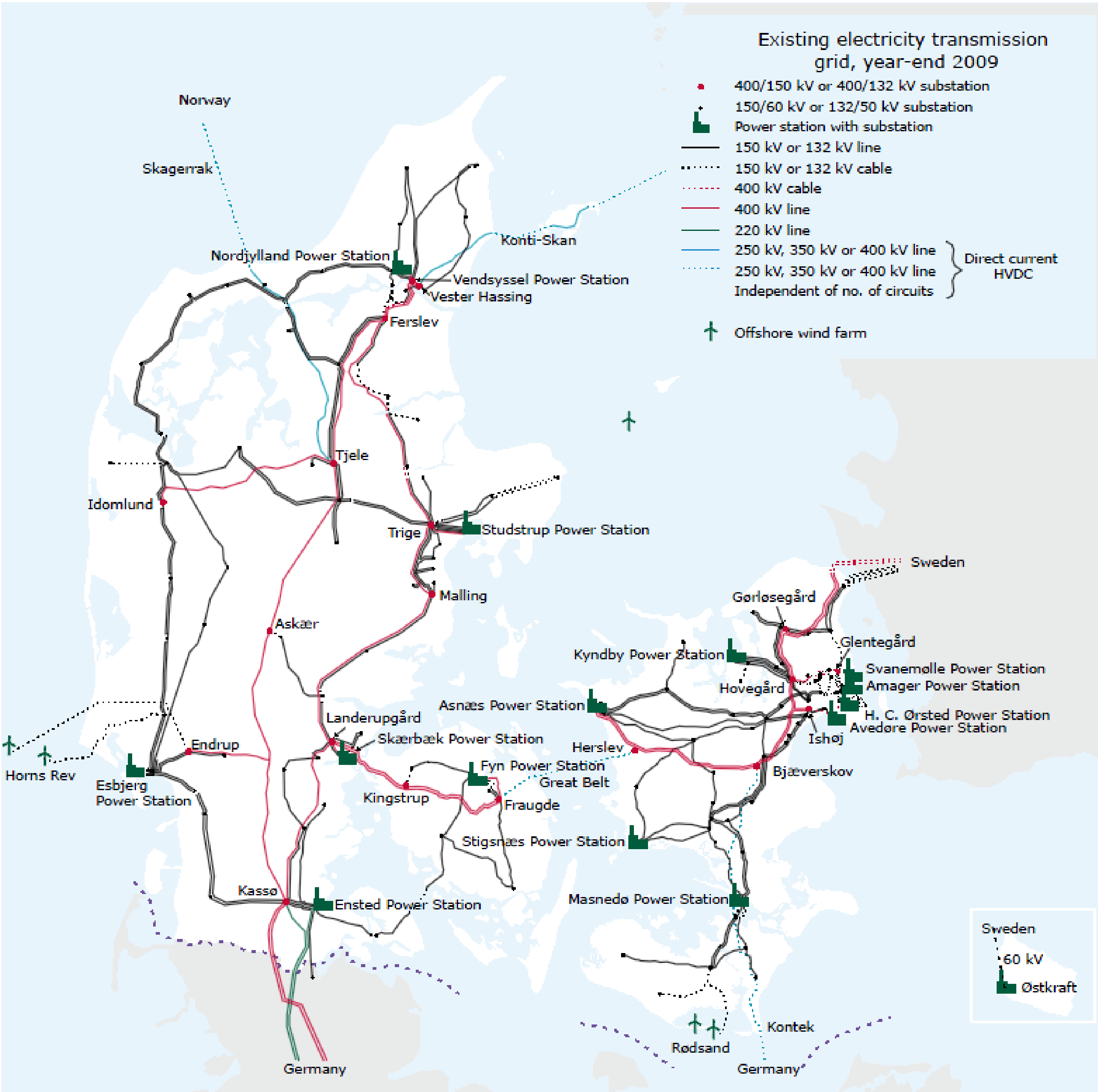
The Danish Transmission System Operator, Energinet.dk, has made a clear list of priorities for integrating the fluctuating productions from wind turbines.

	Short term	Medium term	Long term
Primary focus: Power system balancing	• Expansion of interconnections • Reinforcement and expansion of existing power grid • Downward regulation of generation aided by negative spot prices • Market coupling • Better wind power forecasting	• Geographic distribution of offshore wind farms • Offshore grid • Demand response • Flexible electricity generation • Smart Grid	• Electricity storage in the gas system • Compressed Air Energy storage • Electricity storage in batteries
Primary focus: Integration of RE electricity into other sectors	• Heat pumps at CHP plants • Electric boilers at CHP plants • Heat pumps in households	• Plug-in hybrid vehicles • Electric vehicles	• Use of (electrolysis-based) hydrogen in the transport sector • Use of (electrolysis-based) hydrogen in the gas network

Energinet.dk does not specify what is meant by Short term, Medium term and Long term, and it is assumed that the list is only priorities rather than a time schedule.
From the list it is clear that the Danish TSO first sees the implementation of electricity storages in Denmark after the initiatives listed in the Short term and Medium term. For this reason there are currently no concrete plans for electricity storages in Denmark. In the Long Term the Danish TSO sees CAES, batteries and the production of fuels using electricity as viable electricity storage technologies in Denmark.

Expansion of the interconnections opens for bulk EST, because Norway has pumped hydro storage potential. Using bulk EST in Norway is closely related to developing the transmission network in Denmark and the Scandinavian electricity markets..

The transmission network in Denmark is divided into two separate transmissions grids; Western and Eastern. The West Danish grid is connected to the European continental grid, whereas the East Danish grid is connected to the Nordic grid. The two areas have since autumn 2010 been connected through a 600 MW DC connection across the Great Belt. The Danish transmission grid can be seen in Figure 2, with the interconnectors to Germany, Norway and Sweden.



Denmark is part of the Nordic electricity spot market Nord Pool Spot, which besides Denmark covers Estonia, Finland, Norway and Sweden. Due to bottlenecks in the electrical grid in the Nord Pool Spot area the electricity market is divided into several price areas, where Denmark is divided into the two price areas; West Denmark and East Denmark.
East Denmark is connected to Sweden by four AC interconnections with a total transmission capacity of 1,900 MW, and to Germany by a DC interconnection with a total transmission capacity of 600 MW.

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West Denmark is connected to Germany by AC connections where the total transmission capacity is determined by congestion in the surrounding grids and is normally 1,500 MW in the southbound direction and 950 MW in the northbound direction. West Denmark is connected to Sweden with a DC connection with a total capacity of 740 MW, and is connected to Norway with a DC connection of 1,040 MW.

New offshore grids are being planned. In the figure below is seen the proposed new grid connecting the coming Kriegers Flak wind farm. The new grid is laid out so it can both feed wind power into the onshore grids and exchange electricity between Germany and Danmark and may be later on to Sweden.

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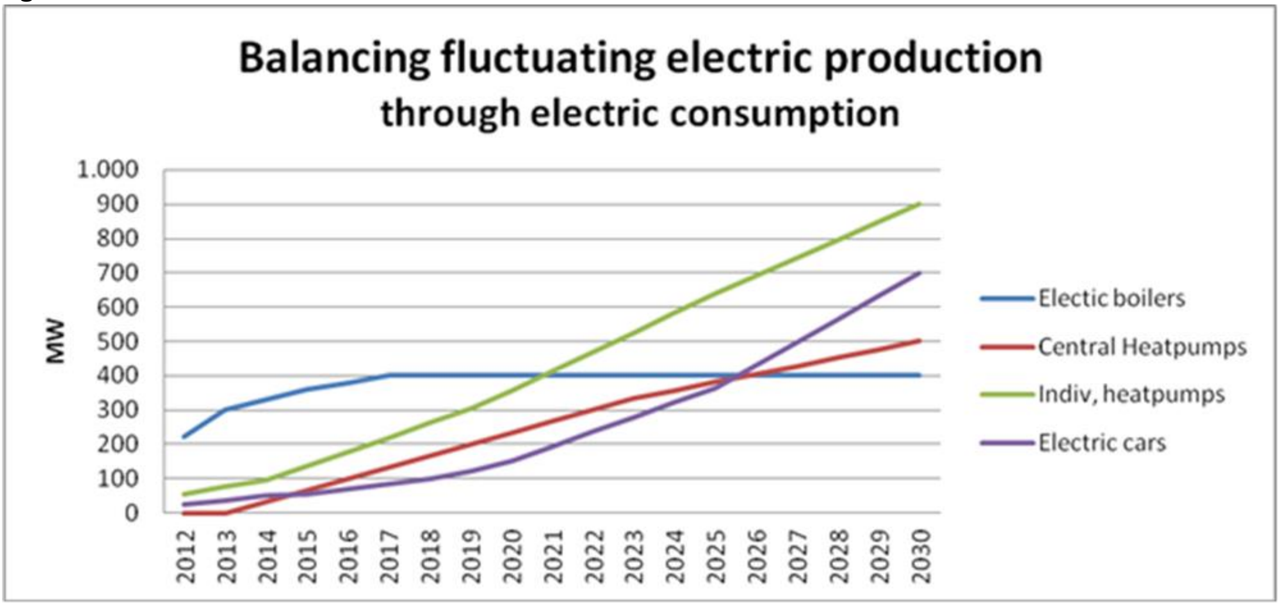
Some of the means that the Danish TSO (Energinet.dk) expects to be taken into action in the period until 2030 for integrating the fluctuating productions from wind turbines is shown in the figure below.



The four means are each considered to be able to swallow several hundred MW when 2030 are reached.
The electric boilers and the central heat pumps are considered to be integrated at the CHP plants (central and de-central), where heat production can be stored in the existing thermal stores.
The individual heat pumps are mainly considered as an option in rural areas, where district heating is not an option.
The fourth mean is electric cars.

Besides these means, the list also includes storing surplus electricity as fuel by using electrolysis, which then will function as energy storage for seasonal adjustments.

One main idea for integrating the fluctuating productions from wind turbines is to connect to Germany. But looking into the correlation between Wind Power in Denmark and Germany, you will see that this is a limited possibility. In te figure below the data is based on the real feed-in curves from wind in both countries in the year 2011.

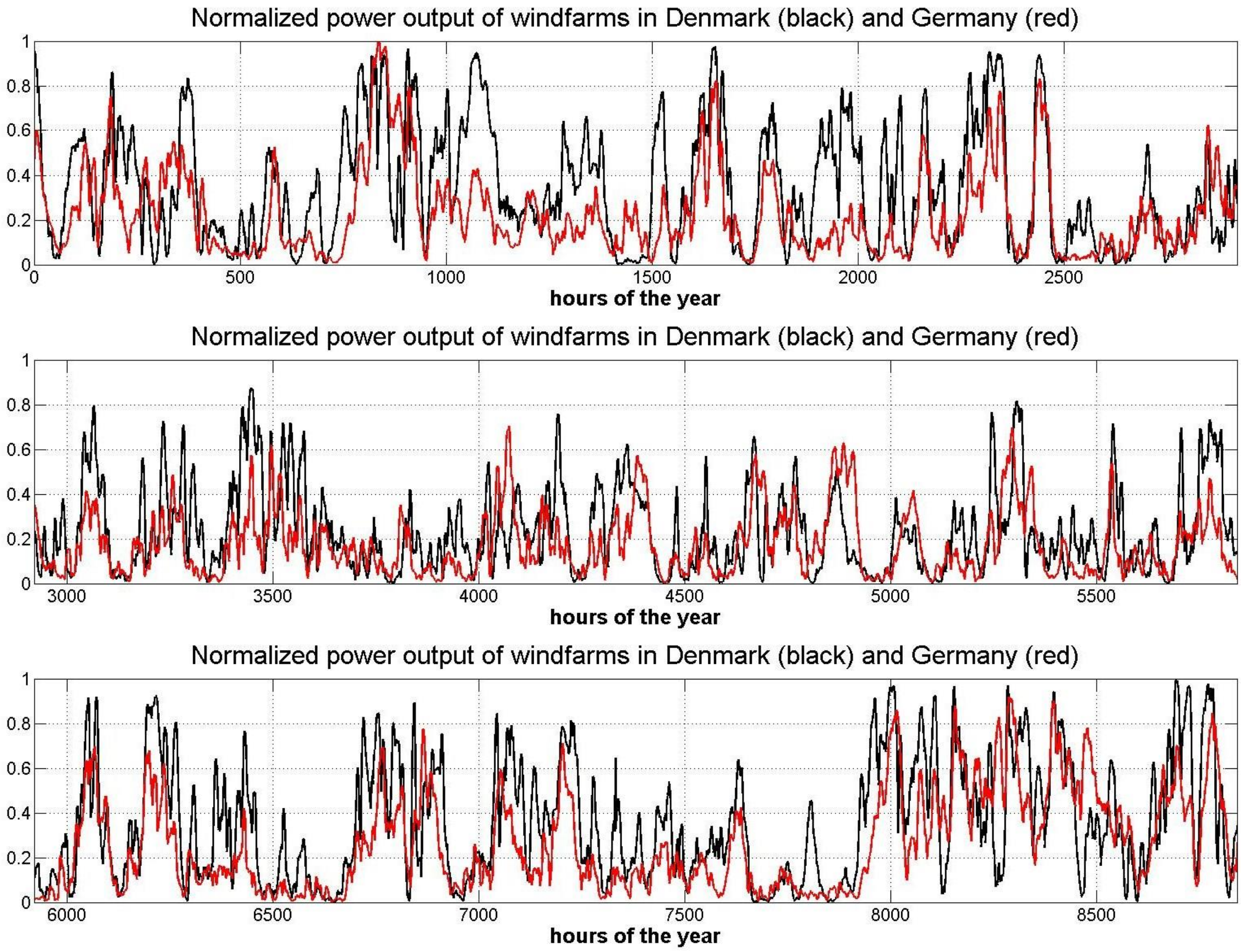
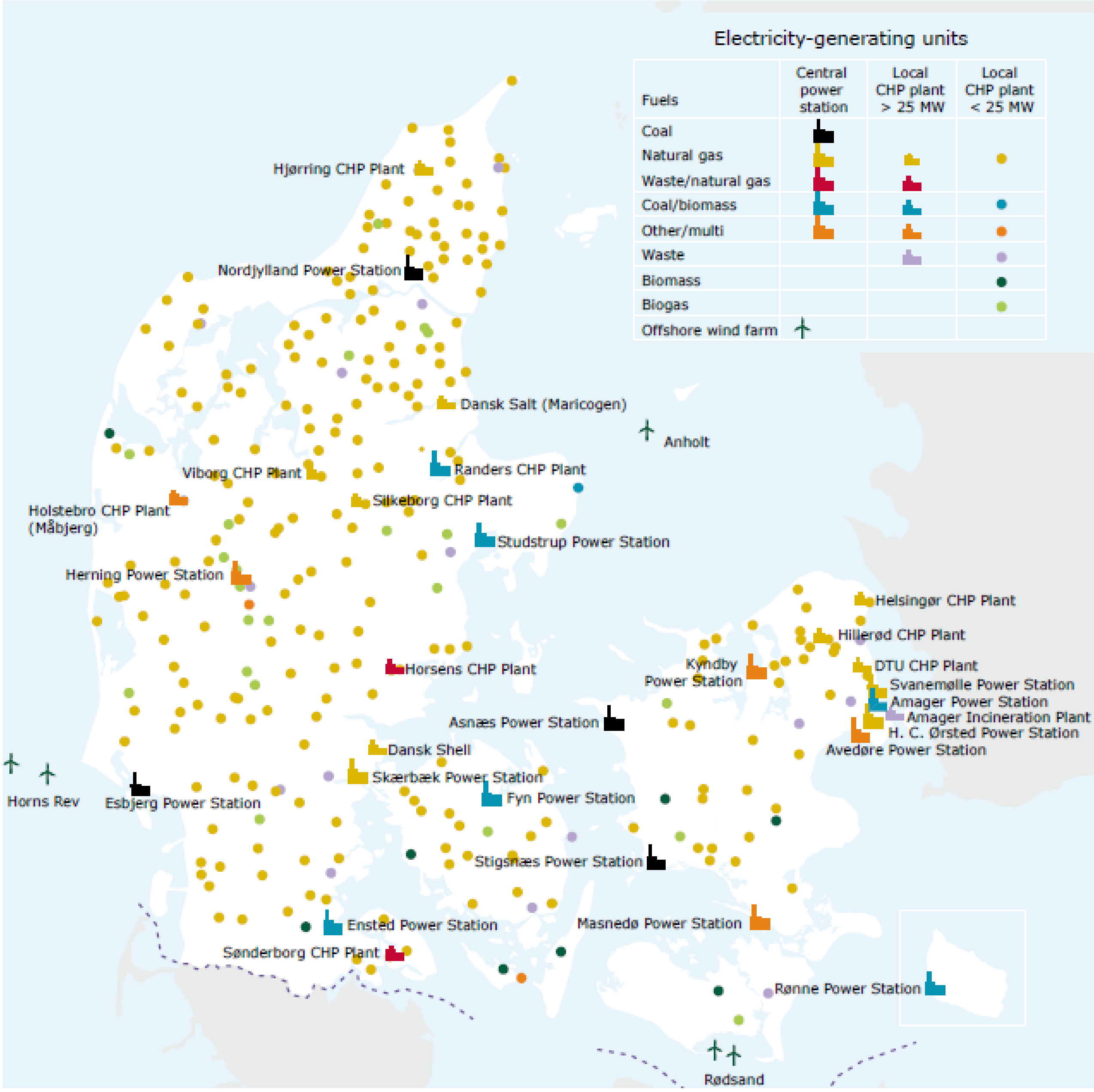


Figure 1: Normalized wind energy production in West Denmark (black) and Germany (red) for the year 2011

This indicates already that it could be difficult to export wind energy to Germany during times of strong wind energy production. It can already be stated that when there is a surplus of renewable energy (negative residual load) in Denmark there is often also a surplus in Germany.

When discussing the need for bulk EST, it is to be kept in mind that Denmark has a large amount of CHP-units at distributed district heating companies.

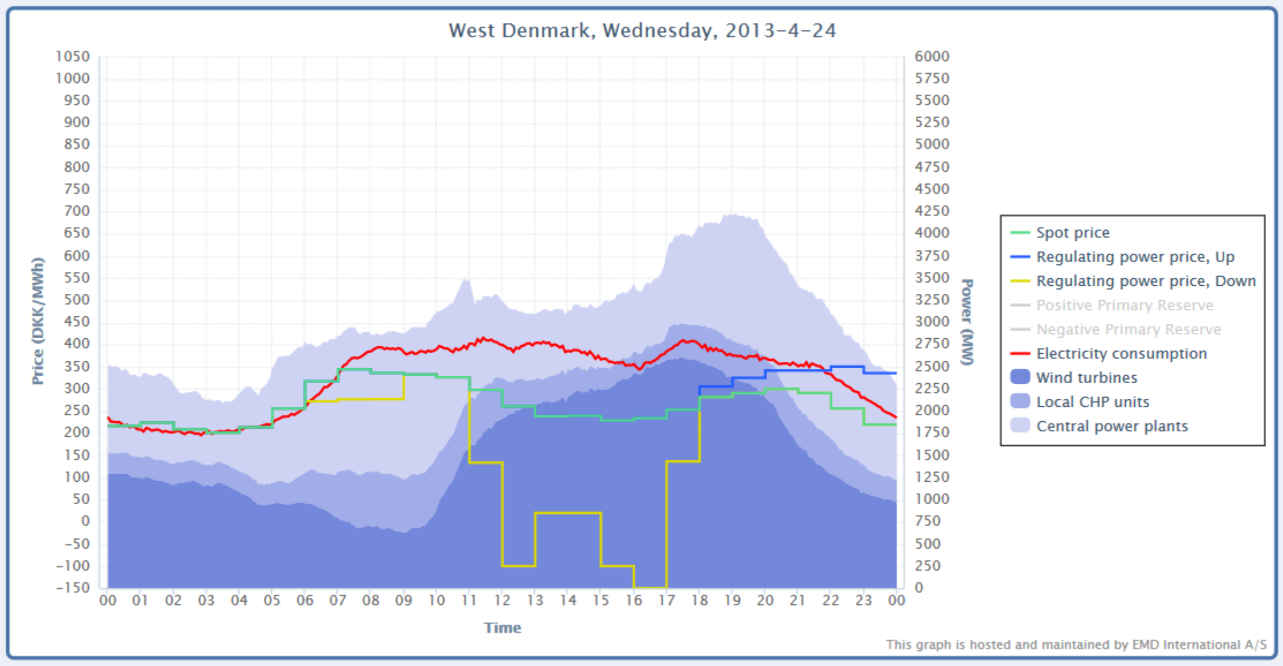


The Figure shows there are many smaller natural gas fired CHP plants throughout Denmark.

These distributed plants can do a similar job as bulk EST, about integrating the large amounts of fluctuating productions from wind turbines.

We show online at http://emd.dk/el/ the challenge of integrating large amounts of fluctuating productions from wind turbines.

As an example. Wednesday 24. April it was blowing heavily, making the price in the regulating power market negative for more hours.



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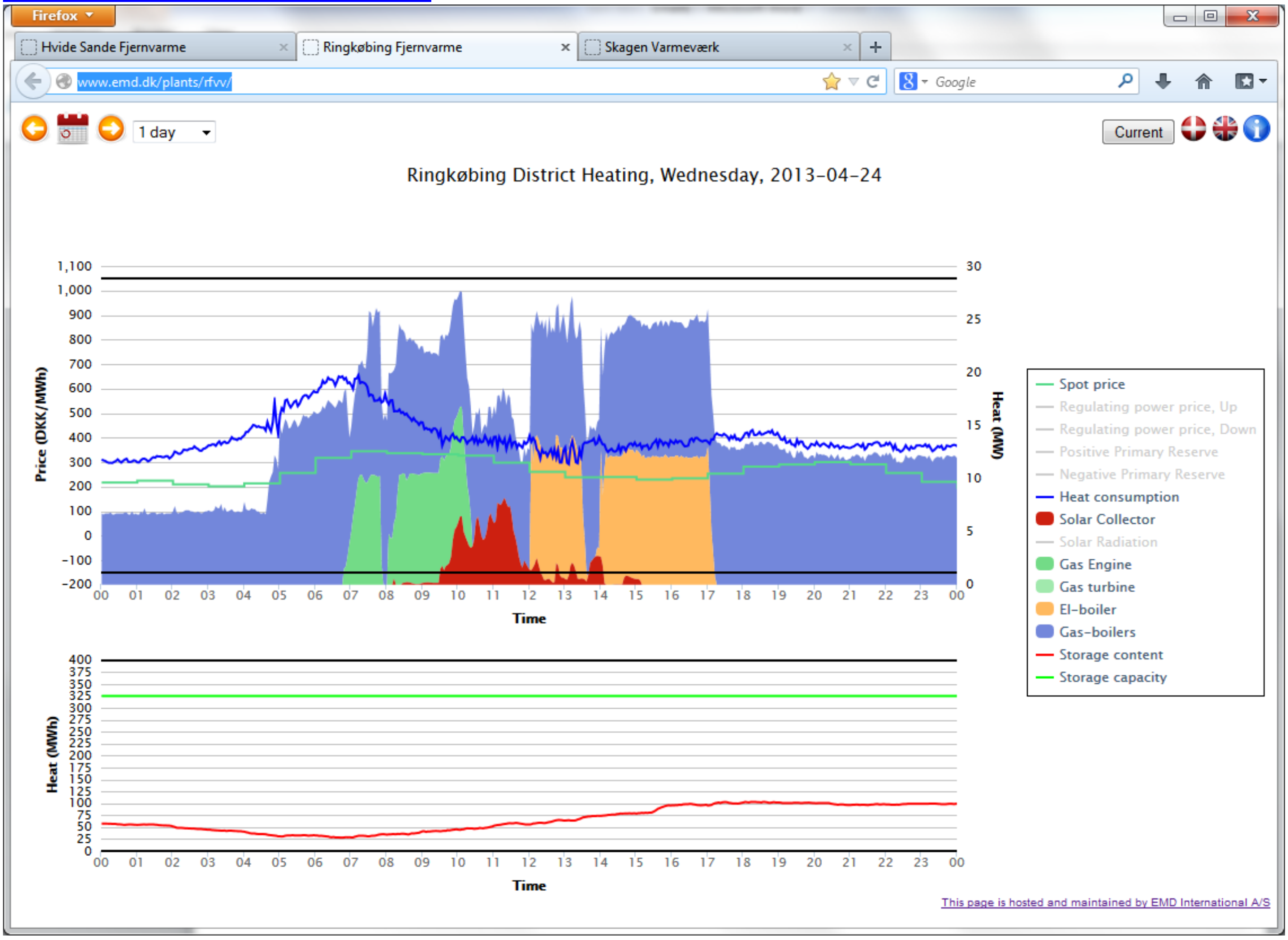
But if you look into online operation of one of the West Danish CHP-plants - their CHP´s and electrical boilers reacted properly on this:

http://www.emd.dk/plants/rfvv/



In the Long Term the Danish TSO sees CAES situated in Denmark as viable electricity storage technologies in Denmark. It is to be expected that when implementing a sustainable energy system in Denmark based on renewable energy, the gas to the CAES plant will to a higher extent become RE gases, and what is even more challenging is that the existing coal fired power plants will not be replaced by new coal fired power plants. The electricity system needs inertia to be stable. When the existing coal fired power plants is taken out of operation, this inertia needs to be delivered by e.g. synchronous generators (inertia wheels) or it might be delivered by the CAES-plant.

1 Introduction

Work-package 5 (WP5) of the stoRE project aims to identify regulatory and market barriers to the development and operation of electricity storage systems (ESS) in the six target countries (Austria, Denmark, Germany, Greece, Ireland and Spain). For achieving that, this document, Deliverable 5.1 (D5.1), provides information about the electricity storage needs in each of the target countries necessary for integrating future RES-E generation in the incumbent electricity system.

This report is dealing with **Denmark** (D5.1 - Denmark) and is structured into three main parts.

Chapters 2 to 6 gives an overview of the Danish electricity system – the status-quo in the year 2011 as well as future prospects until 2020 / 2050 of the Danish electricity generation portfolio and the transmission grid system.

Chapter 7 of this report provides the development of the Danish (hourly) residual load until the year 2020 and as an example a year with 80 % renewable energies on the net electricity consumption.

In chapter 8 the analysis of the future electricity storage needs in Denmark is conducted, considering the existing electricity generation mix and transmission grid system (incl. planned development and reinforcements) along with the national plans for renewable energy development up to 2050. The necessity of new ESS and their feasibility from an energy point of view is investigated with the aid of simulations of the West Danish electricity system operation characteristics, using specially developed software. The produced qualitative and quantitative results highlight the need of energy storage in the future Danish electricity system and show the benefits it can bring. Overall conclusions from the analysis carried out in this report are drawn in section 5.

2 Overview of Denmark's electricity system

2.1 Electricity production capacity in Denmark

The geographical distribution of existing electricity generating units in Denmark can be seen in ***Figure 2***.

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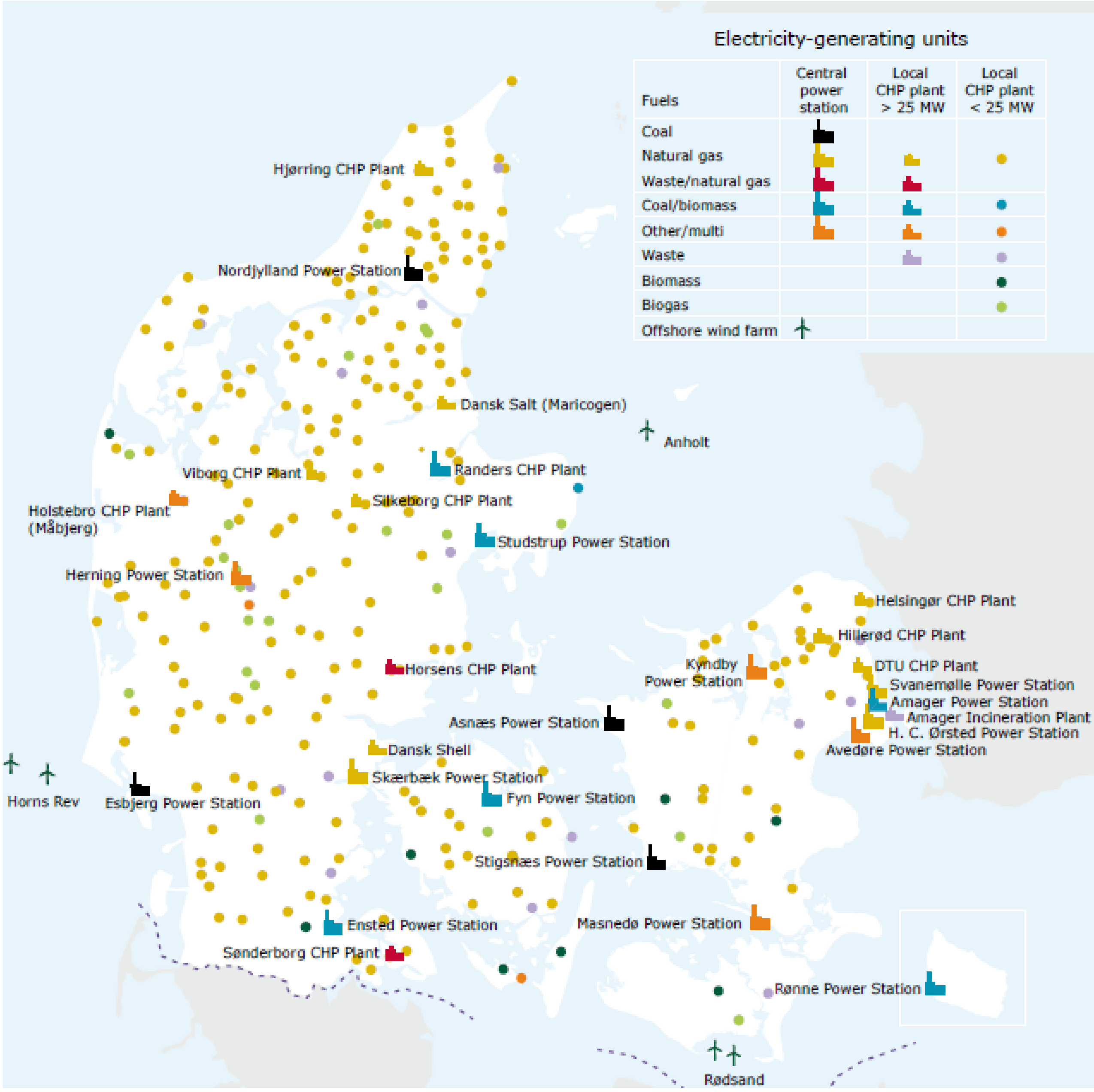

Figure 2: Central electricity generating units in Denmark by fuel type in 2009 [1]

Figure 2 shows there are many small natural gas fired CHP plants throughout Denmark.

The total installed electricity capacity in Denmark in the period 2005-2010 can be found in ***Table 1***.

[1] Map from "Environmental Report 2010" published by Energinet.dk

[MW]	2005	2006	2007	2008	2009	2010
Total electricity capacity	**13,091**	**13,117**	**13,129**	**13,000**	**13,392**	**13,728**
Large-scale units [2]	7,710	7,712	7,634	7,406	7,446	7,446
- Electricity	444	575	850	838	838	838
- CHP	7,267	7,137	6,784	6,569	6,608	6,608
Small-scale units	1,575	1,591	1,688	1,735	1,774	1,784
Autoproducers [3]	664	667	671	683	677	680
Solar energy	3	3	3	3	5	7
Wind turbines	3,127	3,135	3,124	3,163	3,482	3,802
Hydro power units	11	9	9	9	9	9

Table 1: Electricity capacity in Denmark[4]

From ***Table 1*** it is clear that the large-scale CHP units have the largest electricity capacity in Denmark, followed by wind turbines and small-scale units.

Currently there is no electricity storage capacity of note in Denmark; however the Danish electricity system is strongly connected to Norway which has pumped hydro storage potential.

2.2 Transmission network and interconnectors

The transmission network in Denmark is divided into two separate transmissions grids; Western and Eastern. The West Danish grid is connected to the European continental grid, whereas the East Danish grid is connected to the Nordic grid. The two areas have since autumn 2010 been connected through a 600 MW DC connection across the Great Belt. The Danish transmission grid can be seen in ***Figure 3***, with the interconnectors to Germany, Norway and Sweden.

[2] Plants that generate electricity and/or heat for sale to third parties as their primary activity. There are 19 such plants.

[3] Producers of electricity and/or district heating, whose primary activity is not transformation

[4] Data from: "Energy Statistics 2010" published November 2011 by the Danish Energy Agency

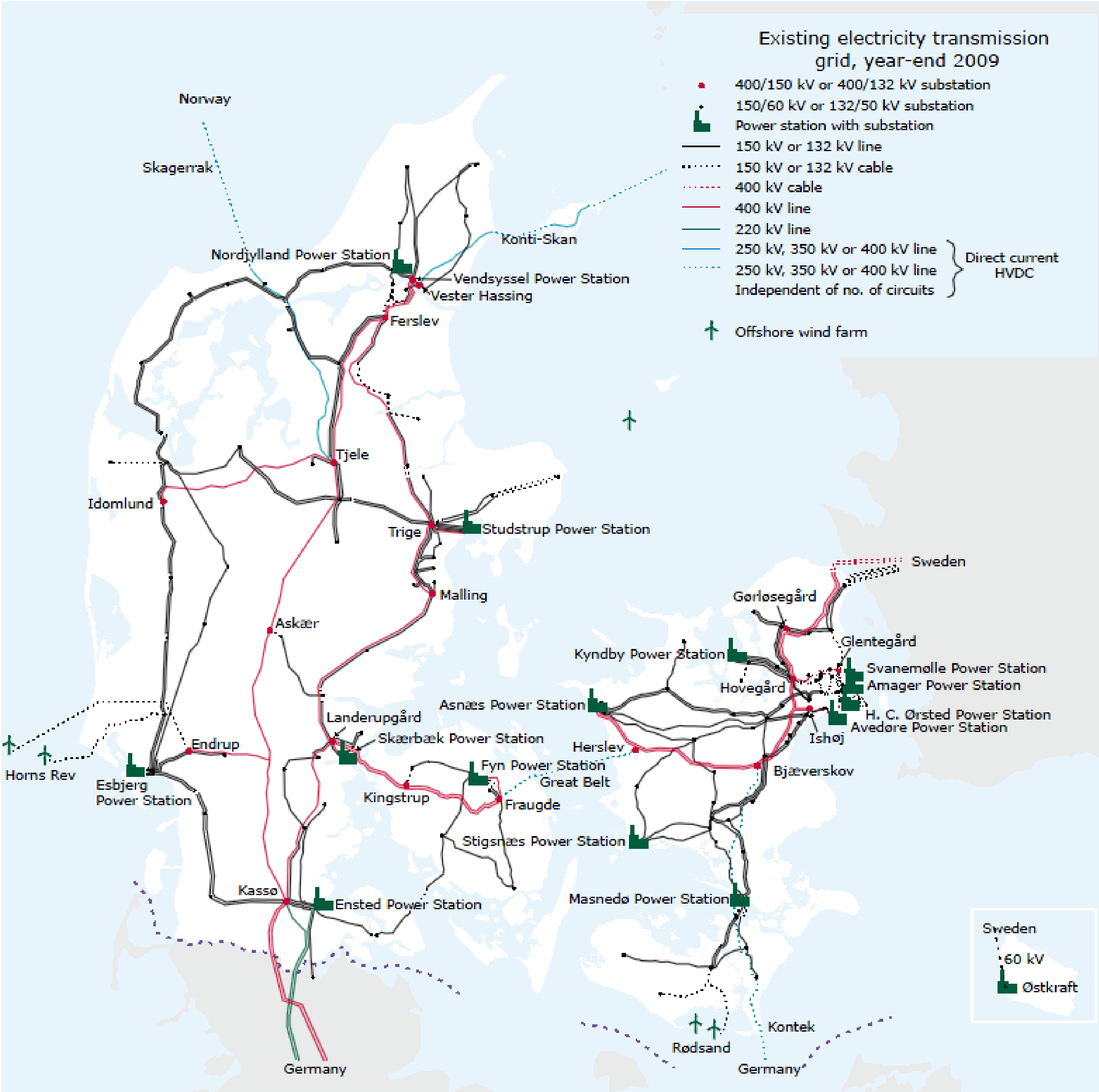

Figure 3: Electricity transmission grid in Denmark [5]

Denmark is part of the Nordic electricity spot market Nord Pool Spot, which besides Denmark covers Estonia, Finland, Norway and Sweden. Due to bottlenecks in the electrical grid in the Nord Pool Spot area the electricity market is divided into several price areas, where Denmark is divided into the two price areas; West Denmark and East Denmark.

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West Denmark is connected to Germany by AC connections where the total transmission capacity is determined by congestion in the surrounding grids and is normally 1,500 MW in the southbound direction and 950 MW in the northbound direction. West Denmark is connected to Sweden with a

[5] Map from "Environmental Report 2010" published by Energinet.dk

DC connection with a total capacity of 740 MW, and is connected to Norway with a DC connection of 1,040 MW. [6]

2.3 Electricity production and consumption in Denmark

As is shown in this section, the Danish electricity system is characterized by having a large share of electricity capacity from CHP plants and wind turbines. ***Table 2*** shows the yearly electricity production by type of producer with the losses, net import and final electricity consumption in the years 2005 and 2008-2010.

[6] www.energinet.dk/EN/ANLAEG-OG-PROJEKTER/Generelt-om-elanlaeg/Sider/Elforbindelser-til-udlandet.aspx

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Direct energy content [TJ/year]	2005	2008	2009	2010
Total gross electricity production	**130,469**	**131,818**	**130,972**	**139,613**
Large-scale power units	**49**	**214**	**197**	**336**
Large-scale CHP units	**74,932**	**80,604**	**82,457**	**83,832**
- Non-CHP electricity production	38,402	47,148	47,985	43,114
- CHP electricity production	36,529	33,456	34,473	40,719
Small-scale CHP units	**21,254**	**17,698**	**16,413**	**19,218**
Autoproducers	**10,344**	**8,269**	**7,643**	**8,039**
- Electricity Production	15	15	18	27
- CHP	10,328	8,254	7,624	8,012
Wind turbines	**23,810**	**24,940**	**24,194**	**28,114**
Hydro power units	**81**	**93**	**68**	**74**
Own use in production	**-6,599**	**-6,353**	**-6,917**	**-7,118**
- Large-scale power units	-2	-30	-44	-18
- Large-scale CHP units	-6,033	-5,800	-6,424	-6,602
- Small-scale CHP units	-564	-523	-449	-499
Total net electricity production	**123,870**	**125,465**	**124,055**	**132,495**
Net electricity import	4,932	5,234	1,200	-4,086
Domestic electricity supply	**128,802**	**130,699**	**125,255**	**128,409**
Transformation consumption	-	-	-20	-105
Distribution losses etc.	- 5,573	- 7,894	- 8,576	- 9,219
Domestic electricity consumption	**123,228**	**122,805**	**116,660**	**119,084**
Consumption in the energy sector	-2,760	-3,581	-3,648	-3,648
Final electricity consumption	**120,469**	**119,225**	**113,011**	**115,436**

Table 2: Electricity production by type of producer for the years 2005 and 2008 – 2010[7]

As shown in ***Table 2*** the CHP electricity production accounts for the largest share of electricity produced in Denmark in the four years shown in the table. The second largest production of

[7] Data from: "Energy Statistics 2010" published November 2011 by the Danish Energy Agency

electricity is produced by the large-scale CHP units running in condensing mode (non-CHP), followed by the production from wind turbines.

The fuel consumption used for electricity production in Denmark in the years 2005 and 2008-2010 is shown in ***Table 3***.

Direct energy content [TJ/year]	2005	2008	2009	2010
Total fuel consumption	**265,330**	**273,972**	**271,687**	**283,994**
Oil	**11,867**	**9,597**	**10,593**	**7,757**
Natural gas	**65,912**	**53,341**	**49,216**	**57,156**
Coal	**127,119**	**145,843**	**146,058**	**139,273**
Waste, non-renewable	**7,004**	**9,093**	**8,639**	**8,272**
Renewable energy	**53,429**	**56,098**	**57,180**	**71,536**
Solar energy	8	9	14	22
Wind power	23,810	24,940	24,194	28,114
Hydro power	81	93	68	74
Biomass	27,115	28,679	30,319	40,695
- Straw	7,715	5,527	6,420	10,168
- Wood	9,405	10,174	11,569	18,721
- Waste, renewable	9,996	12,978	12,330	11,806
Biogas	2,415	2,377	2,585	2,631

Table 3: Fuel consumption for electricity production[8]

As shown in ***Table 3***, coal is the most used fuel for producing electricity in Denmark. This is followed by renewable energy, where especially biomass-fired plants and wind power are utilized, which is followed by natural gas.

To show the peak demand and the demand curve of the Danish electricity consumption, the hourly net electricity consumption in Denmark in 2010 is presented in ***Figure 4***.

[8] Data from: "Energy Statistics 2010" published November 2011 by the Danish Energy Agency

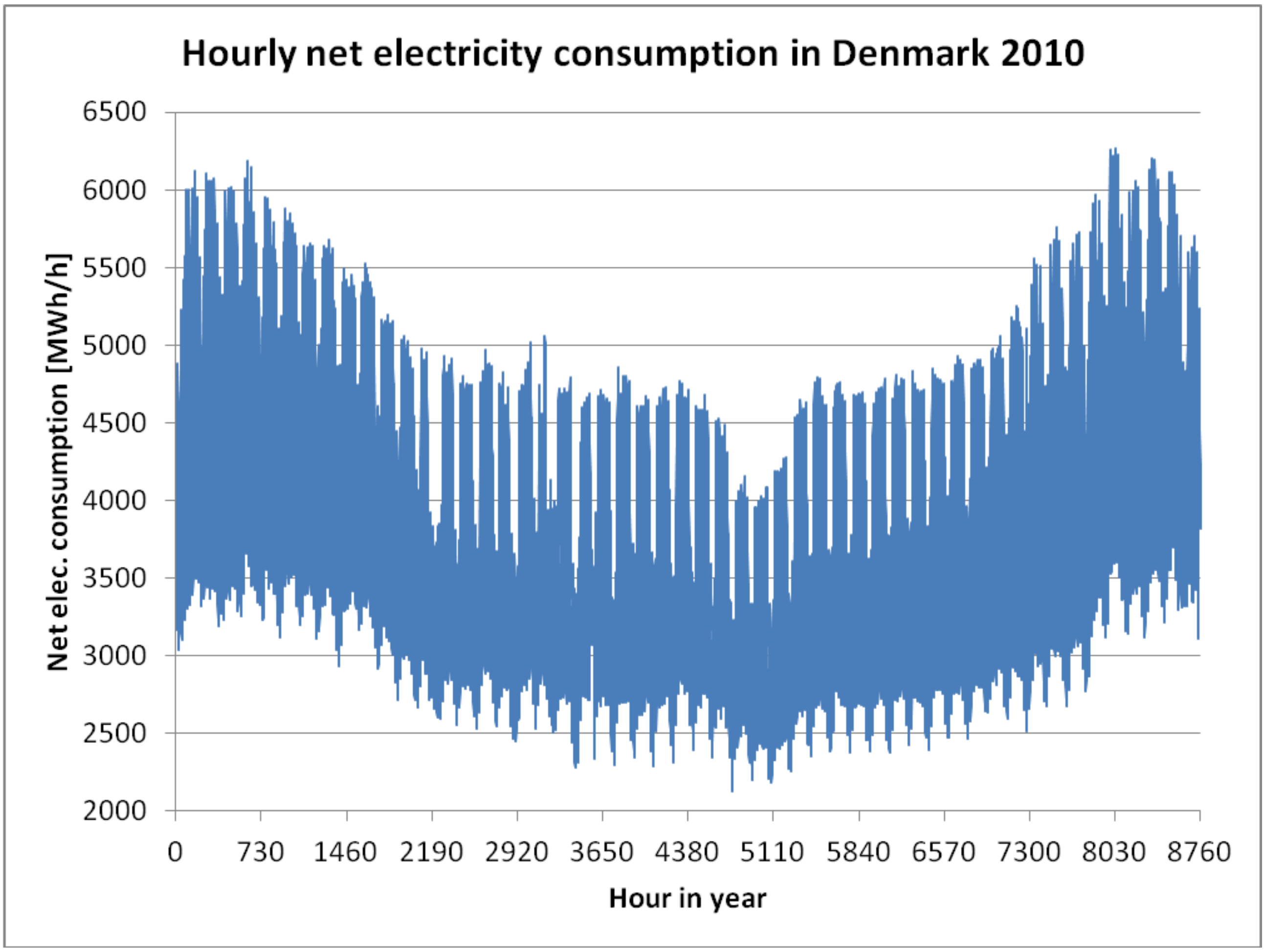

Figure 4: Net electricity consumption in all of Denmark for every hour of 2010 [9]

Figure 4 shows that in 2010 the net electricity consumption peaked at about 6,250 MWh/h in the winter months, and was as low as 2,150 MWh/h in the summer months.

3 Future scenarios for Denmark's electricity system

3.1 Danish Energy Agency baseline scenario

The Danish Energy Agency evaluates the development of the Danish energy system by simulating a baseline scenario for the development of energy consumption and production in Denmark. The baseline scenario shows the expected development in e.g. electricity consumption and fuel usage if no new policies are introduced, and can hereby be seen as a scenario with low renewable energy penetration. The latest baseline scenario is from spring 2011 and projects the development until 2030. In spring 2012 a new political agreement on the Danish energy policy was made, setting up new goals and measures for reaching these goals in 2020. This new political agreement is not included in the baseline scenario from spring 2011.

The projected final electricity consumption in the Danish Energy Agency's baseline scenario can be found in ***Figure 5***.

[9] Based on data from www.energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/

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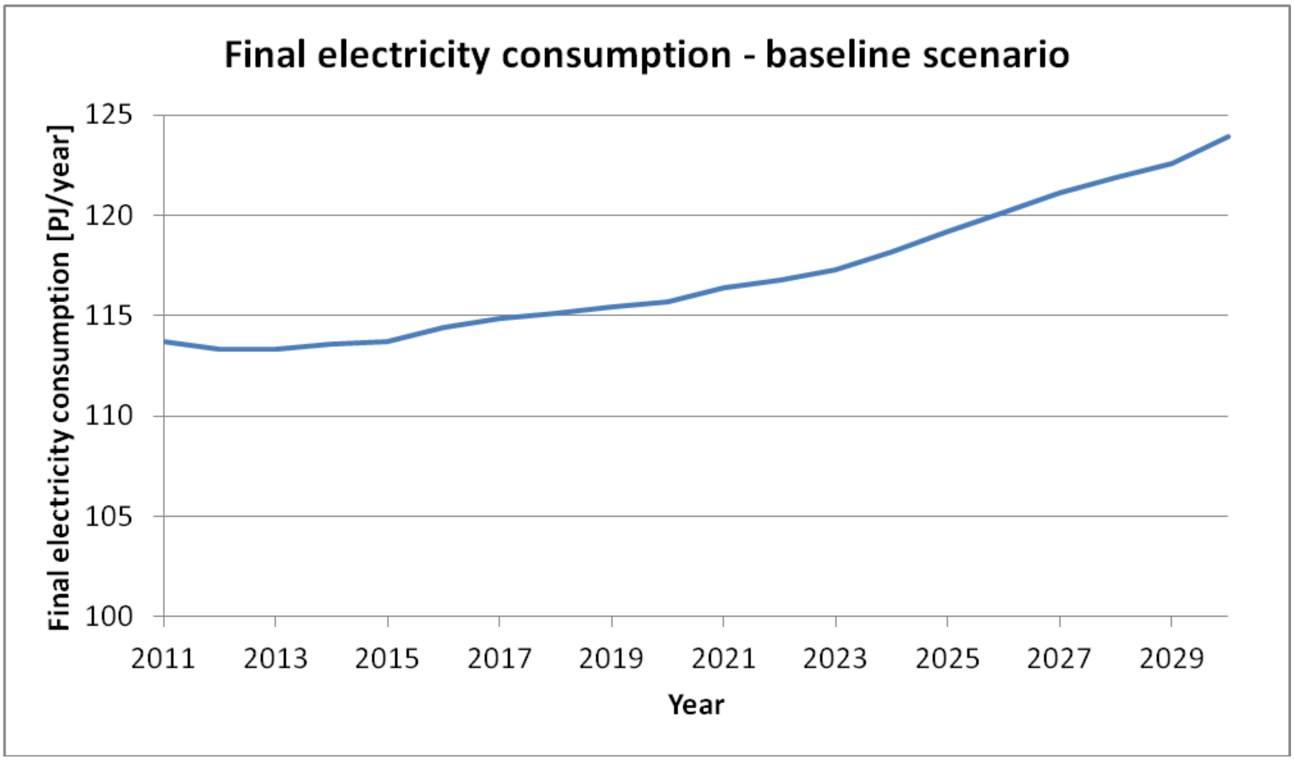

Figure 5: Final electricity consumption in the Danish Energy Agency's baseline scenario. Using the UNFCCC-format. [10]

As ***Figure 5*** shows the final electricity consumption in Denmark is projected to remain fairly constant until 2015, where the electricity consumption will increase. In 2030 the electricity consumption will have increased about 10 PJ/year, if no new policies are introduced.

The Danish Energy Agency does not project the fuel consumption specific for the electricity production, however it projects total fuel consumption for the production of electricity and district heating. The historic (before 2010) and projected fuel consumption for electricity and district heating can for the period 1990 – 2025 be found in ***Figure 6***.

[10] "Danish energy outlook" published by Danish Energy Agency in May 2011

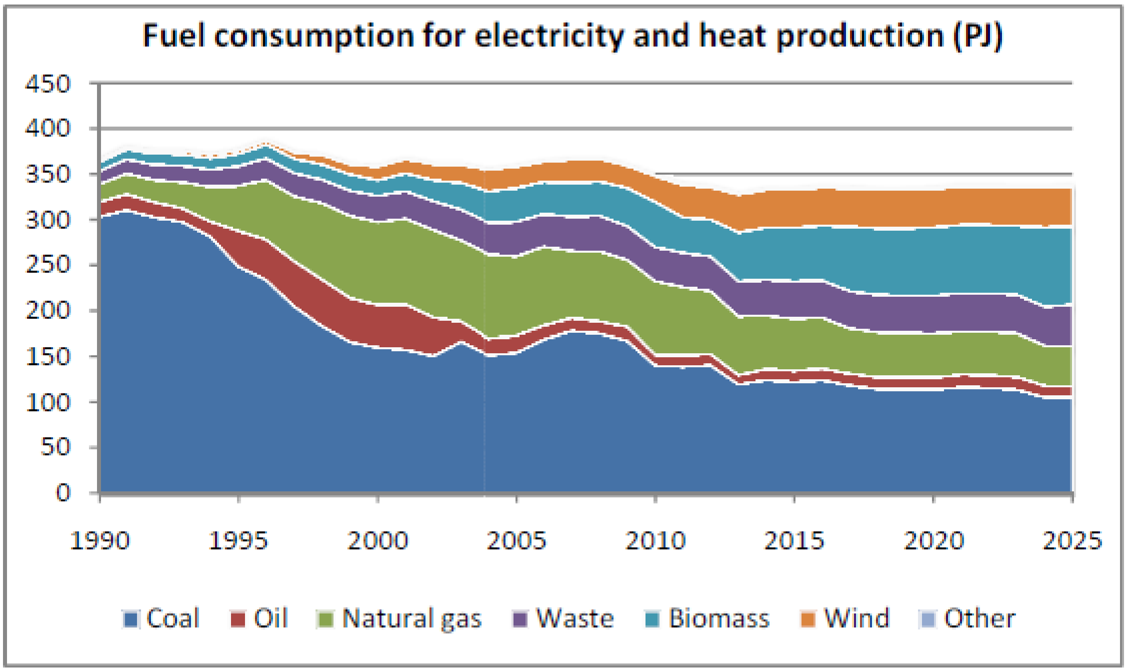

Figure 6: Fuel consumption for electricity and district heating production in the Danish Energy Agency's baseline scenario. Using the UNFCCC-format. [11]

As ***Figure 6*** shows, historically the consumption of coal for production of electricity and district heating has been reduced and replaced by natural gas and renewables. ***Figure 6*** also shows that with no new policies this tendency will only continue a few years, and then the coal consumption will remain fairly constant. The use of biomass is however expected to increase and the use of natural gas is expected to decrease. The overall fuel consumption is projected to fall until 2013. After 2013 it will remain fairly constant.

In the baseline scenario the Danish Energy Agency finds the share of renewable energy of the domestic electricity consumption, which is shown in ***Table 4***.

RE in domestic electricity supply, %	2010	2015	2020	2025
Wind power	22,0	32,4	32,2	32,8
Other RE	11,3	13,8	18,2	21,7
Total RE in electricity consumption	**33,3**	**46,2**	**50,4**	**54,4**

Table 4: Domestic electricity supply covered by RE in the Danish Energy Agency's baseline scenario. Using the UNFCCC-format.

3.2 Energinet.dk's five scenarios for 2030

The Danish transmission system operator, Energinet.dk, has in 2006 developed five scenarios for the development of the electricity system in Denmark. Four of these scenarios are extremes and the last is the development that Energinet.dk finds most likely. The five scenarios are:

- Reference, the development that Energinet.dk finds most likely
- Greenville, an international focus where the environment is highly prioritized

[11] "Danish energy outlook" published by Danish Energy Agency in May 2011

- Grønnevang, a national focus where the environment is highly prioritized
- Blueville, an international focus where the environment is not a priority
- Blåvang, a national focus where the environment is not a priority

A paper quantifying these five scenarios was published in august 2011. The scenarios are all for the year 2030. The capacity on the interconnections and the installed wind power capacity in the five scenarios can be found in ***Figure 7***.

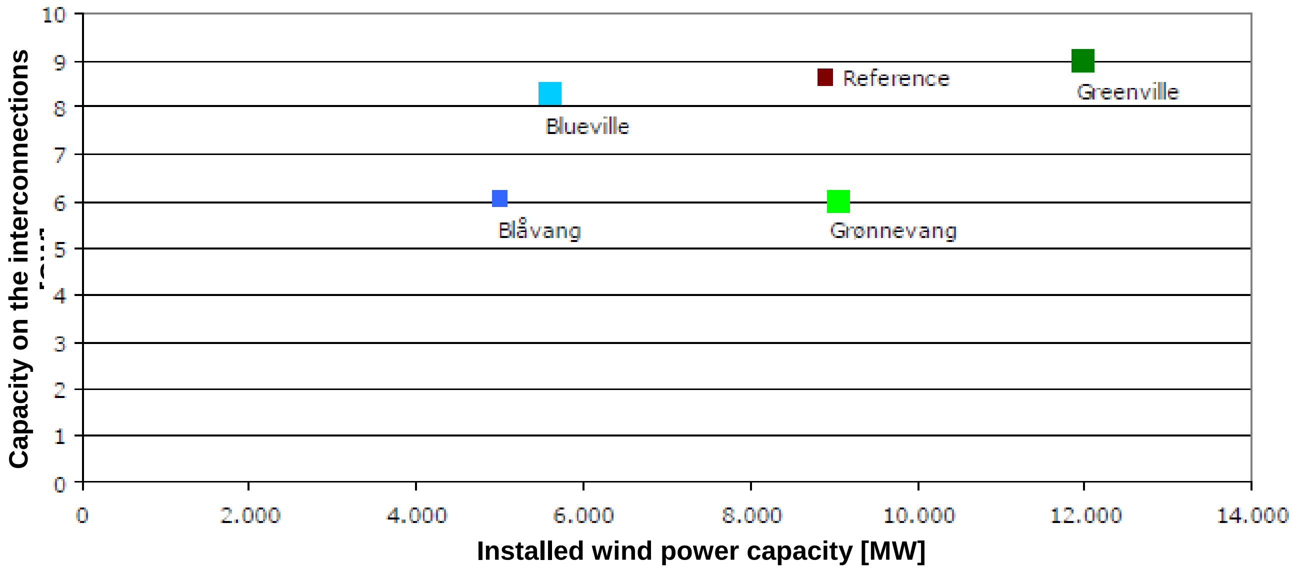

Figure 7: Capacity on the interconnections and the installed wind power capacity in the five scenarios in 2030 [12]

As ***Figure 7*** shows the scenarios with an international focus have a higher capacity of interconnections than those with a national focus. The reference scenario also has a high capacity of interconnections of about 8.5-9 GW. The wind power capacity is higher in the scenarios where the environment is highly prioritized, where Greenville have the most installed wind power due to larger capacity on the interconnections. The reference scenario has an installed wind power capacity of about 9,000 MW.

The electricity consumption in the five scenarios in the year 2030 and the actual consumption in 2010 are shown in ***Figure 8***.

[12] "2030-scenarier for Energinet.dk – Ekstern udgave" published by Energinet.dk august 2011

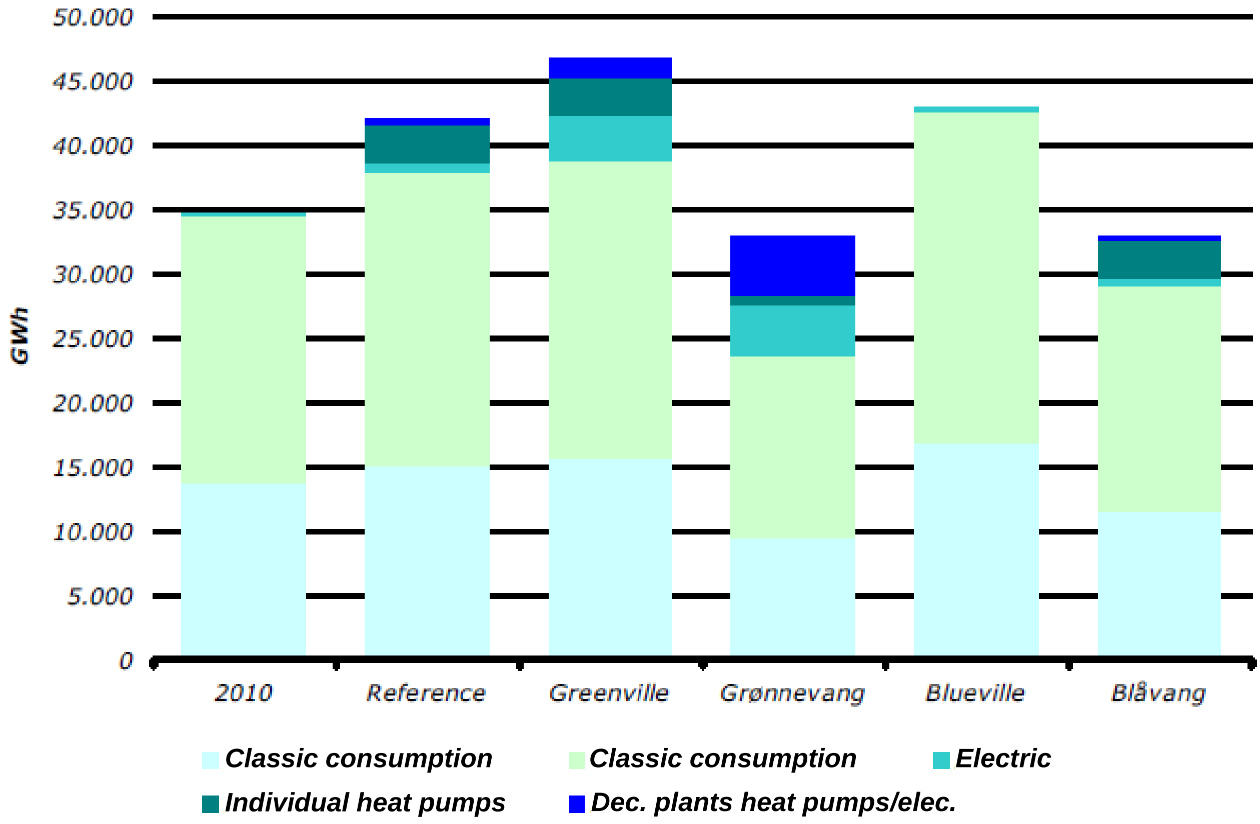

Figure 8: Electricity consumption in 2030 in the five scenarios, and the actual electricity consumption in 2010 [13]

As shown in ***Figure 8*** the electricity consumption is lowest in the two national focused scenarios. In the environmental scenarios there is an increase in the use of electric cars and heat pumps. The reference scenario has a total electricity consumption of about 42,000 GWh.

Figure 9 shows the fuel consumption for the electricity production at thermal plants in the five scenarios.

[13] ”2030-scenarier for Energinet.dk – Ekstern udgave” published by Energinet.dk august 2011

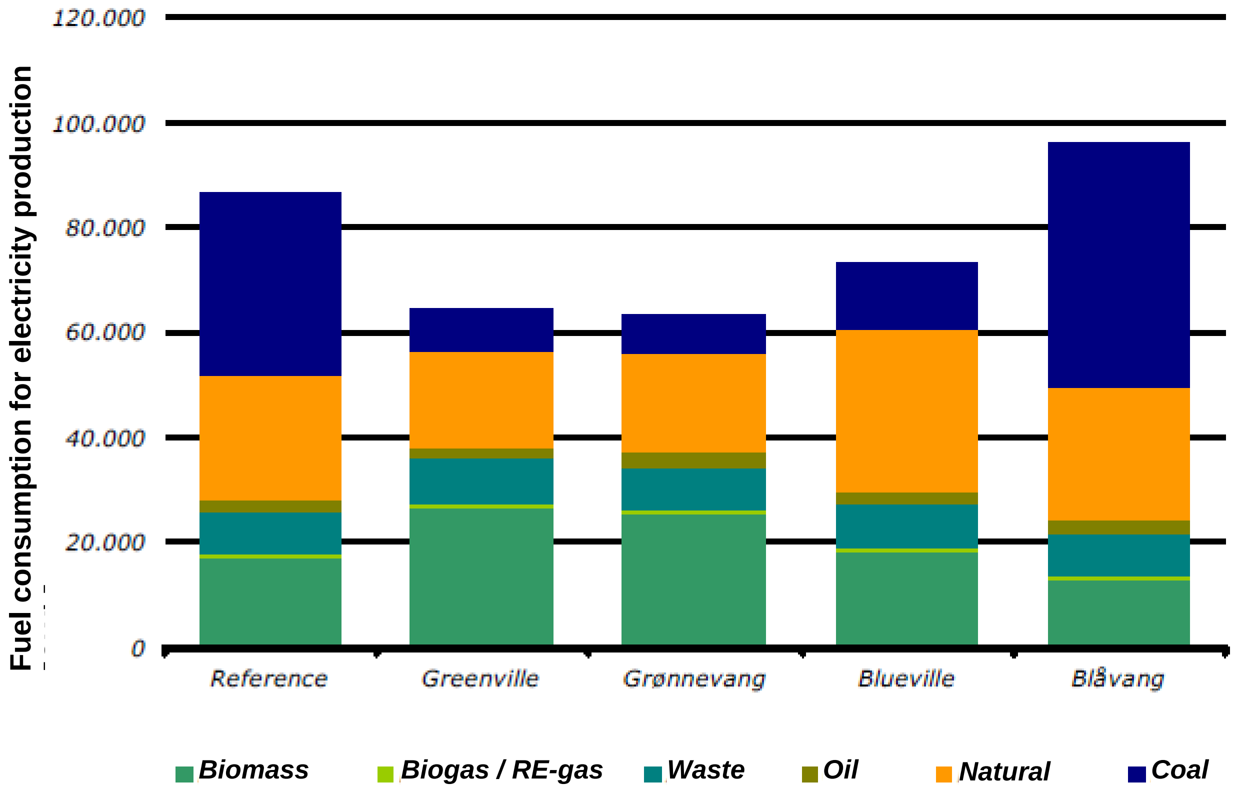

Figure 9: Fuel consumption for electricity production on thermal plants in 2030 [14]

Figure 9 shows that biomass and natural gas will be highly utilized in the thermal plants in the environmental scenarios. In the scenarios where environmental issues are not as dominant, coal and natural gas will be highly utilized, which is also the case in the reference scenario.

[14] ”2030-scenarier for Energinet.dk – Ekstern udgave” published by Energinet.dk august 2011

3.3 The IDA Climate Plan 2050

In 2009 The Danish Society of Engineers (IDA) released the plan "IDA Climate Plan 2050" in which a scenario for reducing Danish CO_2-emissions by 90 % (compared with the year 2000) by 2050 is presented. The plan includes the production and consumption of electricity, heating, cooling and transportation in Denmark.

The yearly primary energy consumption in 2015, 2030 and 2050 of the reference and the IDA Climate plan scenarios can be found in ***Figure 10***. The reference is the Danish Energy Agency's baseline scenario from April 2009, where the reference in 2050 is a projection based on the Danish Energy Agency's baseline scenario, as the Danish Energy Agency only projects till 2030.

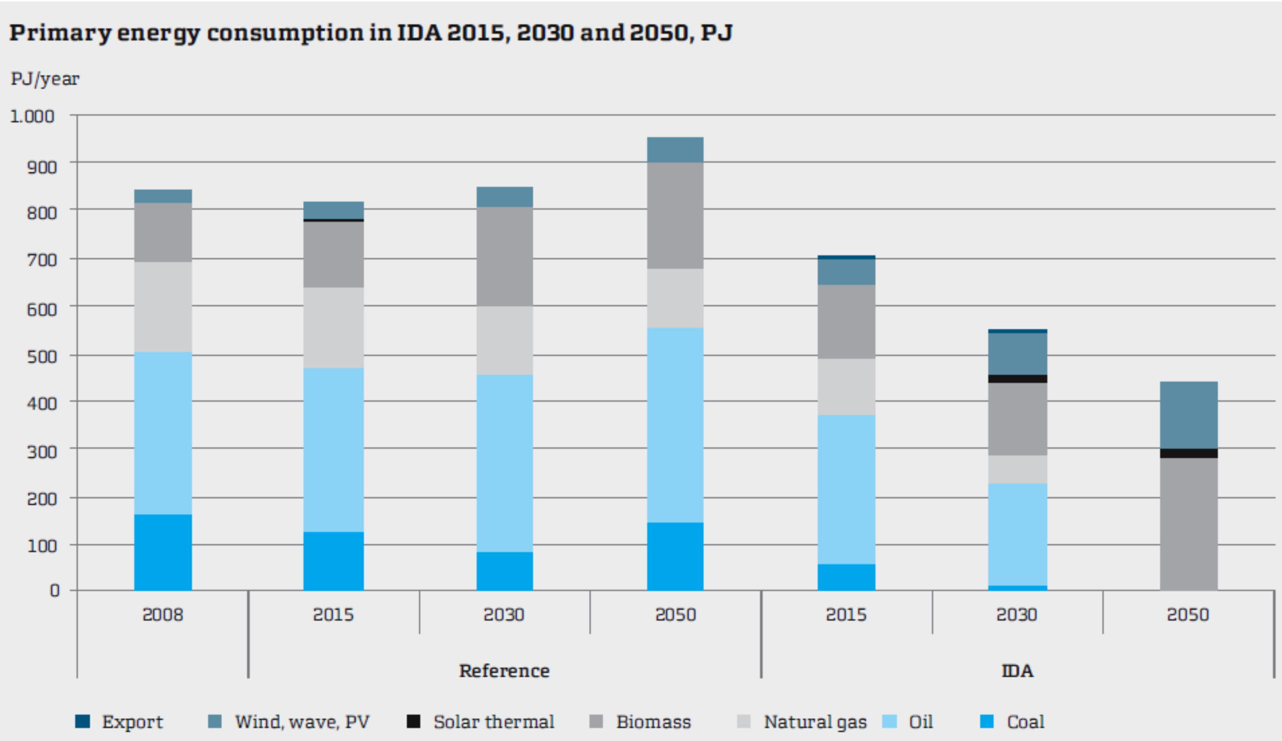

Figure 10: The energy composition in the Danish Energy Agency's projections and in The IDA Climate Plan 2050 respectively. The primary energy consumption includes electricity, heating, cooling and transportation. 15

As ***Figure 10*** shows a major part of reaching the goal for 2050 is reducing the energy demand considerably, while increasing the use of wind power and biomass. In the IDA Climate Plan scenario for 2050 electric vehicles, specifically vehicle-to-grid, play a major role both for removing the oil demand and for balancing the wind power.

A more detailed overview of the energy system proposed in the IDA Climate Plan scenario for 2050 can be seen in ***Figure 11***.

[15]"The IDA Climate Plan 2050" published by The Danish Society of Engineers, IDA in August 2009

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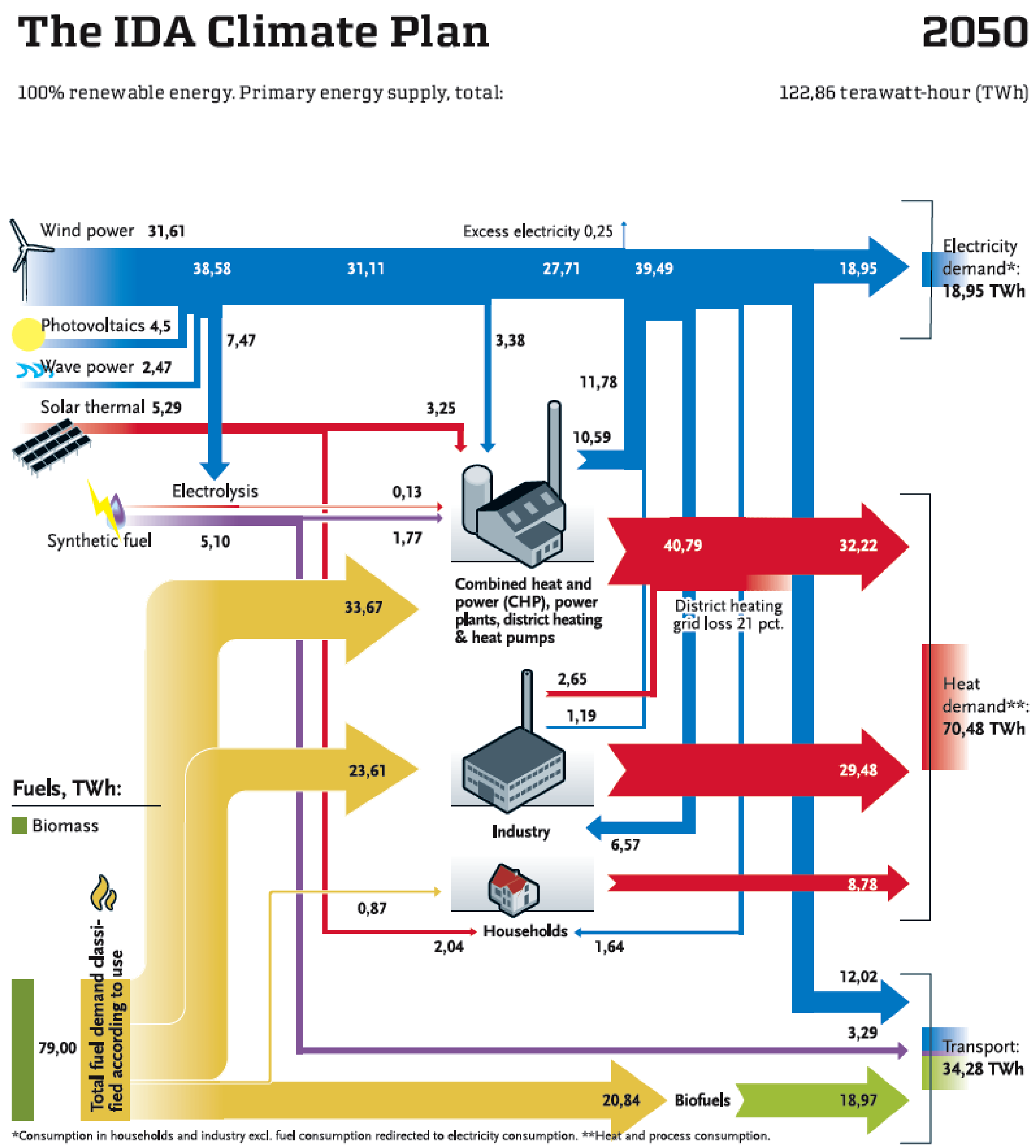

Figure 11: The IDA Climate Plan scenario for the energy system in 2050. [16]

[16] "The IDA Climate Plan 2050" published by The Danish Society of Engineers, IDA in August 2009

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4 Outlook for electricity storages in Denmark

The descriptions in this are based on the descriptions of different scenarios for high renewable energy penetration from chapter 3.

4.1 IDA Climate Plan 2050

The IDA Climate Plan 2050 describes a scenario for reducing Danish CO_2-emissions by 90 % (compared with the year 2000) by 2050.

In the IDA Climate Plan scenario for 2050 it is assumed that the transmission capacity out of the country is not increased. Instead it is assumed that the transmission between West Danish grid and East Danish grid are increased to the extent where the bottleneck between these two grids is insignificant.

To accommodate the high renewable energy penetration in the plan, it is found in the plan that the traditional electricity consumption has to be reduced and the electricity consumption should be made more flexible, so that electricity to a much larger extend are consumed when it is produced on the fluctuating renewable energy sources. The flexible demand is assumed especially to come from making price incentives for consuming when the renewable electricity production is high. It is e.g. electric driven heat pumps, refrigerators and electric vehicles that according to the plan can be used flexible in this way. The plan also includes storing surplus electricity as fuel by using electrolysis, which then will function as energy storage for seasonal adjustments.

4.2 Energinet.dk

The Danish Transmission System Operator (TSO) Energinet.dk has produced ***Figure 12*** to show some of the means they see for balancing fluctuating renewable electricity as more fluctuating sources are implemented in the electricity system. The focus of the figure is wind power, as this is expected to remain the largest fluctuating electricity source in Denmark.

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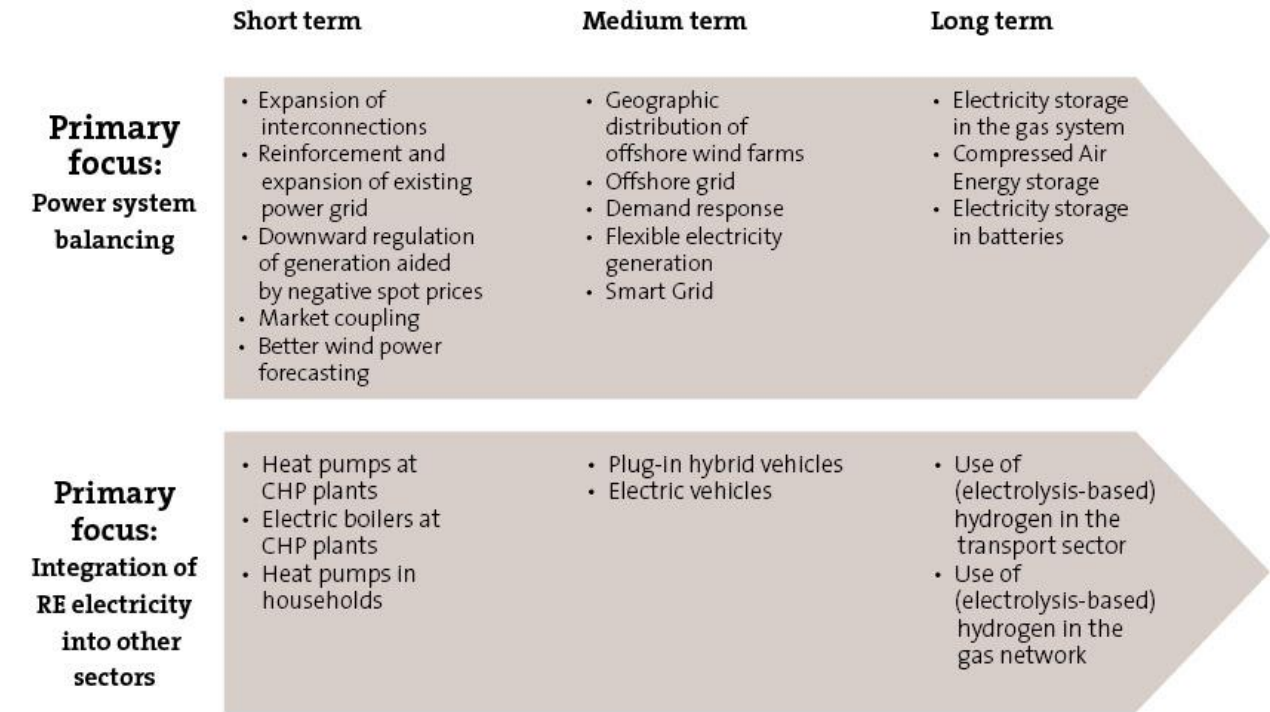

Figure 12: Means for balancing fluctuating renewable electricity production [17]

Energinet.dk does not specify what is meant by Short term, Medium term and Long term, and it is assumed that the figure is meant as a list of priorities rather than a time schedule.

From ***Figure 12*** it is clear that the Danish TSO first sees the implementation of electricity storages in Denmark after the initiatives listed in the Short term and Medium term. For this reason there are currently no concrete plans for electricity storages in Denmark. In the Long Term the Danish TSO sees CAES, batteries and the production of fuels using electricity as viable electricity storage technologies in Denmark.

The means in the Short Term are for the most part already being implemented or planned soon to be implemented. See Task 5.1 for more.

5 Means and incentives in for balancing and integrating large quantities of fluctuating renewables in Denmark

In the following most of means presented in ***Figure 12*** will be presented briefly. If more interested, the means are more detailed in “Strategy Plan 2000” by energinet.dk [18].

5.1 Short term

5.1.1 Expansion of interconnections and Reinforcement of existing power grid

The Danish transmission system operator, Energinet.dk, plans to change the 132-150 kV transmission grids from an overhead line grid to a completely underground grid. The specific timeline for this scheme is currently part of political negotiations.

[17] Energinet.dk Strategy plan 2010 http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Om%20os/Strategy%20plan%202010.pdf
[18] Same as previous reference

Energinet.dk also plans to increase the capacity on the interconnections. Specifically there are plans to:

- Increase the capacity between the west Danish transmission grid and Norway from the current 1,040 MW to 1,700 MW in 2014.
- Increase the capacity between the west Danish transmission grid and Germany for 50-60 million DKK.
- Construct a 700 MW DC interconnection from the west Danish transmission grid to the Netherlands. The interconnection is planned to be in commission in 2016.
- Construct a new connection between the east Danish transmission grid and Germany as part of the planned off-shore wind farm at Kriegers Flak. Currently there is not a specific timeline for the interconnection, see section 5.2.2.

Especially the connection to the hydro based Norwegian power system with large regulating capabilities is of importance of balancing fluctuating renewable electricity production in Denmark. With the increase of capacity on the transmission line regulation capacities will be increased with 70 % in 2014

5.1.2 Downward regulation of generation aided by negative spot prices

Negative spot prices have been seen in recent years when too much electricity is offered the electricity market price independent, typically when wind turbines have a high production and thermal electrical production (Including CHP) is high.

“When the electricity price is negative, framework conditions increasingly require electricity producers to adjust their generation according to demand. Moreover, offshore wind farms and many land based wind turbines are controllable today. Consequently, the introduction of negative prices should mobilise the flexibility of both producers and consumers in future so that the market can manage situations that would have previously required the intervention of Energinet.dk to maintain the necessary balance between consumption and generation” [19].

5.1.3 Better wind power production forecasting

Better wind power forecasts will reduce the need for regulation.

5.1.4 Balancing through new electric consumption

[19] Energinet.dk : strategy plan 2010. http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Om%20os/Strategy%20plan%202010.pdf

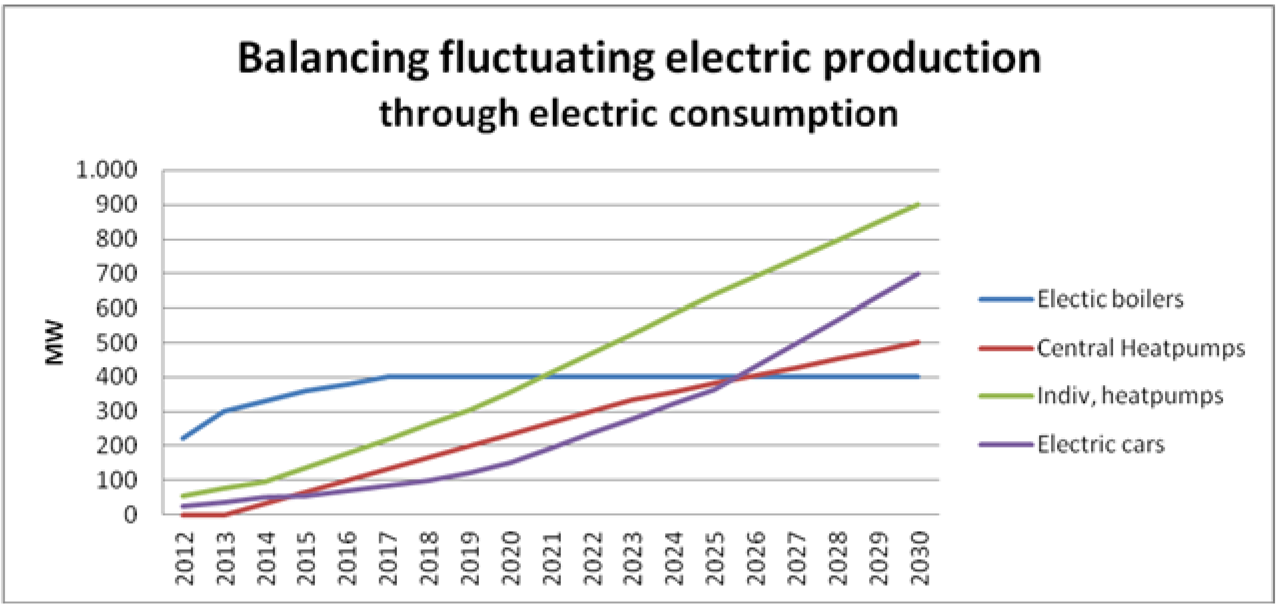

Figure 13 shows the means that the Danish TSO (Energinet.dk) expects to be taken into action in the period until 2030. The four means are each considered to be able to swallow several hundred MW when 2030 are reached.

The electric boilers and the central heat pumps are considered to be integrated at the CHP plants (central and de-central), where heat production can be stored in the existing thermal stores.

The individual heat pumps are mainly considered as an option in rural areas, where district heating is not an option.

The fourth mean is electric cars, see medium term means.

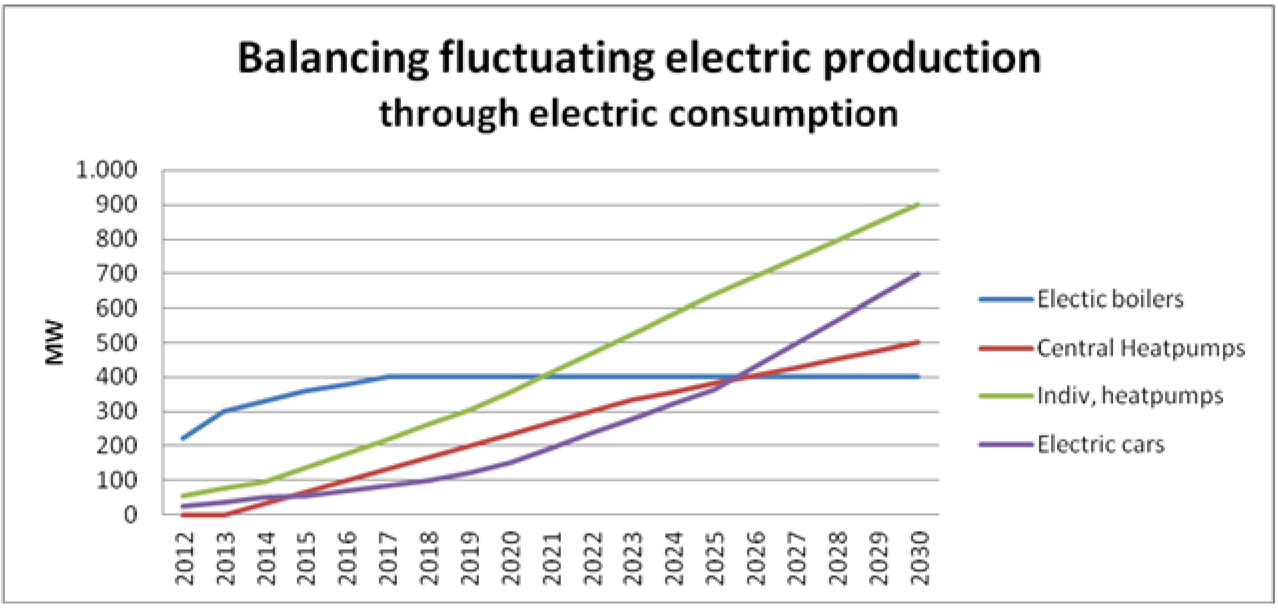

Figure 13: Balancing fluctuating electric production through electric consumption20. (Source: Energinet.dk)

5.2 Medium term

5.2.1 Geographic distribution of offshore wind farms

Geographic considerations has been an issue concerning the already decided off shore wind farms. The geographical distribution is of interest for more reasons. Two important reasons are the strength of existing electricity grid and that the electricity production will have better distribution in time. A front reaching the Danish west cost will reach eastern Denmark hours later. ***Figure 14*** show the installed and decided capacity in Denmark.

[20] http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Energinet.dk%27s%20analyseforuds%C3%A6tninger%202012-2035,%20juli%202012.pdf

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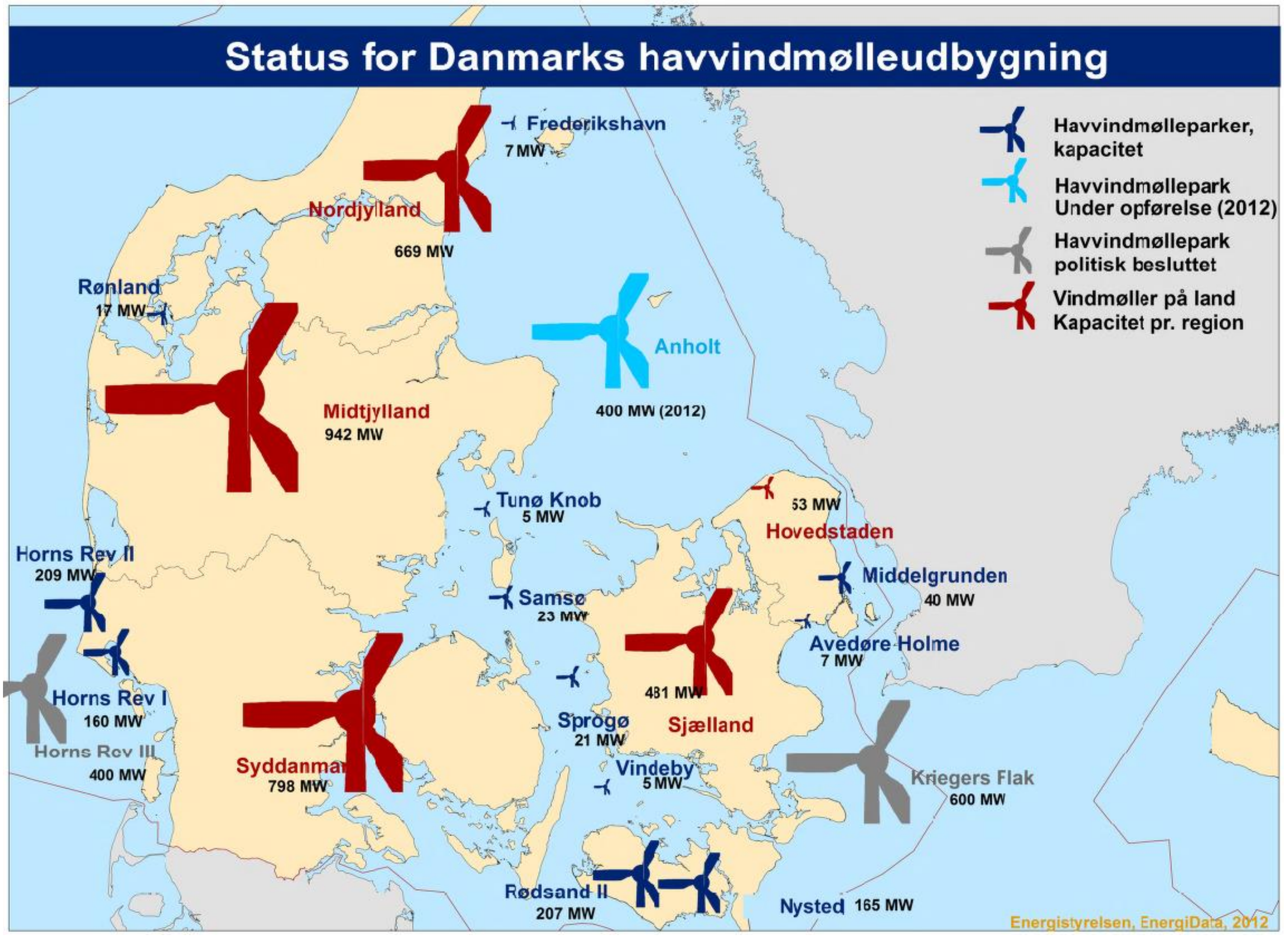

Figure 14 Status for wind turbines in Denmark[21]. Red: Inland turbines in operation. Dark blue Offshore farms in operation. Light blue: Offshore farms under construction: Grey: Offshore farms decided. (source: Danish energy agency)

During the last year a planning process for near shore wind farms has taken place and six sites has been chosen. As ***Figure 15*** indicates a desired geographical distribution has been taken into account.

These farms are not expected to be in operation not before 2020.

[21] http://www.ens.dk/da-DK/UndergrundOgForsyning/VedvarendeEnergi/Vindkraft/Havvindmoeller/Documents/Havm%C3%B8lle_Udbygning_2012_x_.pdf

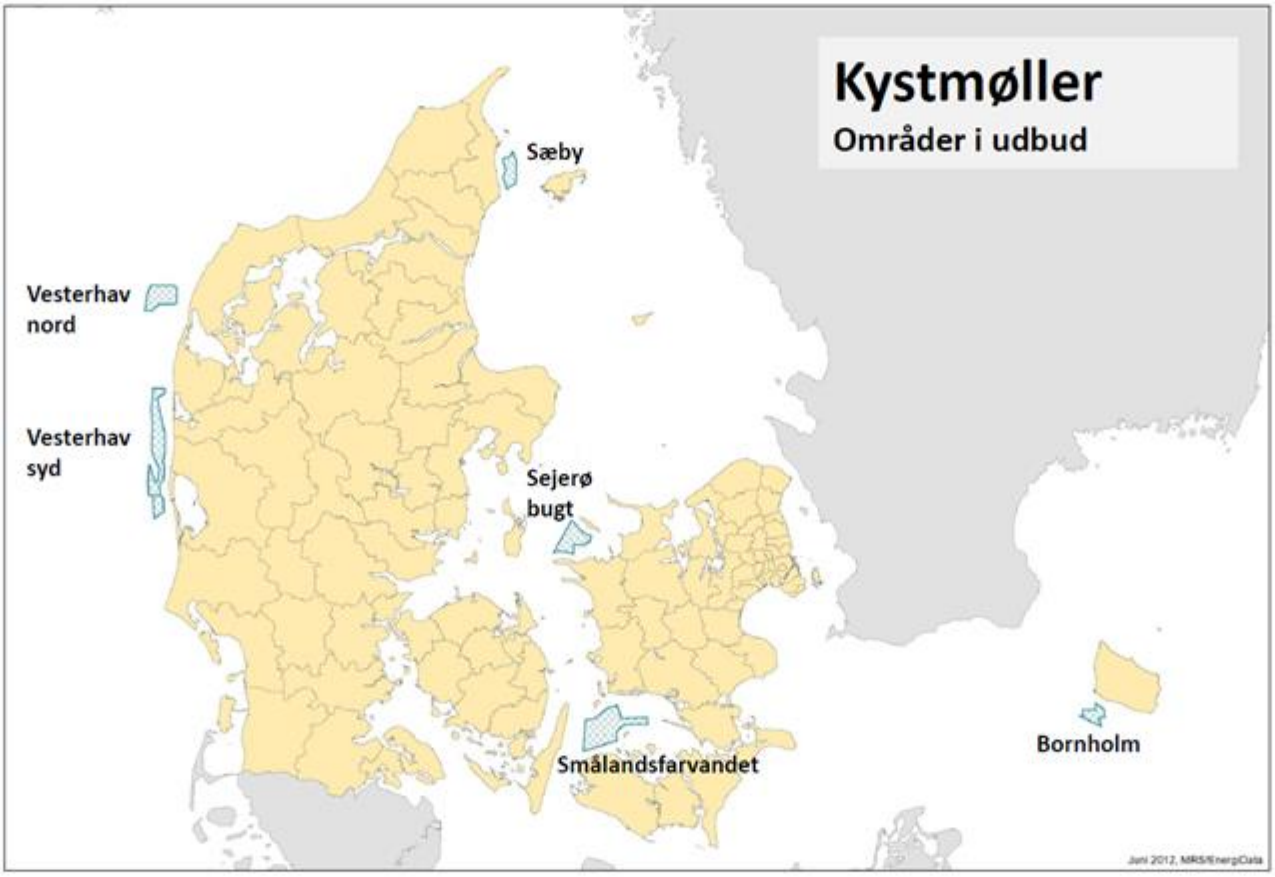

Figure 15: Near shore wind sites considered[22] (source: Danish energy agency)

5.2.2 Offshore electricity grid

New offshore grids are being planned. In ***Figure 16*** is seen the proposed new grid connecting the coming Kriegers Flak wind farm. The new grid is laid out so it can both feed wind power into the onshore grids and exchange electricity between Germany and Danmark and may be later on to Sweden.

[22] http://www.ens.dk/da-DK/UndergrundOgForsyning/VedvarendeEnergi/Vindkraft/Havvindmoeller/kystnaere/Documents/Kystm%C3%B8lleomr%C3%A5der%20i%20udbud_28%2011%2012.pdf

Figure 16: New offshore electricity grid at coming Kriegers Flak wind farm (Source Energinet.dk)[23]

A number of other means are expected to be introduced before large scale introduction of electric storage technologies situated in Denmark. These means are

a) Demand response
b) Flexible electricity generation
c) Smart Grid

5.3 Long term

The long term means considered and supported by R&D funding are:

a) Electric storage in the natural gas system (electricity converted to methane)
b) Compressed air energy storage (CAES).
c) Electricity storage in batteries
d) Use of hydrogen (electrolysis-based) in the transport sector
e) Use of hydrogen (electrolysis-based) in the natural gas network

[23] http://www.energinet.dk/Flash/Kriegers-Flak/EN/index.html

6 Special characteristics regarding the Danish electricity system

The Danish starting point for balancing large amount of fluctuating renewables are quite different to what is seen elsewhere and it might be valuable to know this development and the actual construction of the Danish energy system in order to understand the incentives and measures that are used in the actual plans balancing large amount of fluctuating renewables.

The Danish electricity system is characterized with a very share of CHP and wind turbines. About 50 % of all electricity generated in Denmark is co-produced with heat as CHP and more than 20 % is generated on Wind turbines.

The development is illustrated by the development of a fictive distributed CHP plant in town “CHP-ville”. The town has around 10.000 citizens. CHP-ville is modeled in energyPRO.

6.1 CHP-Ville 1985

When the development towards this started in the late 1980’ies shares like these were widely considered as technical and economic unrealistic. Practical no plants were build and the construction and what most people had in mind were base load constructions and production, see ***Figure 17*** and ***Figure 18***. No public regulation was in place to facilitate a development with distributed CHP-plants.

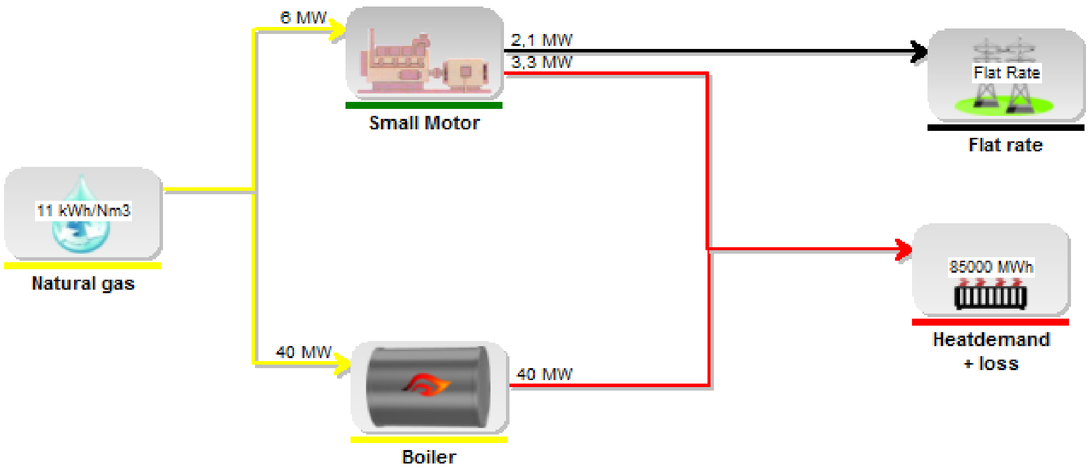

Figure 17: CHP-ville 1985. Base load design.

A core argument against a development with distributed CHP and wind power were already in this period anticipated problem with electric overflow, during cold windy winter nights with electric production from wind turbines and heat-tied electric production would exceed electric demands.

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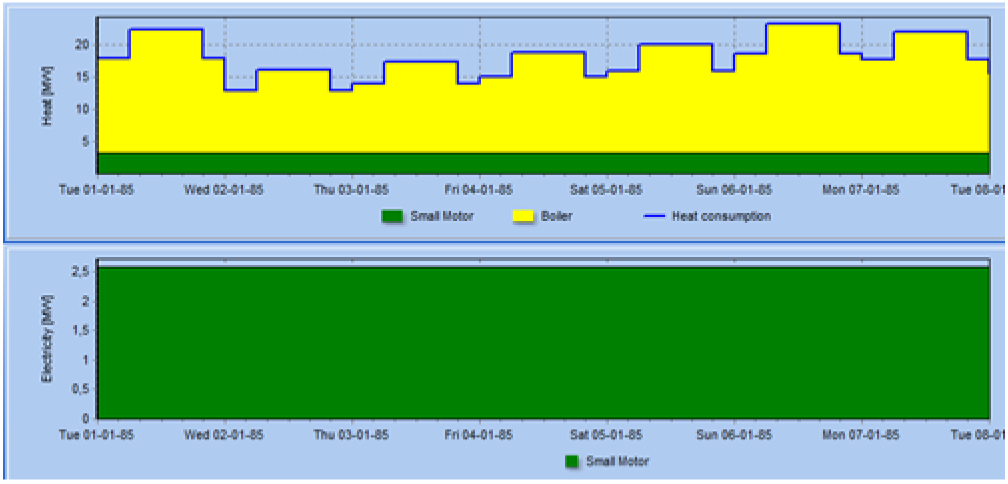
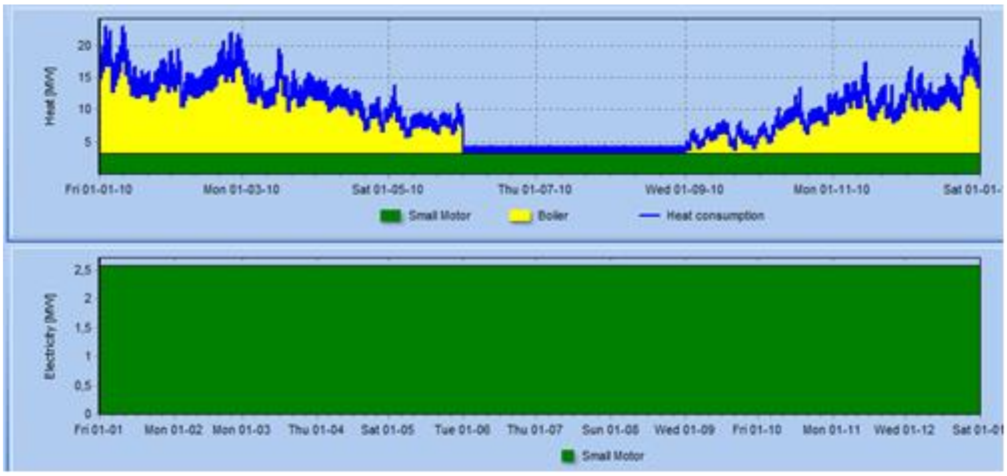


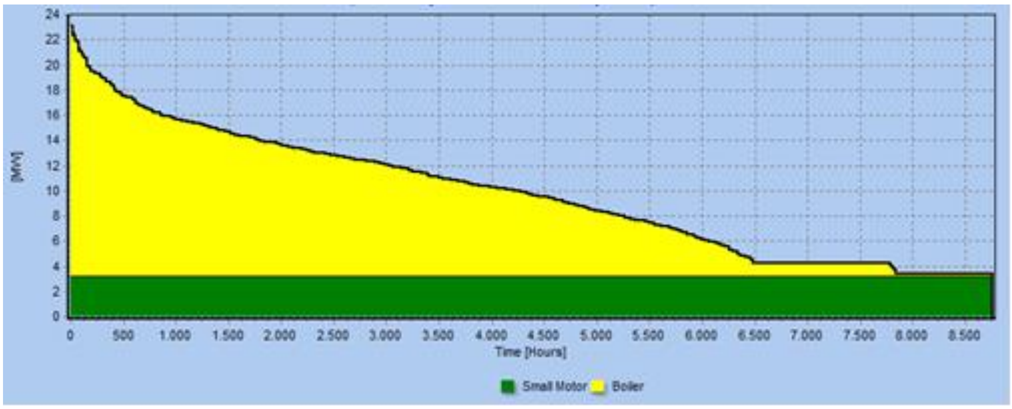
Week in January



All Year

Heat Production

Electric production



Duration Curve

Figure 18: CHP-ville 1985. Plant was not build. If it had been build, it would have been designed for base load production.

6.2 CHP-Ville 1990

Up to 1990 public regulation were established to facilitate an expansion of the CHP capacity. The most important regulation was the electricity triple tariff that was introduced in order to reflect that electricity in general had more value in day time that in night time. The principle was that the tariff should reflect the long term avoided cost in the rest of the electric system.

The result was that the CHP plants were constructed with a high electric capacity and large thermal stores. As a rule of thumb the plants were established with a thermal store that could contain about 8-12 hours of heat demand during wintertime and an electric capacity that often was several times higher than pure base load operation. The technical configuration could be as seen in ***Figure 20***.

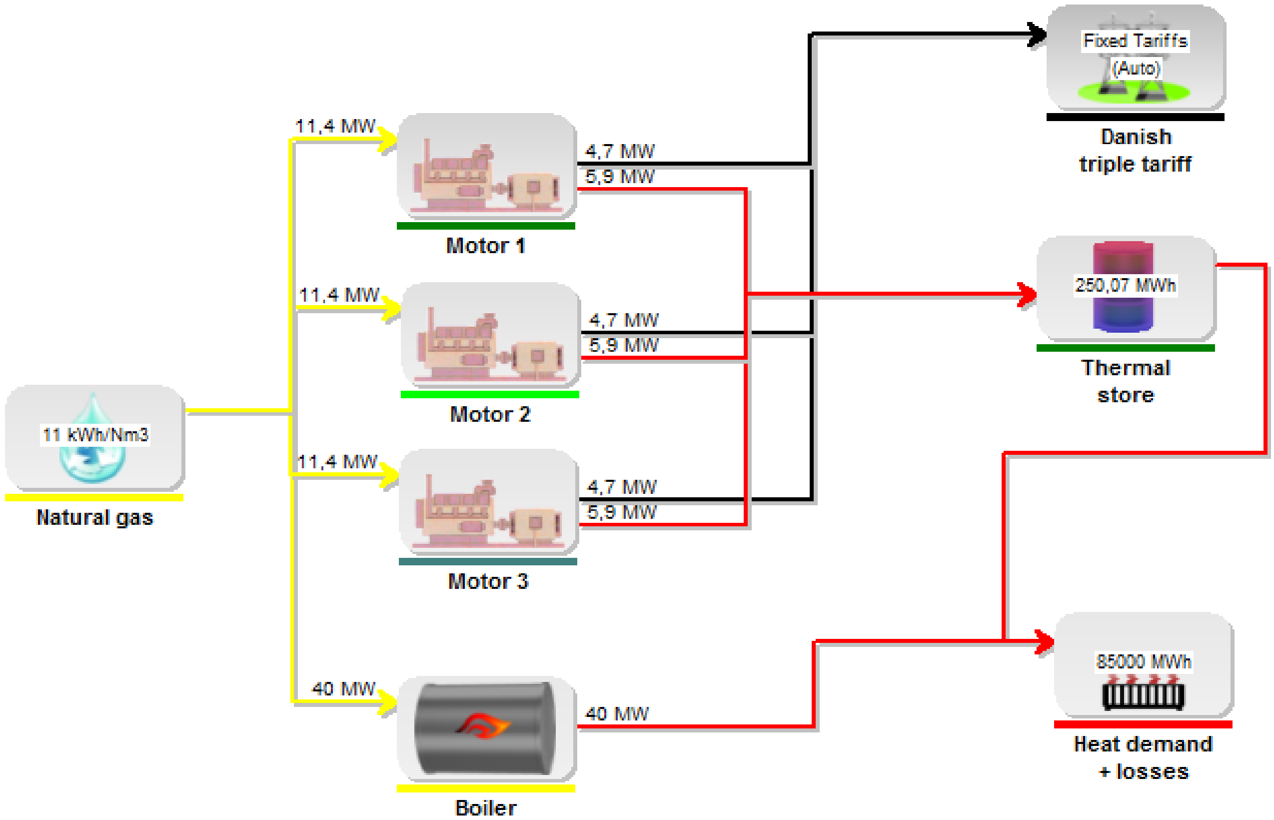


Figure 19: CHP-ville 1990. Design with high electric capacity and thermal store.

This led to highly flexible CHP plants compared to the plants seen elsewhere, where plant were constructed to base load operation and without thermal stores. Production was moved from night time and weekends towards daytime on weekdays.

Where CHP-ville 1985 had a constant production of 2 MW_{el} CHP-ville 1990 had a capacity of 14 MW_{el}. The Plant has a thermal store with a capacity of maximal 250 MWh, which is approximately the heat production of 14 hours full load production on all motors.

In ***Figure 20*** is seen how CHP-ville 1990 is producing when optimizing against the triple tariff. Note how the production en moved from nighttime and weekends towards daytime and how the thermal store used actively.

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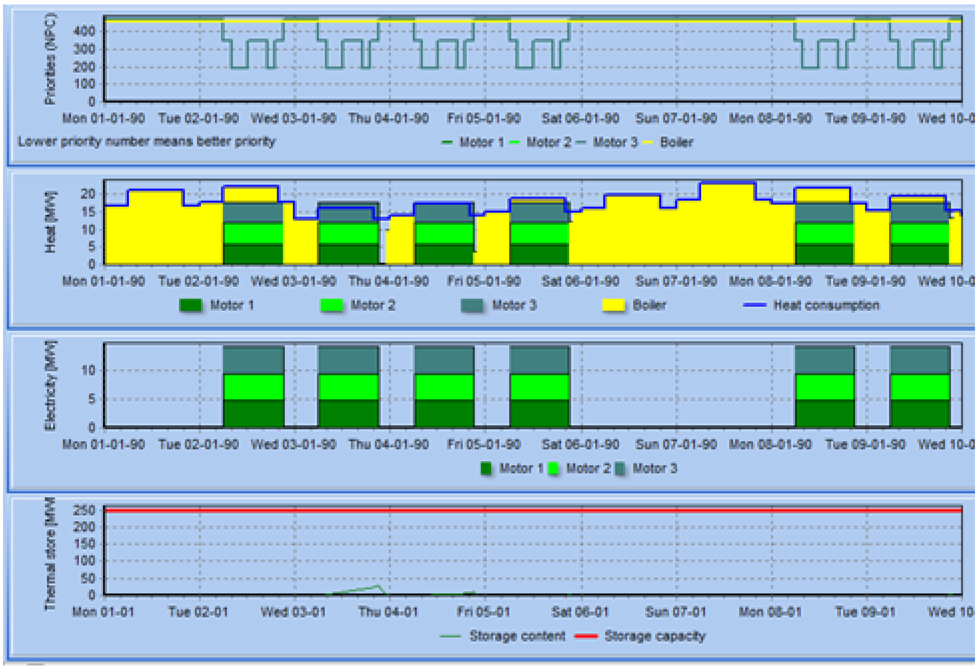


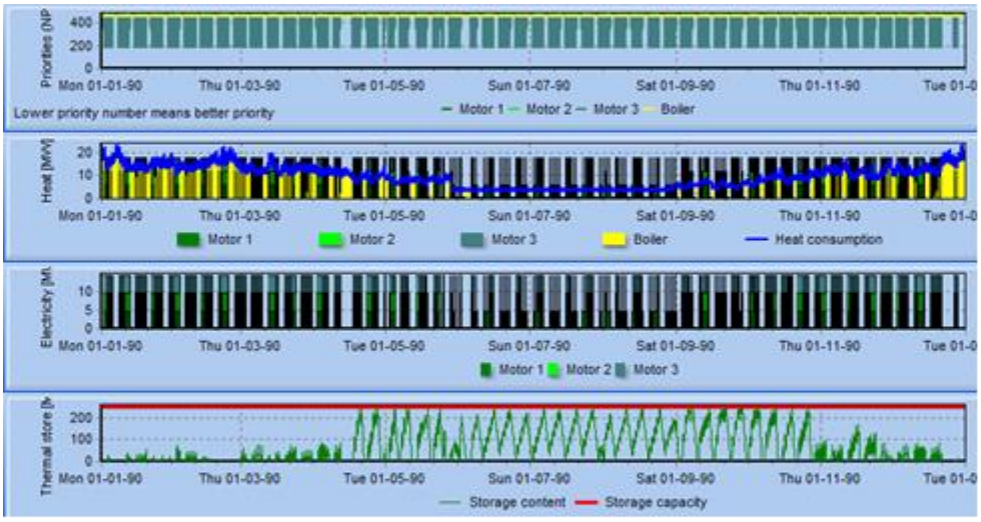
Week in January

Heat production costs

Heat production

Electricity production

Thermal store operation



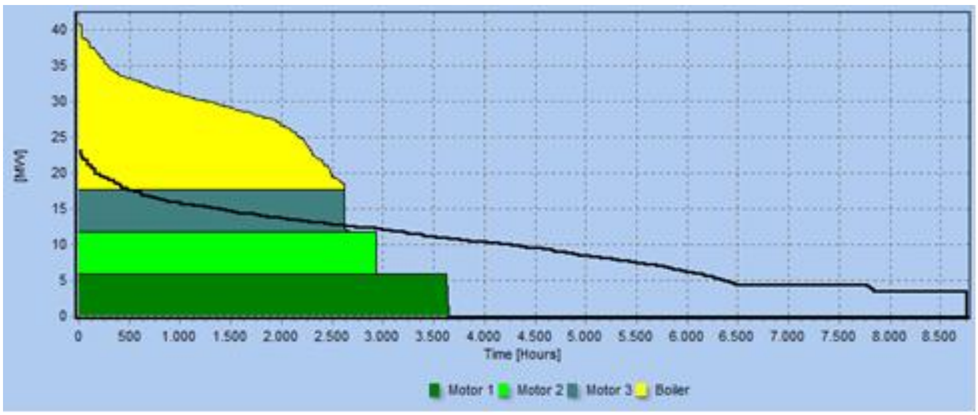
All Year

Heat production costs

Heat production

Electricity production

Thermal store operation



Duration Curve

Note that the productions above the demand curve (left side) are equal to the not filled production under the curve (right side). It is production displaced by the thermal store.

Figure 20: CHP-ville 1990. Triple tariff introduced. Investment in high electric capacity an engines and thermal stores

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6.3 CHP-Ville 2005

In the period round the millennium change, hours with electricity overflow were starting to occur frequently and the market price mimicking triple tariff was criticized for economical encouraging electricity production in hours with overflow problems, especially during night hour. Here to come that the general trend of liberalization of energy markets was pushing the change.

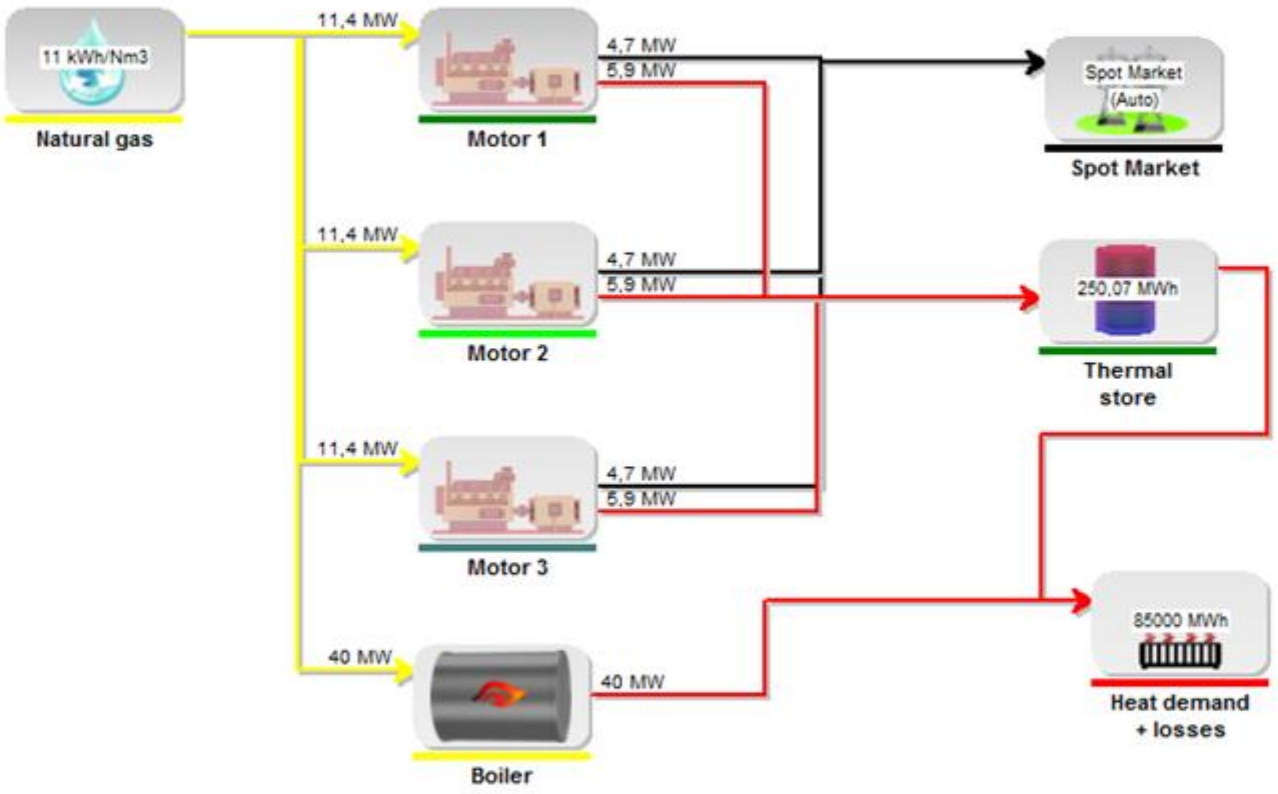
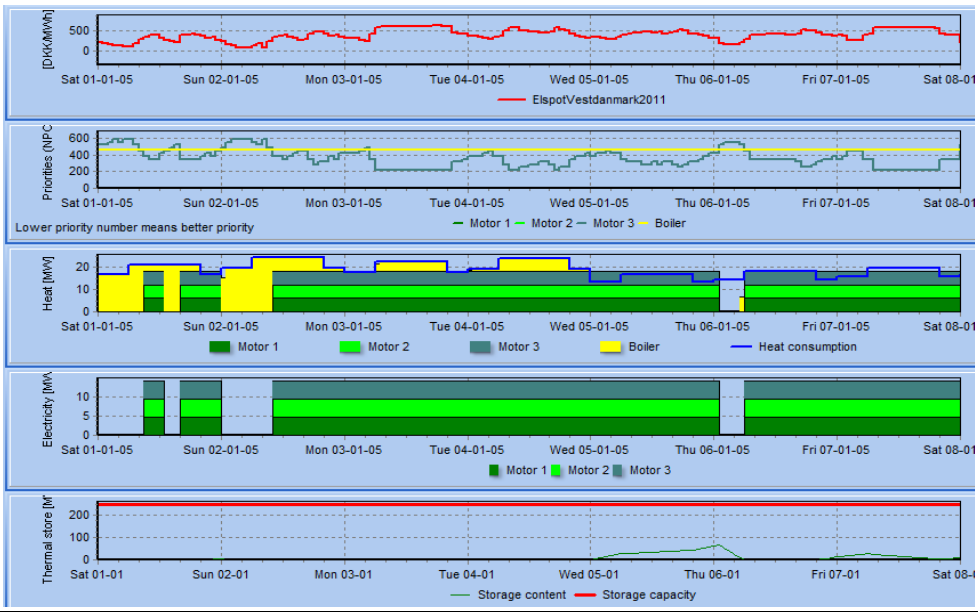


Figure 21: CHP-ville 2005. Same design as CHP-ville 1990 but with spot market instead of triple tariff.

Therefore a scheme for transferring plants from the triple tariff to a spot market tariff was introduced. In the periods round year 2005 most of the CHP production was transferred to selling their production at the Nordpool market. The transfer was accommodated with a compensation guaranteeing that the plants would not lose money selling at Nordpool compared to selling at the triple tariff if operating reasonable; this is illustrated in ***Figure 22***.

The result was/is that these plants have moved their production from hours with low spot prices, these hours include the problematically hours mentioned above.



Week in January

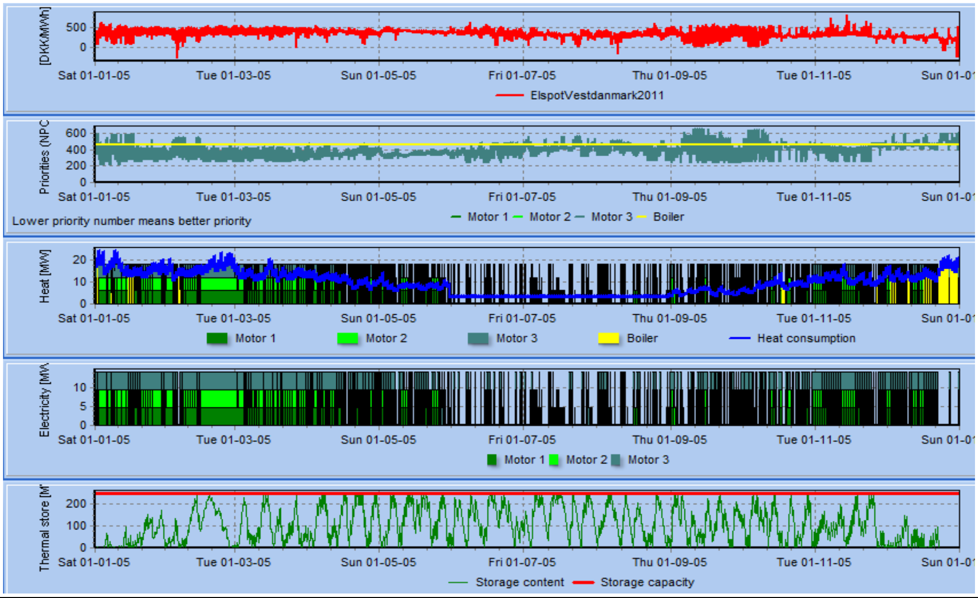
Spot prices

Heat production costs

Heat production

Electricity production

Thermal store operation



All Year

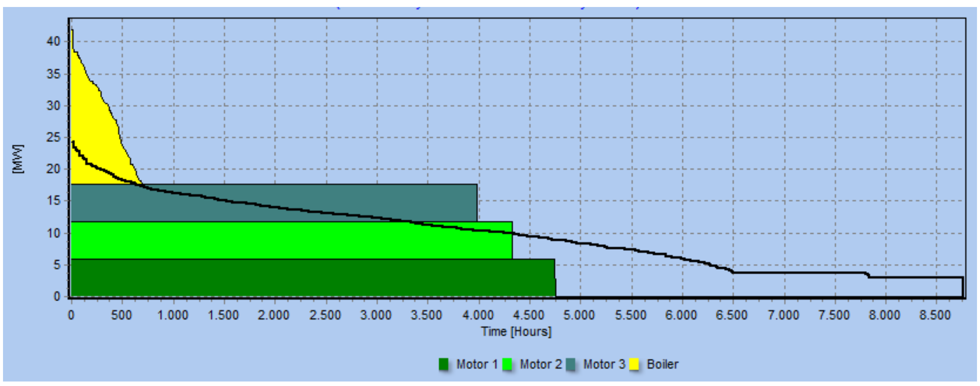
Spot prices

Heat production costs

Heat production

Electricity production

Thermal store operation



Duration Curve

Note that the productions above the demand curve (left side) are equal to the not filled production under the curve (right side). It is production displaced by the thermal store.

Figure 22: CHP-ville 2005. Plant is leaving the triple tariff and is entered the spot marked

6.4 CHP-Ville 2010

In recent years the CHP's units have furthermore been introduced on the regulating power market, were plants are operation at both at the upward and downward regulating power market.

Also within the last five years some of the CHP plants have improved their flexibility even further through installation on electricity consuming units (mainly electrical boilers). So if the spot prices are low the heat is produced on the electrical boilers (or electrical heat pumps) and if the prices are high the heat is produced on the CHP's and the electricity is sold on the spot market. Hereto comes that plants to some degree are participating in the electric balancing market.

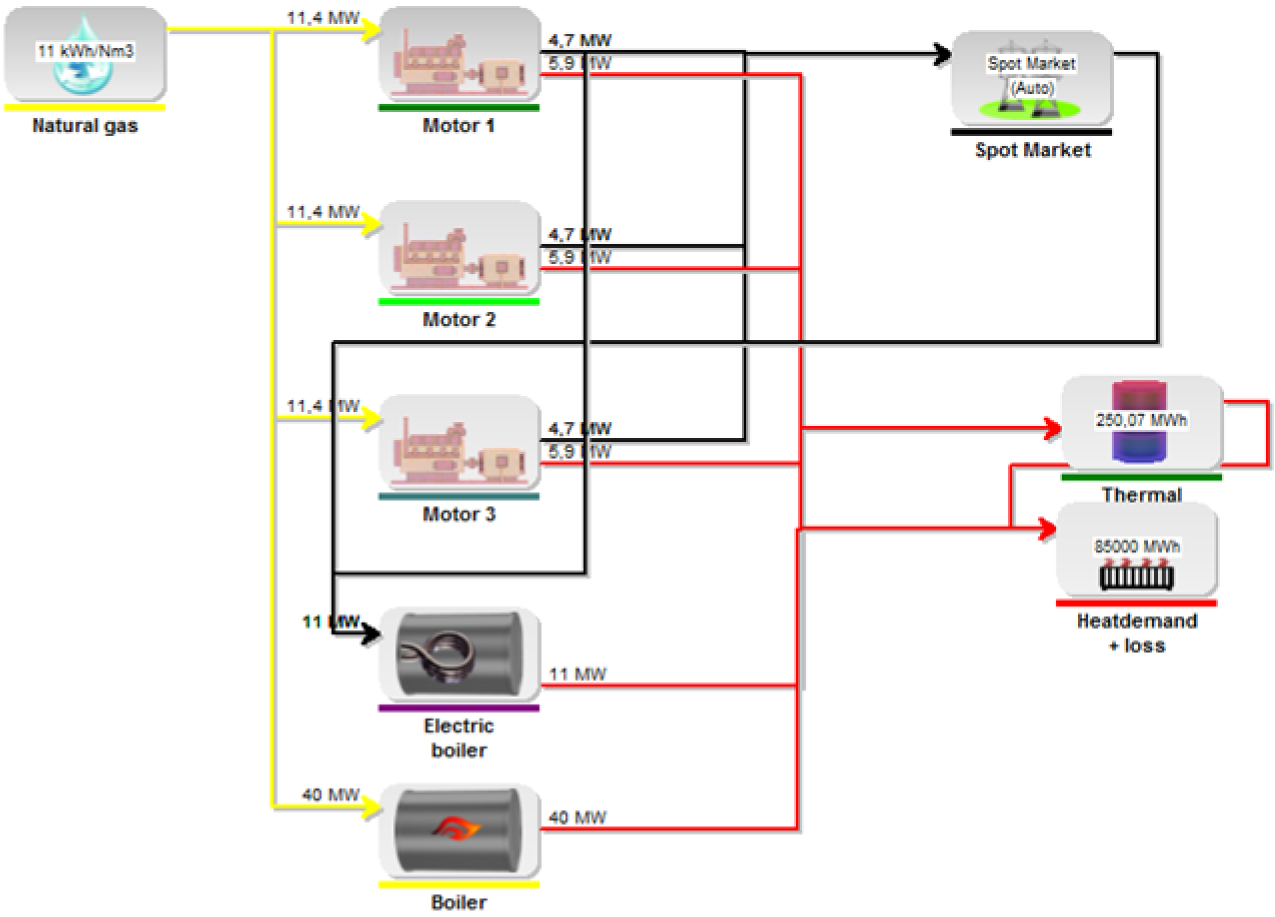
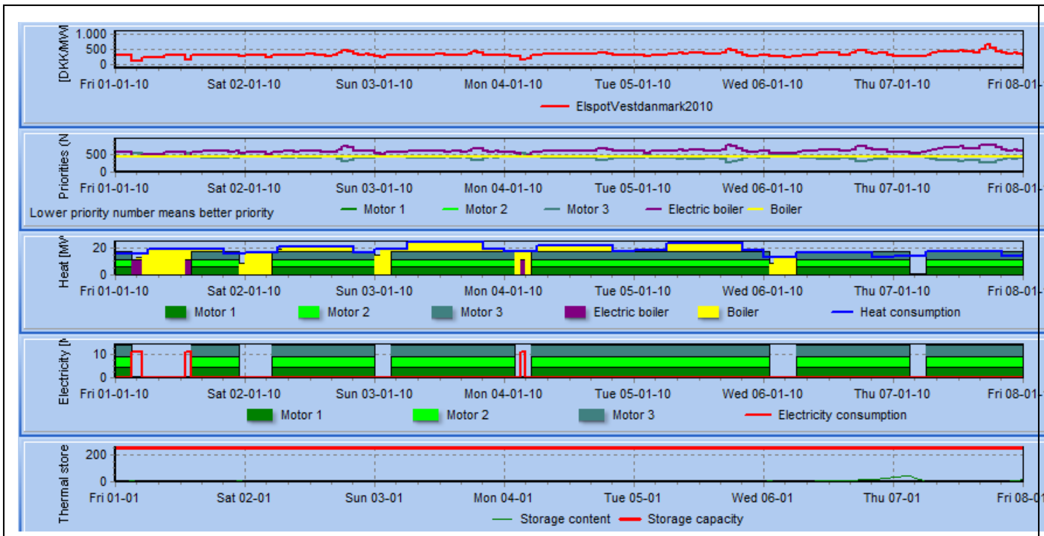


Figure 23: CHP-ville 2010. Electric boiler is added.

CHP-ville has now added and electric boiler of 11 MW_{el}. Hereafter the plant has a scope of regulation from – 11 MW_{el}, when producing heat by at electric boiler and natural gas boiler and + 16 MW_{el}, when producing heat by the CHP units. This gives a large flexibility for balancing fluctuating renewables.

In ***Figure 24*** is illustrated and example of where CHP-ville 2010 with the electric boiler is optimized against the electric spot prices.



Week in January

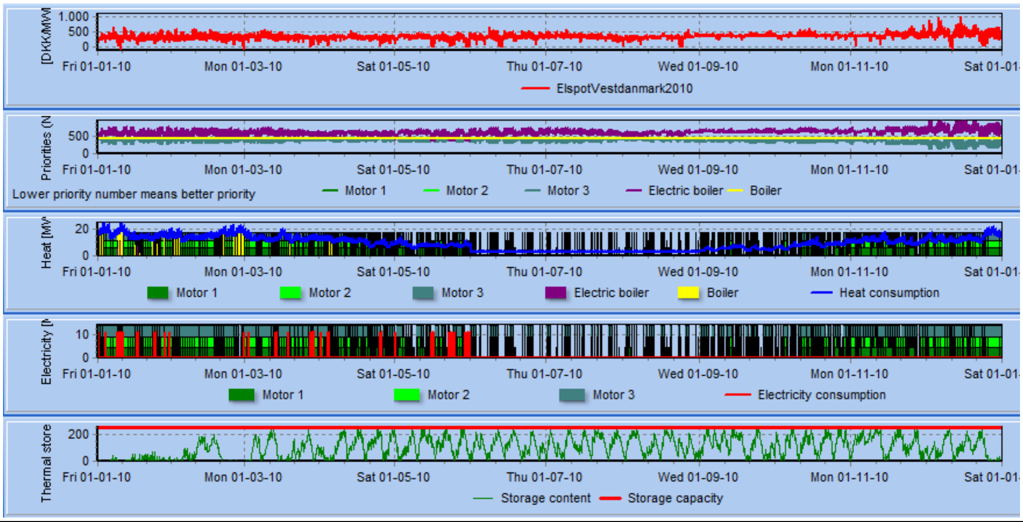
Spot prices

Heat production costs

Heat production

Electricity production

Thermal store operation



All Year

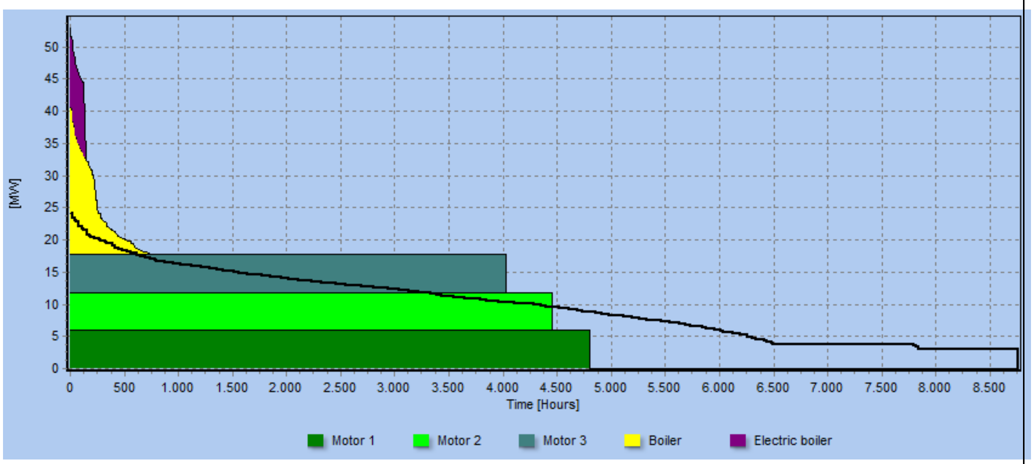
Spot prices

Heat production costs

eat production

Electricity production

Thermal store operation



Duration curve

Note that the productions above the demand curve (left side) are equal to the not filled production under the curve (right side). It is production displaced by the thermal store.

Figure 24: CHP-ville 2010. Production example when electric boiler added

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6.5 CHP-Ville -2030?

What will happen in CHP-ville within the coming years? A trend that might already be started is construction of larger thermal stores enabling the plants to store heat not only on day/night basis but also weekly basis. For instance could heat produced on electricity from wind power produced Monday be used for heating the next Saturday. This will give the plant more flexible production options and better possibilities for operating on the electricity balancing markets. Part of the natural gas might be substituted by biogas injected in the natural gas grid. Hereto, come that introduction of heat pumps might be an options as well as charging stations for electric cars might be established?

In the households and at the work places in CHP-ville demand response solutions and smart gird solutions are expected to be developed.

6.6 CHP-Ville -2050?

What will happen? If 100 % renewable scenarios are to be met long term means for balancing fluctuating renewable electricity production, see ***Figure 12***, will be relevant. Some of these technologies will affect CHP-ville. Electric storage in the natural gas system as methane or hydrogen substitute natural gas. Larger thermal stores eventually with seasonal storage might be seen.

The other means compressed air energy storage (CAES), Electricity storage in batteries and use of hydrogen (electrolysis-based) in the transport sector will not directly affect the CHP-ville plant but might be part of a system solution.

7 Development of the Residual Load

7.1 Input Data and Scenario Assumptions for the Analysis

Before analysing the future electricity storage needs in Denmark, the development of the (hourly) residual load until 2020 and until an 80% share of renewable energies on the net electricity consumption is studied. For this, hourly data sets for the different RES-E technologies and the electricity load of the year 2011 were taken as input and linearly scaled up to 2020 and beyond.

For this report two different points of time have been investigated. First The year 2020 with the amount of installed wind power defined in the National Renewable Energy Action Plan (NREAP). Here a further differentiation into 3 scenarios has been made. As it is plausible that the onshore expansion until 2020 will be smaller than assumed, a scenario B with 25 % less installed onshore capacity and scenario C with 50 % less new onshore wind turbines respectively have been added.

The second scenario investigates the impact on the electric power system with a RE share of 80%. This scenario was chosen to specifically avoid restriction to a specific year. No studies were found that clearly forecasted for 2050 and it was therefore difficult to estimate the development of RE after the year 2020. This second scenario uses data from the NREAP and scales them accordingly. The cases in this scenario investigate a RE share of 80 % in an isolated system without energy storage, with energy storage and with interconnections which allow for export and import. An overview of these scenarios and the installed power of each technology can be found in Table 5.

In addition to the export scenarios for the 80 % scenario the potential of storing energy in the heating sector is investigated for all scenarios. For that purpose the existing electric boilers as well as the future development of heat pumps are taking into account.

Table 5 Overview of the scenario assumptions for Denmark

	Ref.	2020 Scenario (in MW)			80% Scenario (in MW)	
		A	B	C	A	B
RE power plants						
Wind (onshore)	3210	4568	4246	3639	5983	Import / export investigations
Wind (offshore)	742	2142	2142	2142	5542	
PV	0	6	6	6	10	
Hydropower	0	10			15	
Other RES	0	0			0	
Yearly peak load	6.22	6.5			7.37	
Energy Consumption in TWh	34.57	36.14			41	
RE production (TWh)	9.77	18.47	17.8	16.54	35.67	
RE share	28.29 %	51.1 %	49.3 %	45.8 %	~80 %	

For the further investigation the focus is on West Denmark. The reason for this assumption is that Western and Eastern Denmark are just connected via a HVDC link and can therefore be treated as separated systems. The reason to choose West Denmark lies in the fact that the main wind energy exploitation will be in West Denmark and the problems with high feed-in from wind will be stronger here. The installed amount of different RES-E just for West Denmark is shown in table 6. In the 80 % RE scenario for Denmark the share of renewable energies on the net electricity consumption in West Denmark reaches already 100 %.

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Table 6 Overview of the scenario assumptions for West-Denmark

	Ref.	2020 Scenario (in MW)			80% Scenario (in MW)		
		A	B	C	A	B	C
RE power plants							
Wind (onshore)	2603	3483	3238	2993	4368	Import / export investigations	
Wind (offshore)	369	1169	1169	1169	3769		
PV	0	6	6	6	10		
Hydropower	0	10			15		
Other RES	0	0			0		
Yearly peak load	3.66	3.83			4.34		
Energy Consumption in TWh	20.7	21.64			24.55		
RE production (TWh)	6.95	12.13	11.63	11.12	24.88		
RE share	33.6 %	56.1 %	53.8 %	51.4 %	~ 100 %		

All data used for the calculation are in hourly values. The load demand of Denmark was obtained by ENTSO-E. The onshore wind production data was provided by EMD and obtained by the Danish TSO Energienet DK. The data for the offshore wind production of Denmark were calculated using the energyPRO program. Therefore the total yearly production for Horns Rev I and Horns Rev II was found at lorc.dk [1] and was split into hourly values by using energyPRO and NCAR wind speed data for the North Sea. Present hydropower production is 20 GWh/year. In year 2020 the amount will be 15 GWh/year due to nature rehabilitation. No feed in curves available. For the calculation a constant feed in over the whole year was assumed.

Table 7 shows the wind parks that will be connected to the Danish grid by 2035. The last column indicates in which part of Denmark the wind farm will be. As just Western Denmark is modeled in more detail, only the wind farm is western Denmark are taken into account.

Table 7: Overview of wind parks and their installed power taken into account until 2035

		2011	2020	2030	....	2035	Location
Offshore generation	MW						
Rødsand	MW	373	373	373		373	East
Horns_Rev	MW	369	769	1.569		1.569	West
Anholt	MW	0	400	400		400	West
Kriegers_flak	MW	0	600	800		800	East
Store_Middelgrund	MW	0	0	0		200	East
Rønne_Banke	MW	0	0	400		400	East
Ringkøbing	MW	0	0	800		1.000	West
Jammerbugt	MW	0	0	400		800	West
Total offshore	MW	742	2142	4742	0	5542	
Onshore generation	MW						
Eastern Denmark	MW	607	1.085	1.585		1.615	
Western Denmark	MW	2.603	3.483	4.333		4.368	
Total Onshore	MW	3.210	4.568	5.918		5.983	
Total All Wind	MW	3.952	6.710	10.660		11.525	

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7.2. Results for the Residual Load Development

The residual load (RL) is defined as the "non flexible" load demand minus the production from non-controllable renewable energy sources. In other words, the RL is the part of the load demand that may need to be covered by controllable power plants (fossil or renewable), import/export of energy or energy storage. For Denmark therefore, the RL is defined as the load demand minus wind power production minus the non-controllable part of hydropower. In this way a positive RL indicates a level of load that needs to be covered by either conventional or controllable renewable power plants, imports or energy recovered from storage facilities. In the same way then, a negative RL indicates that there is a surplus of fluctuating energy that either needs to be stored, exported or curtailed.

The rejected energy is the energy from fluctuating renewable sources that cannot be integrated onto the grid. This does not take into account energy storage or import and export of energy. In other words, it is the energy that is initially rejected if there is no energy storage systems or transmission lines (or interconnectors) to neighbouring countries.

Synchronous generation units help the grid to maintain a constant supply of frequency, whereas non-synchronous do not. This is because the majority of wind turbines are connected indirectly to the grid via power electronic converters to operate with a variable rotational speed to better adapt to different wind conditions. Other non-synchronous generators are: tidal turbines, marine wave devices, photovoltaic (PV) and HVDC imports.The TSO’s therefore impose limits on the instantanoues proportion of system load that can be served by non-synchronous generators. All additional non-synchronous generation has to be rejected (curtailed), or if possible, stored or exported (Mc Garrigle et al., 2013). In Denmark no non-synchronous penetration limit is known.

Figures 24 and 25 are showing the load (black) and the residual load in Demark for the reference year as well as for scenario 2020 A and the scenario with an 80% share of RE. As can be seen the residual load stays positive the whole year in the reference scenario. This means that there is no surplus of wind energy in the Danish system at this point. This doesn’t take into account the possible problems in the transmission or distribution system due to high feed in from wind.

In 2020 there will already be a surplus of wind energy (see negative peaks in figure 25). However the surplus is only during some minor hours during the year.

In the 80% scenario this changes completely. The residual load turns negative very often and during long periods of time. This shows that there will be a strong surplus of wind energy that cannot be used in the Danish system if not stored, exported or used in other energy sectors like heat or transport.

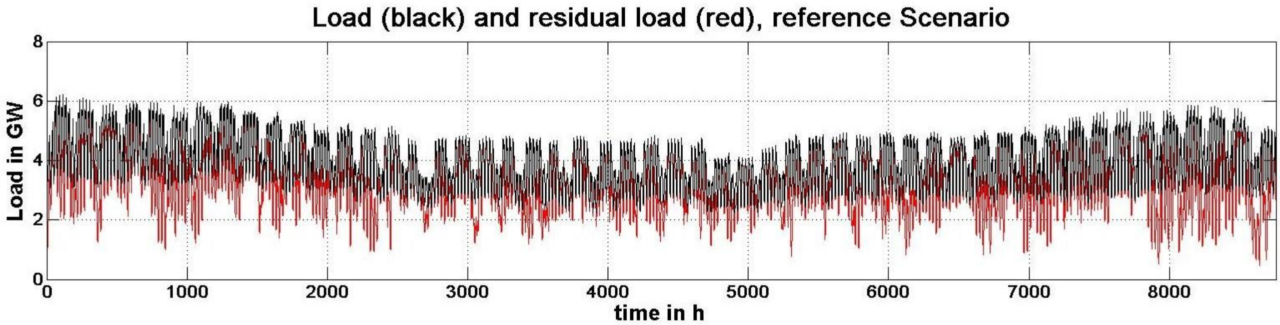

Figure 25: Load (black) and residual load (red) for reference scenario

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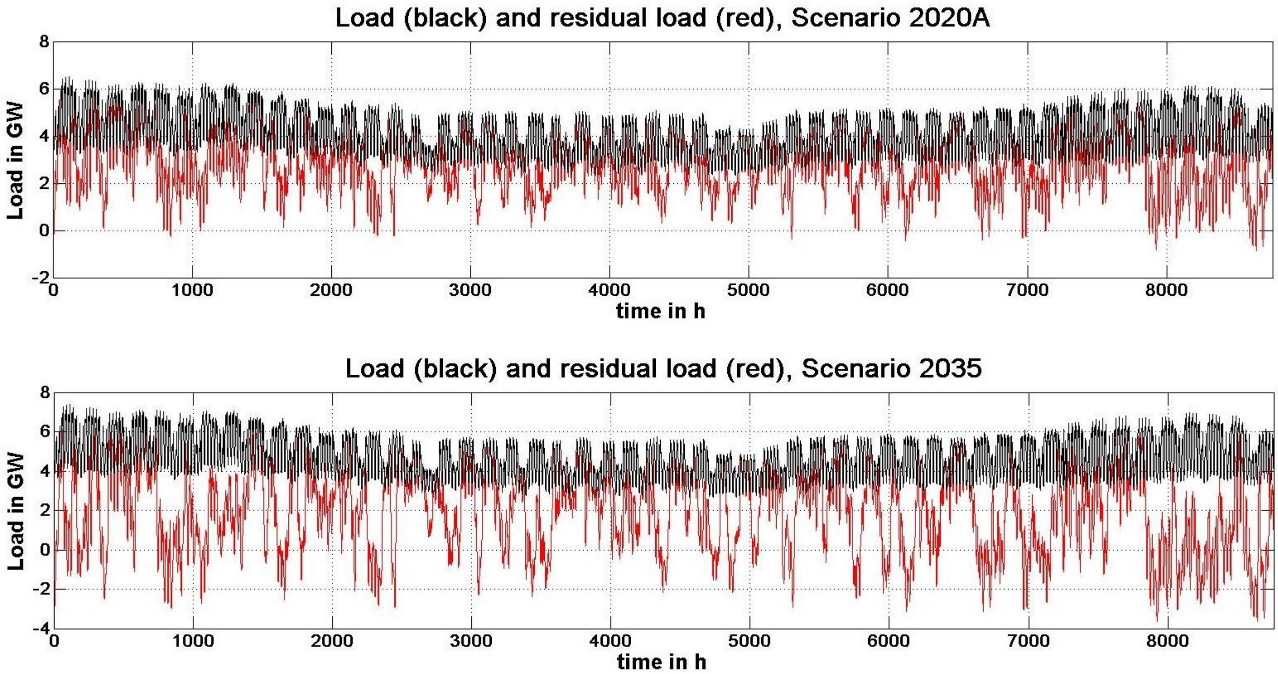

Figure 26: Load (black) and residual load for 2020 and 2035 in Denmark

Figure 26 is now showing the load (black) and residual load just for West Denmark with and without the possible influence of the heating sector. As can be seen already in 2020 (in contrast to whole Denmark) Western Denmark as a strong surplus of wind energy in the electricity system. Negative peaks of the residual load appear often and with an excess power of up to 2 GW in scenario A, 1.82 GW in scenario B and 1.63 GW in scenario C respectively.

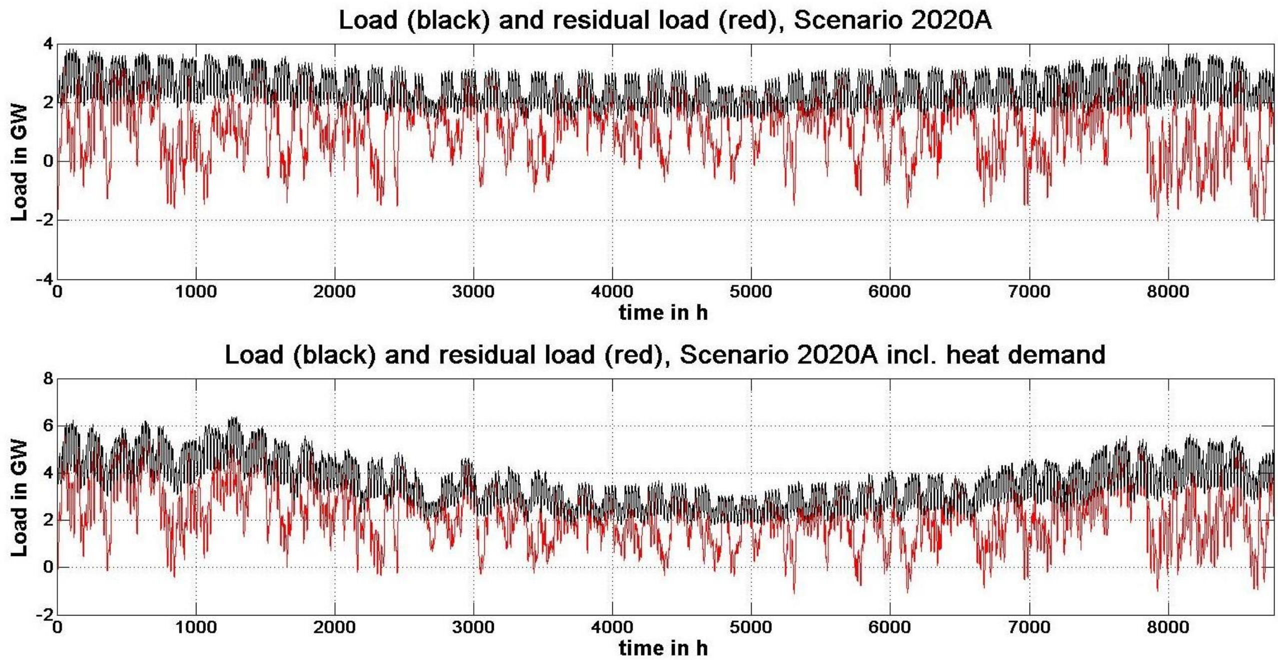

Figure 27 Load (black) and residual load (red) for West Denmark, scenario 2020 A with (above) and w/o (below) integration of heat demand

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When adding the heat demand to the general load demand of West Denmark it can be seen that the residual load increases. This shows, in a very general way, the possible influence the heating sector can have in raising the load at times of excess wind power.

The same can be observed in the year 2035, when the share of RE on the electricity production in Denmark reaches 80 %. The surplus energy in West Denmark is higher than in the combined system and the negative peaks appear over long periods of time. Without any measures to deal with this surplus, 4.12 TWh of wind energy would be rejected in 2035 just in West Denmark. This is already 16.78 % of the total load demand of West Denmark.

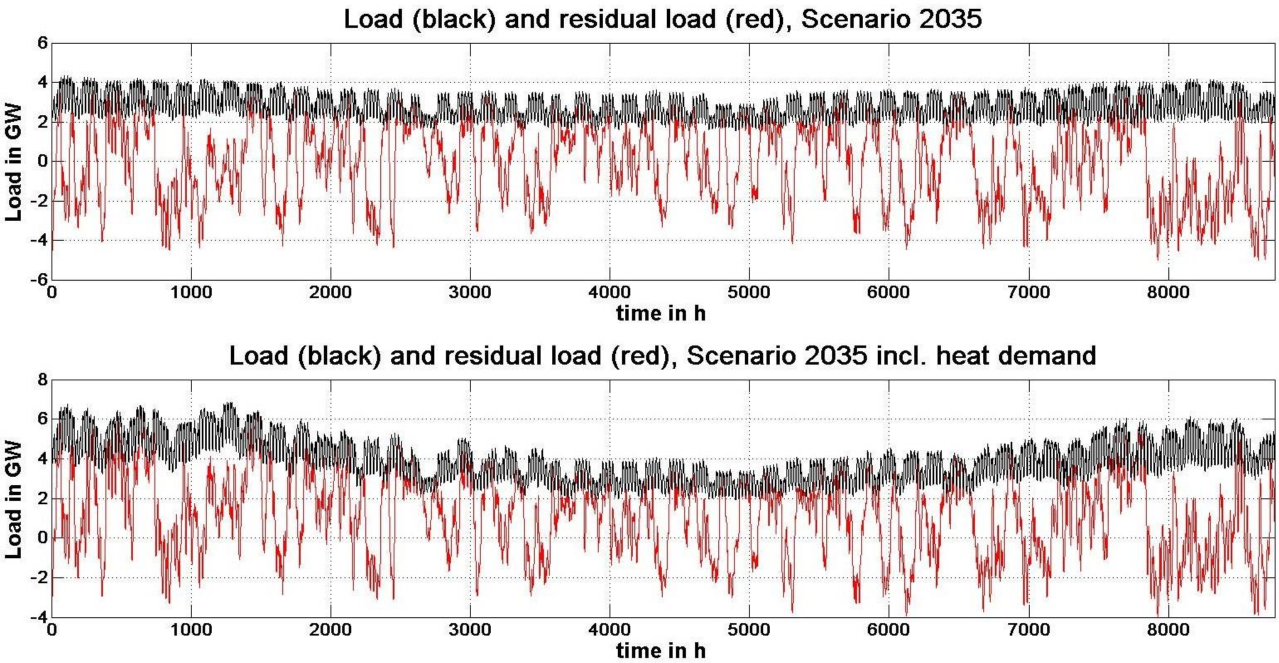

Figure 28 Load (black) and residual load (red) for West Denmark in 2035 with (above) and w/o (below) integration of heat demand

The variation of the load demand for scenario 2020 A and the 80% RE scenario is shown in figure 27. It can be seen that the load variations of the residual load increase with a higher share of wind energy. Especially the load variations of less than 1 hour decrease a lot whereas the maximum variations in GW per 8 hours increase.

These results show that an electricity system with high shares of fluctuating renewable energy sources needs a fast reacting power plant fleet to quickly adapt to high load variations.

All results analyzing the residual load of West Denmark are again summarized in table 8.

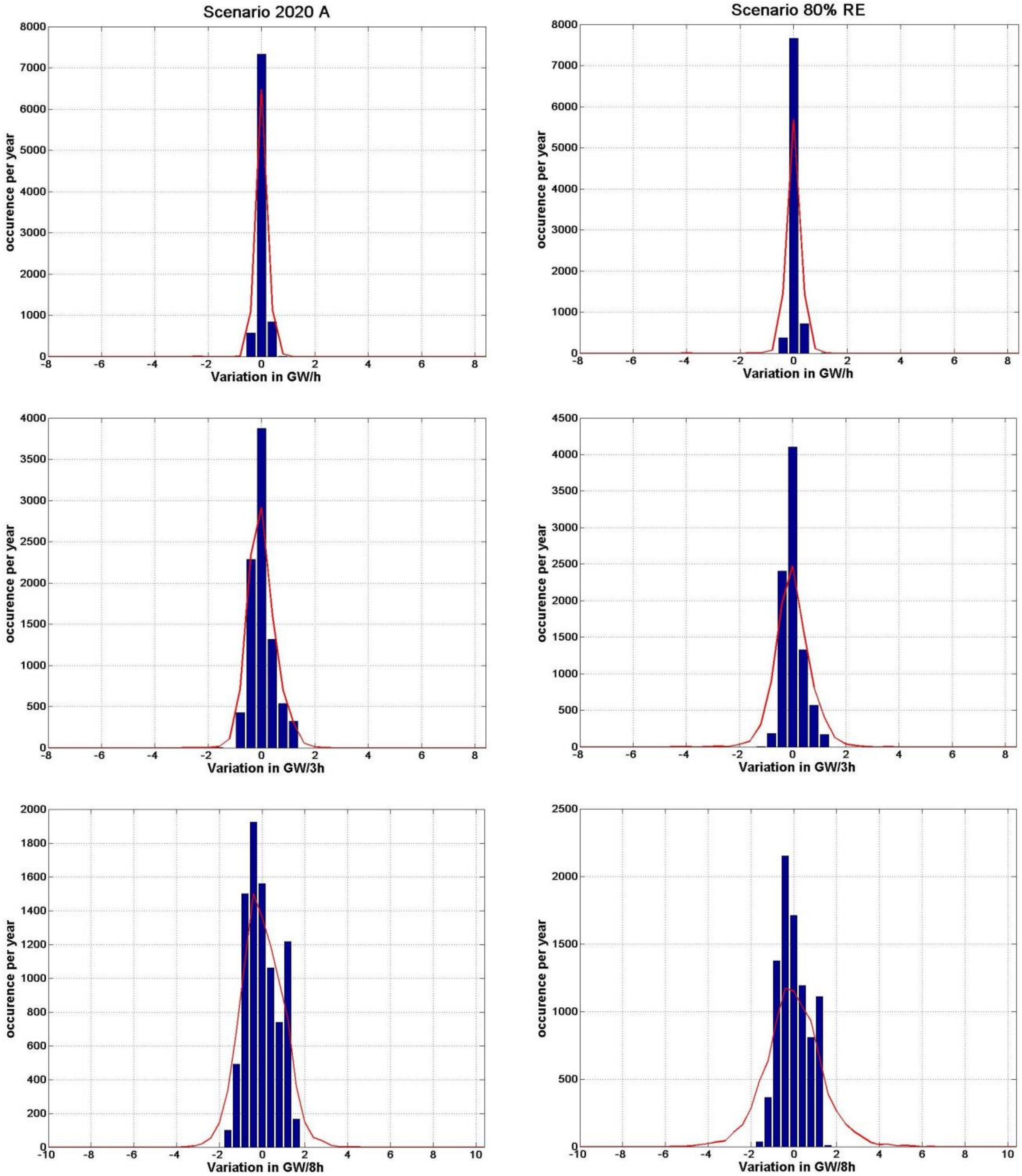

Figure 29: Variation of load demand (blue bars) and residual load (red line) in GW per hour, per 3 hours, per 8 hours

Table 8: Overview of the outcomes of the residual load analysis of West Denmark

Scenario	Max. rejected power [MW]	Rejected Energy [GWh]
2020 A	2,000	591 GWh
2020 B	1,819	449 GWh
2020 C	1,628	328 GWh
2035	4,848	4,122 GWh

8 Storage Needs

In the following the 2020 and 80% scenarios for Denmark described beforehand are investigated in respect to their electricity storage needs for the complete integration of all energy from (variable) RES-E generation. For that purpose an algorithm was developed by the Helmut-Schmidt-University (HSU) to calculate the electricity storage needs from an electricity system point of view - this implies that there are no market models or economic considerations made within the algorithm. The main aim of the operation of the electricity storage system (ESS) in the analysis therefore is, on the one hand, the smoothening of the residual load as far as possible to allow an easier and safer planning of the operation of the remaining power plants and to integrate the rejected (surplus) RES-E on the other hand. A brief explanation about the implemented optimization algorithm can be found in the following section –a more detailed description is found in Deliverable 5.1 - Germany of the stoRE project. As there are a lot of electrical boilers in the Danish district heating plants, the heat storage potential of these systems will be analysed as well. For the future development also heat pumps are taking into account as they will gain importance within the heating sector.
Denmark has no bulk energy storage facilities, so the capacity of heat storages in distributed CHP plants is of high importance.

8.1 Computer Modelling

The computation methodology follows two steps. First, the residual load for the scenario under investigation is calculated (see previous chapter). The second step is the calculation of the overall storage needs. For this purpose an algorithm was developed at the HSU to estimate the electricity storage needs just from a system point of view. The aim of the energy storage facilities in this approach is to integrate the maximum amount of RES-E possible without any focus on the electricity spot market price.

The residual load is defined as the load demand minus the non-controllable RES-E generation. As an example the residual load curve of Western Denmark in the 80 % RE scenario is shown in Figure 30.

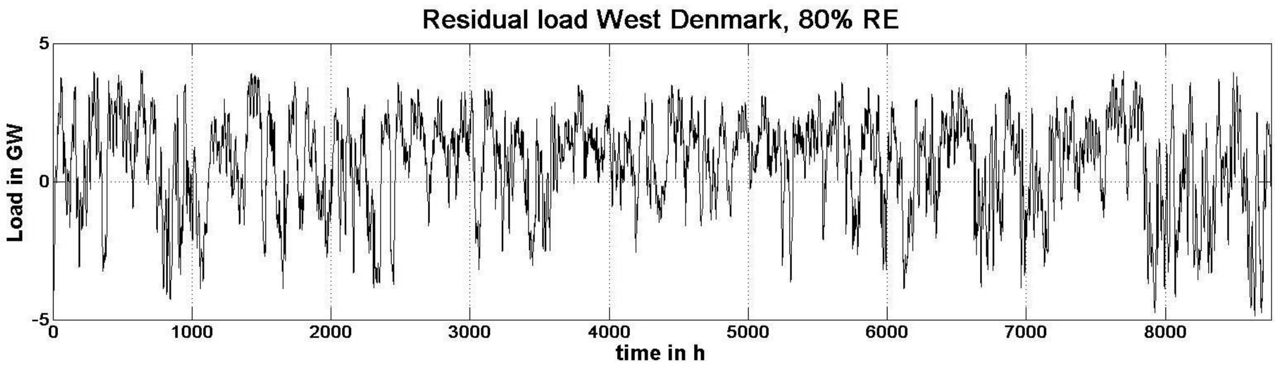

Figure 30: Residual load in West Denmark in 2035, without heat demand (Source: HSU)

A negative residual load means that there is a surplus of electricity from RES-E that exceeds the electricity demand. This surplus can either be rejected by down regulation of RES-E generation units, exported to neighbouring countries or stored in ESS. However, down regulation or energy export is not an option within the computation algorithm. The aim is to use as little power and capacity of the ESS to fully integrate all the surplus RES-E generation. In principle the algorithm follows a peak-shaving and valley-filling strategy as shown in Figure 31. To minimize the energy storage needs, an intelligent operation strategy was implemented. If a high surplus of RES-E in the electricity system can be expected, the ESS plans its operation in a way to be able to fully integrate this surplus. If the surplus of renewable energy is expected to exceed the storage capacity of the ESS, it tries to plan the operation in a way to empty the reservoirs completely beforehand in order to integrate as much RES-E as possible.

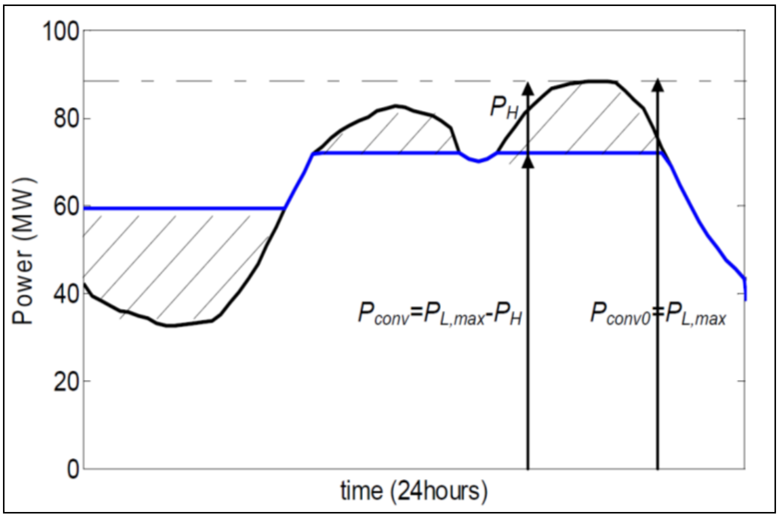

Figure 31: Indicative effects of PHES operation on the residual load curve (Source: NTUA)

To estimate the additionally needed storage capacity a further technology, in addition to the already existing ESS, is introduced which has an unlimited storage capacity and power. This technology can take the surplus RES-E that cannot be stored by the existing system. Due to the unlimited power and capacity this technology enables the full integration of all RES-E. The actual used power and capacity of this second technology is an indicator of the additionally needed ESS.

8.2 Storage needs of West Denmark as isolated system

As discussed before, West Denmark is modeled as an isolated system first to determine the maximum possible storage needs and to be able to determine the influence of the heating sector and transmission lines in later sections.

8.2.1 2020 scenarios

For the 2020 scenarios only scenario A is analysed in detail. The energy storage needs of the other two scenarios are smaller than scenario A, see also table 9. The plots of scenario B and C can be found in the Annex.

Figure 32 shows the residual load after the use of the defined energy storage system (ESS). It can be seen that the residual load curves is smoothened a lot and no more negative peaks appear. This however is due to the unlimited nature of the defined ESS because the power and capacity is big enough to take all the surplus of RE production.

Figure 33 is showing the needed power and capacity of the ESS to integrate all wind energy. As can be seen the ESS is used constantly during the whole year. The maximum used charging power is 2.33 GW whereas the maximum discharging power is 2.36 GW. This is more or less the same needed power so that a symmetric dimensioning of the energy storage facility is possible. The maximum needed capacity (maximum size of the reservoir) is 55.22 GWh. The maximum charging level is reached at the end of the year where there is a period with high feed in from wind energy.

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When taking a closer look at the charging level, 3 periods with a longer surplus of wind can be observed: The first one between hour 2000 and 3000, the second one around hour 8000 and the third one at the very end of the year. This not yet a clear seasonal characteristic but it shows already the problems a high share of wind energy on the net electricity production can bring.

The needed charging and discharging power as well as the needed capacity of the ESS is smaller in scenarios B and C than in scenario A due to an overall smaller installed power of wind energy. All outcomes of the simulation are again summarized in table 9.

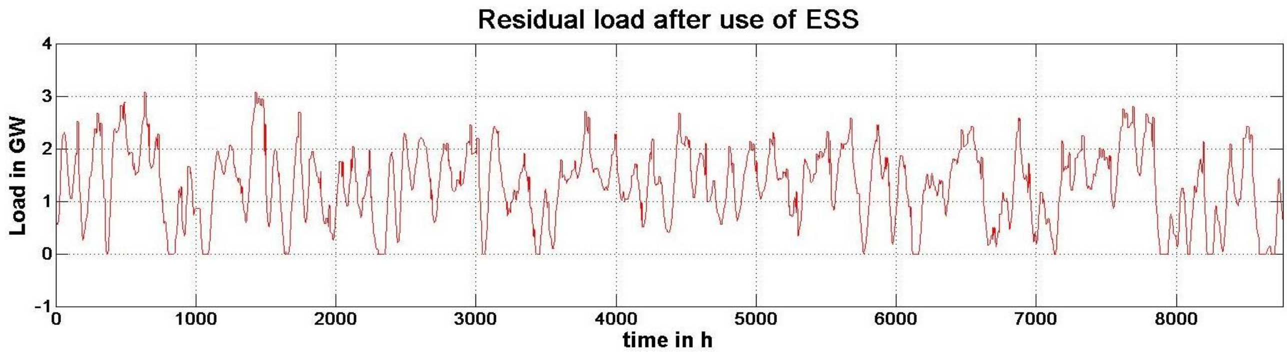

Figure 32: Smoothened residual load after use of unlimited ESS

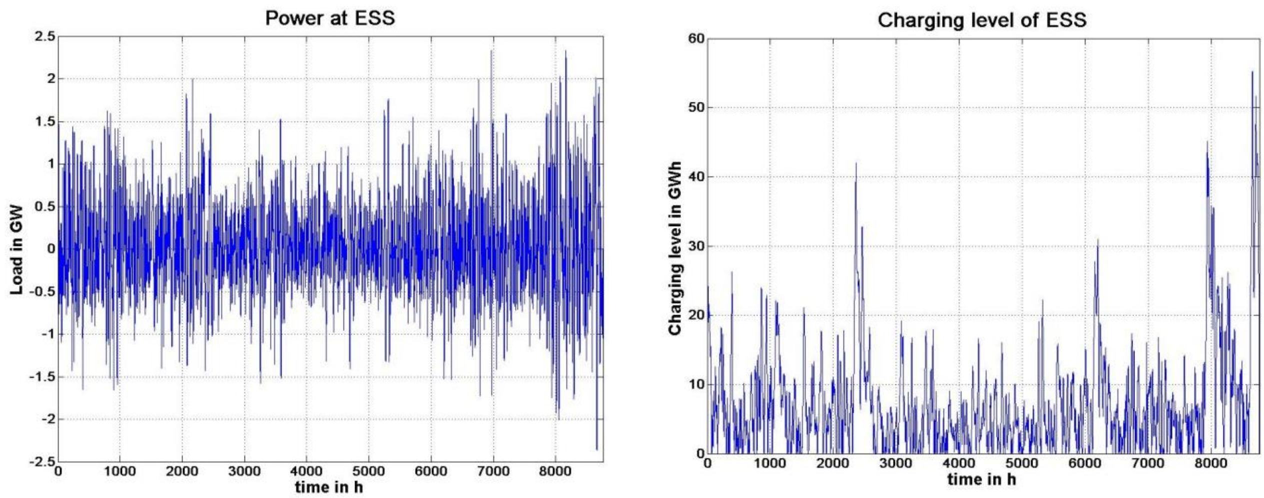

Figure 33: Needed power and capacity of an ESS to fully integrate all wind energy

8.2.2 80 % Renewable energies on net electricity consumption

Again the residual load is smoothened very well, high fluctuations are filtered out and no more negative peaks appear, see ***Figure 34***. This is again caused by the unlimited nature of the ESS. The needed power and capacity of the Energy Storage System is plotted in Figure 34. Like in the 2020 scenarios the ESS is use constantly during the whole year but with higher peaks. The maximum needed charging power is 4.85 GW whereas the maximum needed discharging power is 3.25 GW. The maximum needed capacity is 660 GWh. This is caused by the unsteady character of wind energy that can produce surpluses over periods of multiple days to weeks. This is why in contrast to the 2020 scenarios, the ESS in the 80 % scenario shows a clear seasonal storage characteristic. Charged and discharged only a few time a year to a high extend: during spring and winter. Especially the period of strong wind at the end of the year that could already be observed in scenario 2020 A, causes a strong rise in the needed storage capacity.

All outcomes are again summarized in Table 9.

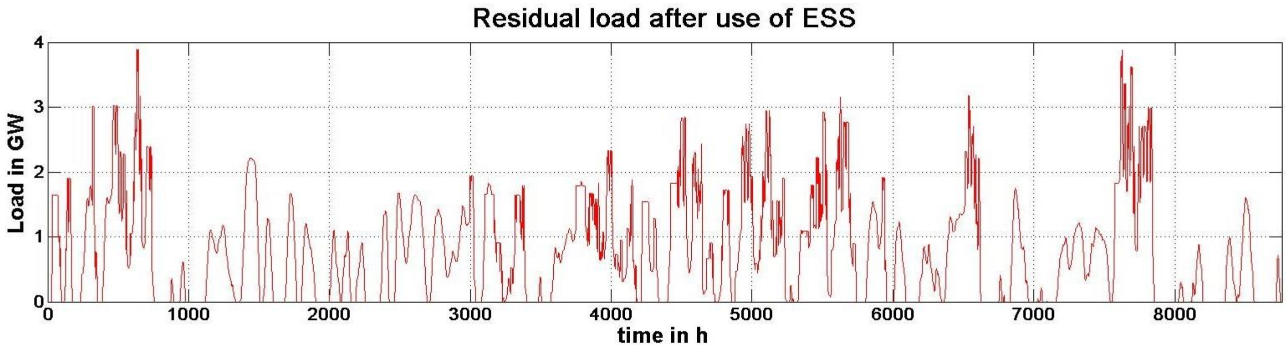

Figure 34: Smoothened residual load after use of unlimited ESS

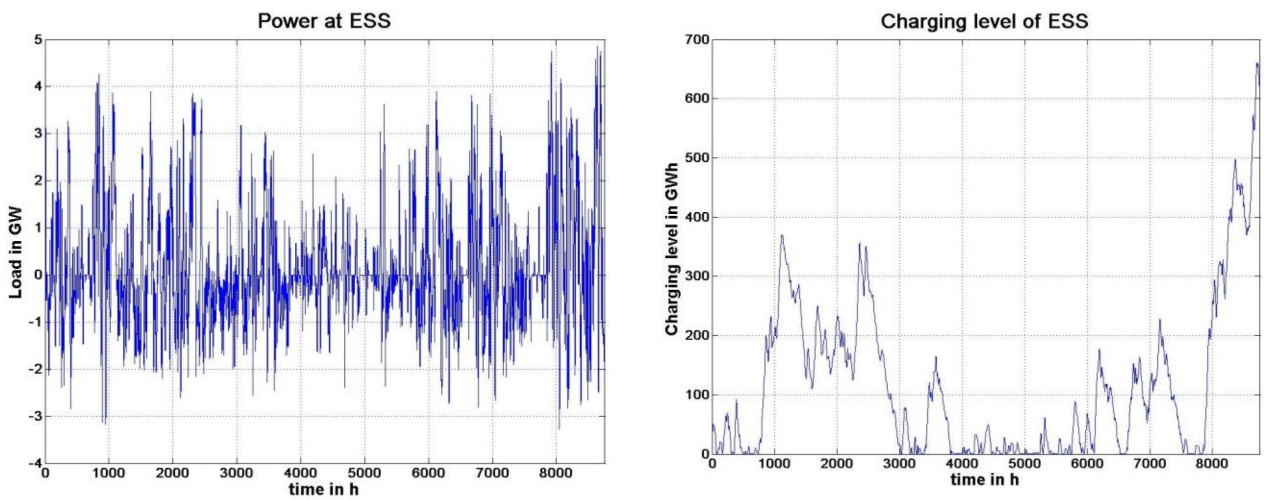

Figure 35 Needed power and capacity of an ESS to fully integrate all wind energy

As can be seen in table 9 the capacity factors of the ESS is all scenarios is relatively low. Surprisingly it is higher in the 80 % scenario than in the 2020 scenarios. In this simulation it is difficult to determine a clear statement from the CF because no economical framework conditions are applied.

Table 9: Overview of results

2020 Scenarios	**Stored Energy [GWh]**	**Provided Energy [GWh]**	**Capacity Factor**			**Max. Used Power [GW]**		**Max. needed energy [GWh]**
			Charge	Disch.	Total	Charge	Disch.	
A	2170.58	1743.08	10.6 %	8.43 %	19,03 %	2.33	2.36	55.22
B	2096.92	1691.62	10,6 %	8,51 %	19,11 %	2.26	2.27	46.71
C	2032.20	1647.61	10,6 %	8,63 %	19,23 %	2.19	2.18	38.68
80 % Scenario								
A	4592.37	3224.58	10,8 %	11,3 %	22,1 %	4.85	3.25	660.75

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8.3 Storage needs of West Denmark including the heating sector

In this section of the report the storage needs of West Denmark are calculated again but with the integration of the heating sector. As already discussed in the first chapters and especially in chapter 6, Denmark has a lot of district heating power plants where there are already electric boilers installed. With these electric boilers and the thermal storage capacity of the district heating plants wind energy can be balanced out to certain extend. To which extend exactly will be the center of investigation in this chapter. Figure 35 is showing the heat demand and temperature in West Denmark for the year 2011. As expected the heat demand is highest during winter when the temperatures are low. During summer, from around hour 3500 to 6000, there is no temperature dependent heat demand.

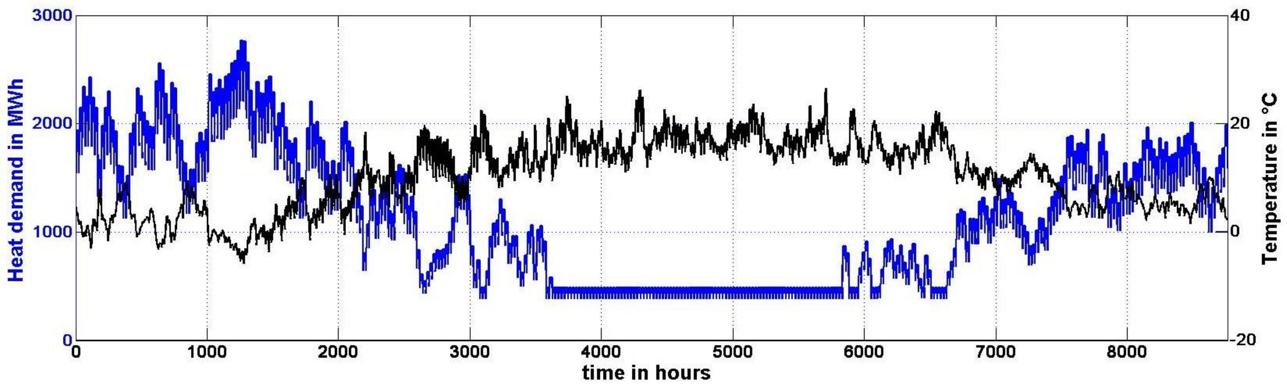

Figure 36: Heat consumption (blue) and temperature (black) in Denmark in 2011

There are installed 640 MW dencentralized energy plant in eastern Denmark and 1992 MW in western Denmark. The total heat storage capacity in West Denmark is 610.000 m^3. To transform m^3 into MWh a temperature difference of 50 °C between inlet (40 °C) and outlet (90°C) of the storage as well as an utilization of 90 % is set as a base. This gives a storage capacity of approximately 31800 $MWh_{thermal}$. Between 70 % and 80 % of these storages are located at distributed CHP plants. The rest is placed at biofuelled or conventional heat plants and at centralized Power stations. For this calculation only heat storages at dezentralized heat plants are taken into account. For the simulation there are two assumptions made:

1. During positive residual load the heat demand is covered by the CHP, biofueled and centralized power plants. The heat storage is used accordingly to the operation planing of the particular power plant. The planning of the operation should be in a way that the storage capacity is fully available when a surplus of renewable energy is expected.
2. During periods with surplus of renewable energy the heat storage capacity is fully available.

Total heat storage capacity for this report is: 80% of 31800 MWh = 25440 MWh, because the heat storage of conventional heat plants cannot be used for our purposes.

Furthermore different installed amounts of electric boilers and heat pumps are investigated up to the year 2035, see Table 10.

At present most electric boilers are built in Western Denmark, 198 MW in western Denmark and 25 MW in Eastern Denmark (see energinet.dk). Energinet.DK assumes a further expansion reaching a total of 400 MW in Denmark by 2017. To distribute between Western and Eastern Denmark it is assumed by EMD that Western Denmark has a share in 2017 of 61 % of the 400 MW, making a total of 244 in both 2020 and 2035.

In addition to electric boilers heat pumps will gain importance in the following decades because they are more efficient than electric boilers. The development of the installed power of heat pumps is also shown in table 10. There are two different types of heat pumps listed in this table: Heat pumps in District Heating (DH) and individual heat pumps.

At present there are no large heat pumps installed at district heating plant s in Denmark. The share of Western Denmark (values above divider in figure) is calculated to 61 %. To calculate the capacities, there is assumed a COP (Coefficient Of Performance) of 3.7 (assumption made by EMD). The COP is the amount of thermal energy that can be produced with a certain amount of electric energy. A COP of 3.7 means that 1 MWh_{el} equals 3.7 $MWh_{thermal}$. The COP of electric boilers was set to 1.

Energinet .dk provides the annual expected electricity consumption from individual heat pumps. Whether or not they will have regulating capabilities will depend on whether thermal stores and backup production options will be available.

The calculated capacities have been calculated based on the following assumptions, assumed by EMD.

- 80 % of heat demand is weather dependent
- 17 °C reference temperature
- Heating season start September to end May
- 61 % of capacity established in western Denmark
- Heat pump are the only heating source

Table 10: Overview of installed electric boilers and heat pumps in West Denmark

Western Denmark		2012	2020	2035
Heat pumps (DH)	MW-el	0	44	82
Heat pumps (indiv)	MW-el	40	222	631
Elec. Boilers (DH)	MW-el	207	244	244
Total	**MW-el**	**247**	**510**	**957**

Figure 37 shows the residual load and the influence of the electric boilers for scenario 2020A. The peaks are the ones used for the electric boilers and heat pumps. It can already be seen that the negative peaks are cut off.

Figure 38 shows the same for the 80% scenario.

Finally these outcomes will be integrated in the energy storage needs calculation. Table 11 summarizes the outcomes of the simulation of the energy storage needs of West Denmark as an isolated system but with the integration of possible potential of heating sector. The numbers in brackets are the outcomes of the simulation without the heating sector. It can be seen that the needed power and capacity of the ESS is decreasing in all scenarios and the capacity factor is increasing. Nevertheless there is still a very high need for energy storage especially in the 80% scenario.

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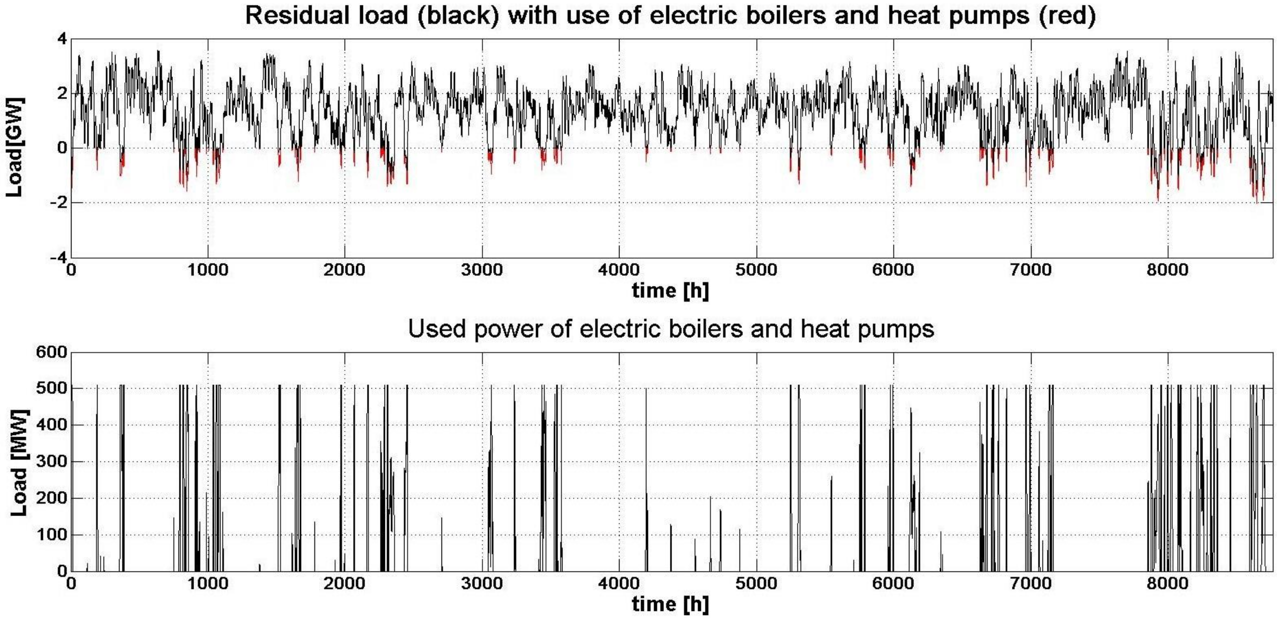

Figure 37: operation of electric boilers and heat pumps in times of surplus of wind energy, scenario 2020A

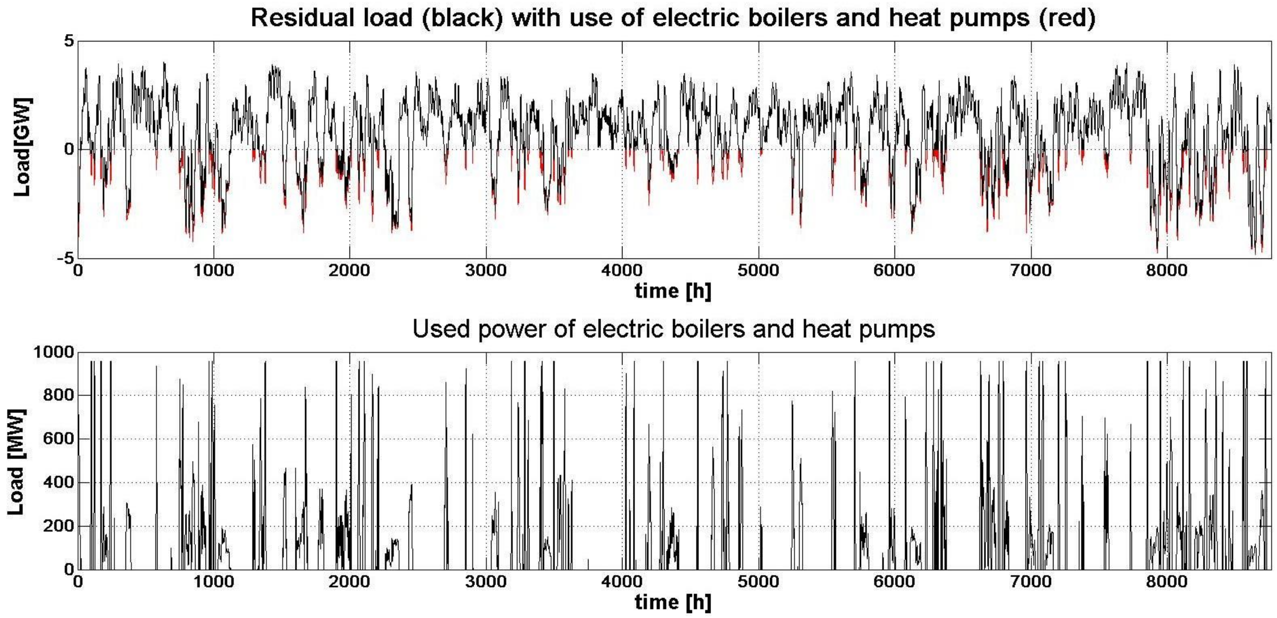

Figure 38: operation of electric boilers and heat pumps in times of surplus of wind energy, scenario 80% RE

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Table 11: Overview of the impact of heat pumps and electric boilers on total energy storage needs. Values in brackets are without heating sector, see chapter 7.1

2020 Scenarios	Stored Energy [GWh]	Provided Energy [GWh]	Capacity Factor			Max. Used Power [GW]		Max. needed energy [GWh]
			Charge	Disch.	Total	Charge	Disch.	
A	2092.04 (2170.58)	1682.66 (1743.08)	13.12 % (10.6 %)	9,70 % (8.43 %)	22,82 % (19.03 %)	1.82 (2.33)	1.98 (2.36)	45.89 (55.22)
B	2036.65 (2096.92)	1645.38 (1691.62)	13.43 % (10.6 %)	10,73 % (8.51 %)	24,16 % (19.11 %)	1.73 (2.26)	1.75 (2.27)	40.2 (46.71)
C	1983.49 (2032.20)	1606.63 (1647.61)	13.47 % (10.6 %)	11.25 % (8.63 %)	24.72 % (19.23 %)	1.68 (2.19)	1.63 (2.18)	32.5 (38.68)
80 % Scenario								
A	4301.93 (4592.37)	3004.27 (3224.58)	12.6 % (10.8 %)	11 % (11.3 %)	23.6 % (22.1 %)	3.90 (4.85)	3.12 (3.25)	600 (660.75)

In the next section the import/export possibilities to Germany are investigated.

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8.4 Time correlation of wind energy production and influence on export possibilities

As determined in the previous section the heating sector can help to balance out fluctuations of the wind energy production and thus reduce the future energy storage needs. In the previous sections West Denmark was regarded as an isolated system. In this part the export possibilities of excess wind energy to Germany are investigated. This investigation is done only for Germany, as at the moment it is the only country with HVAC transmission lines to West Demark. Furthermore the Danish government is planning to increase the transmission capacity to Germany to be able to export more surplus wind energy than it is possible with the actual transmission capacity of 1500 MW. The residual load taken into account for the export investigations is the one obtained from the previous section and includes the potential of the heating sector.

As a first part in this chapter the correlation of wind energy production in Denmark and Germany is investigated. As second part the residual load curves of both countries are investigated to see if at times of wind surplus in Denmark there will be a surplus of RE in Germany as well. Finally the outcomes of this analysis are integrated into the energy storage needs calculation. Like this the influence of the transmission capacity to Germany on the total energy storage needs of Denmark can be determined.

8.4.1 Correlation between Wind Power in Denmark and Germany

For the correlation of wind the wind data for the 80 % RE scenarios for Denmark and Germany were investigated. The data is based on the real feed-in curves from wind in both countries in the year 2011.

The cross-correlation factor was calculated with equation 1, whereby $\rho(\tau)$ is the correlation factor, x(t) and y(t) are the signals that are compared and τ is the shift factor.

$$\rho(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-\infty}^{\infty} x(t)y(t+\tau)dt \tag{1}$$

For the calculations in this report the two signals that are compared are the wind production in Denmark and Germany. First, the complete wind production is analyzed. Second, only the offshore wind farms of both countries are compared. For quality reasons the two time series are normalized before calculating the correlation factor. This way the influence of the amplitudes of the two signals is filtered out. As the time series are in hourly values and the period of investigation is one year, there are 8760 measured data for each signal. This means that τ will run from -8759 to 8759. This way a correlation factor for each time difference will be calculated and it can be seen at which time lag the wind production of the Denmark and Germany correlates the most.

Figure 39 shows the normalized production of wind energy in Denmark and Germany and Figure 40 shows the results of the correlation factor of the measured feed-in curves. The time series have been normalized by their corresponding maximum. As can be seen the production of wind in Denmark and Germany correlates well. This merits further investigation. The maximum correlation factor of offshore wind is 0.915 at a time lag of - 2 hours, which means that the maximum wind energy production appears on average 2 hours earlier in Germany than in West Denmark. The reason for this is that the German offshore wind farms are more west the Danish ones and the wind direction is mostly onshore. For the total wind production the maximum correlation factor decreases to 0.876. The time lag changes as well to +2 hours. This is caused by the areal distribution of the wind farms in whole Germany as well as in whole Denmark. Nevertheless the maximum correlation factor is still very high.

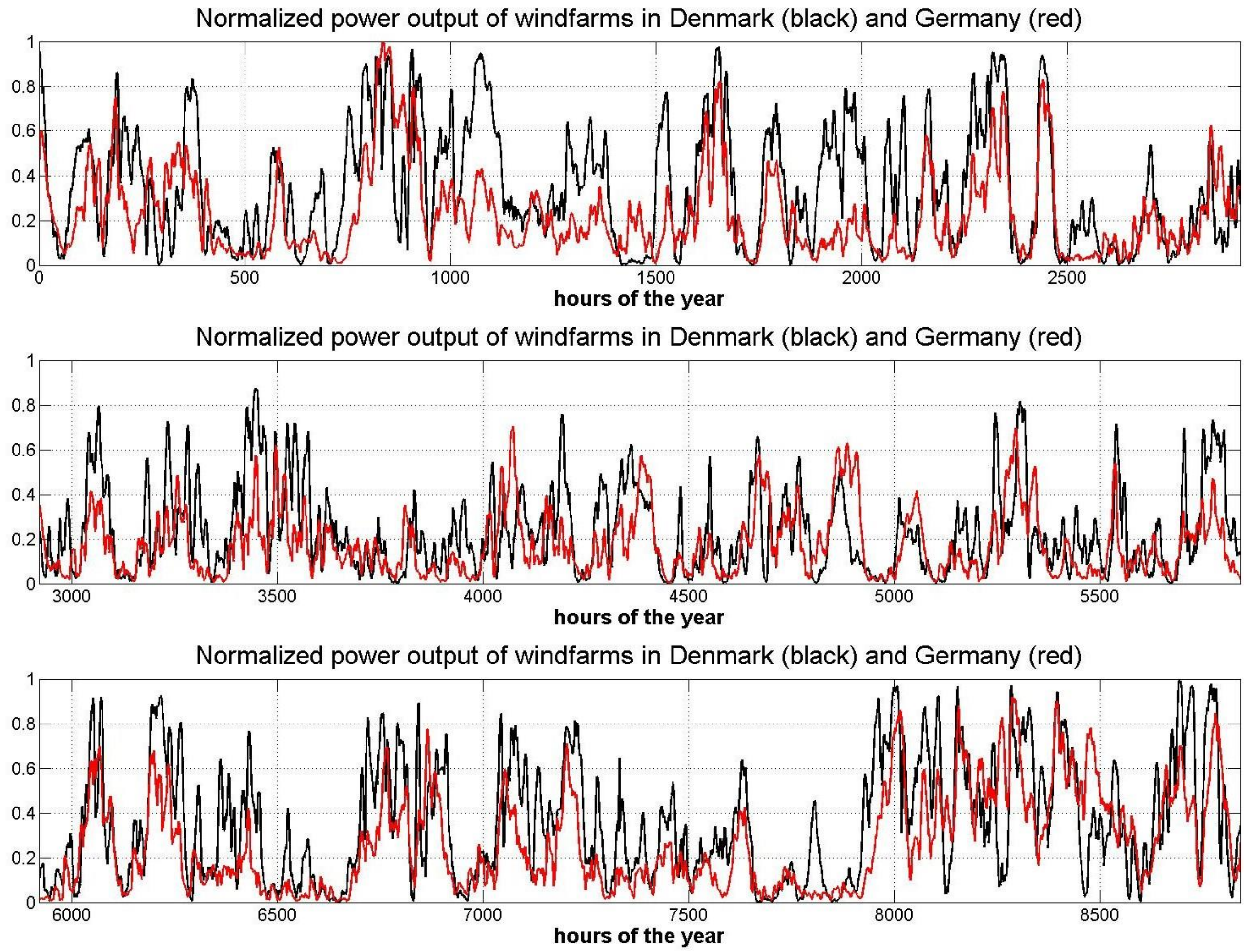

Figure 39: Normalized wind energy production in West Denmark (black) and Germany (red) for the year 2011

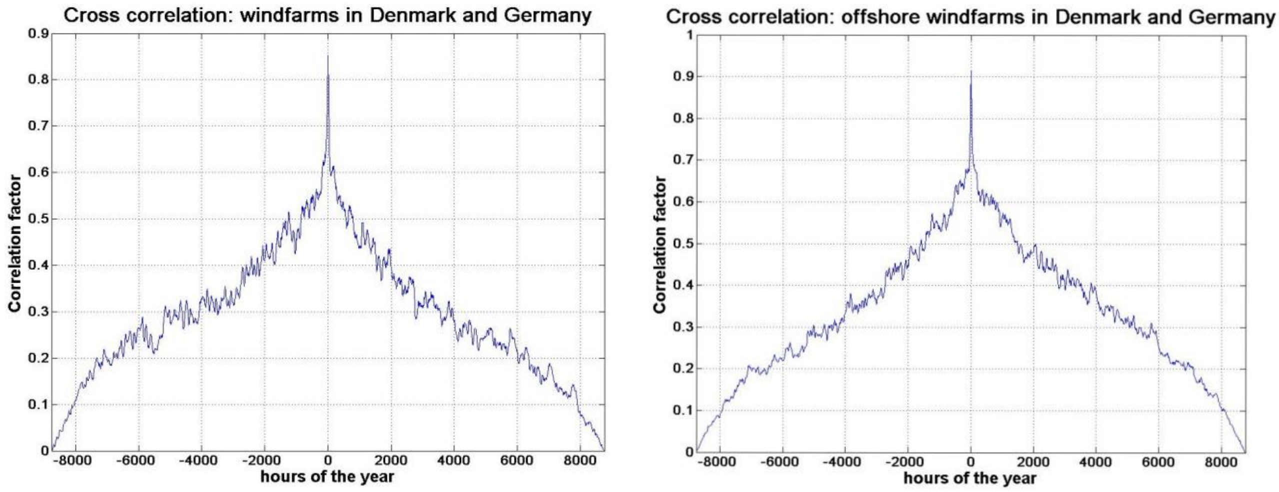

Figure 40: Correlation factor of wind production in Denmark and Germany as a function of lag time, comparing the whole wind energy production (left) and only offshore wind energy (right)

This indicates already that it could be difficult to export wind energy to Germany during times of strong wind energy production. To take a closer look at this issue ***Figure 41*** is showing the normalized residual load in Denmark (black) and Germany (red) for the year of investigation. The particular residual load was normalized with its corresponding maximum. It can already be stated that when there is a surplus of renewable energy (negative residual load) in Denmark there is often also a surplus in Germany.

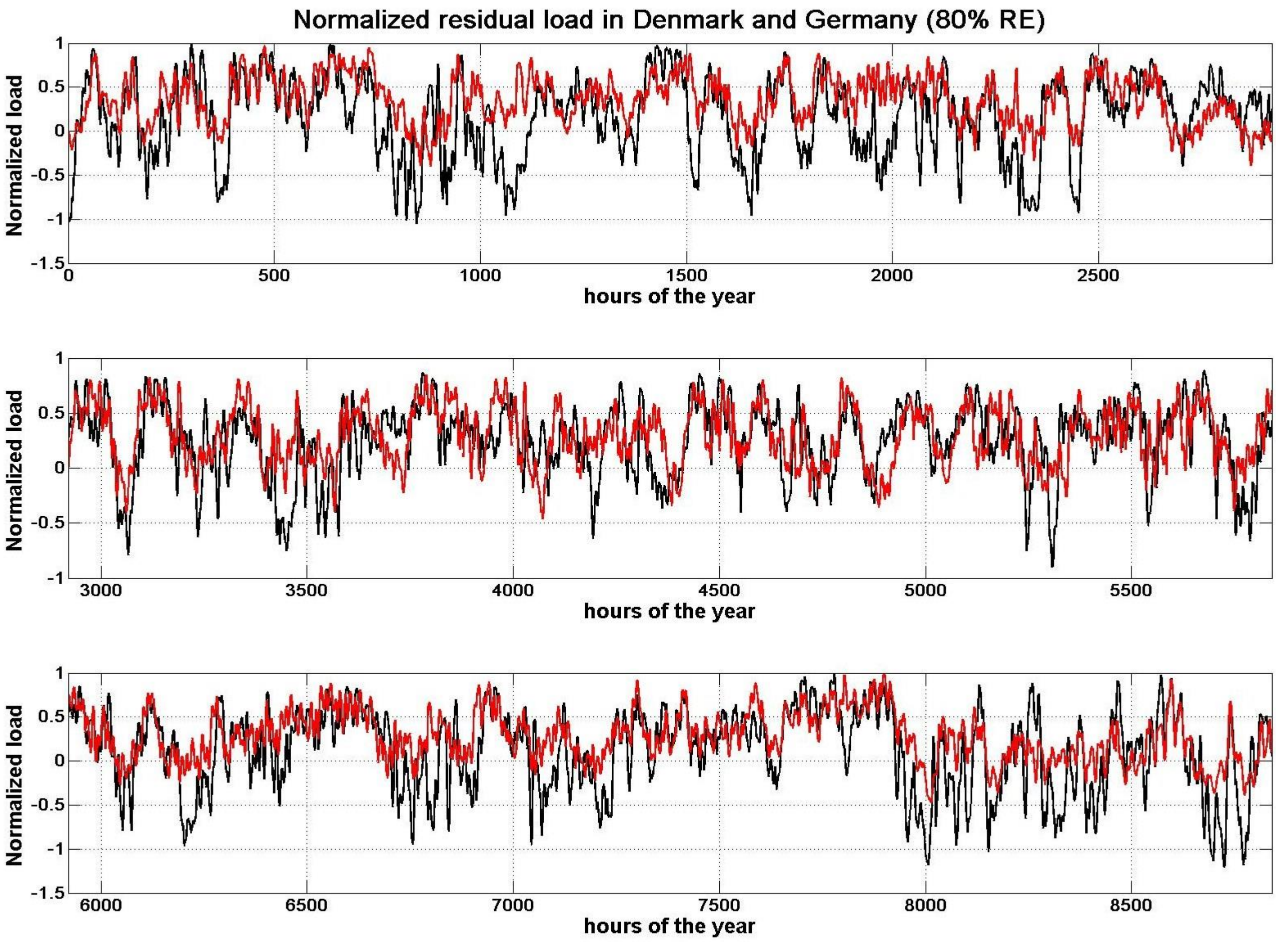

Figure 41: Residual load in Denmark (black) and Germany (red) with an 80 % share of renewable energies on the net electricity consumption

To show the effect a high transmission capacity to Germany can have, 2 extreme and 2 realistic scenarios are investigated. First, as a reference scenario, a simulation with no transmission capacity at all (see results of chapter 8.3) has been carried out. The other extreme will be an unlimited transmission capacity. This is done to determine the maximum effect of transmission lines in comparison to energy storage facilities. As realistic scenarios the actual transmission capacity of 1500 MW is investigated and a transmission capacity of twice the size of 2012, which means a transmission capacity of 3 GW.

The outcomes of the simulations are summarized in table 12 and 13. E_{max} is the maximum needed storage capacity, whereas $P_{max,\ charging/discharing}$ is the maximum needed power in charging and discharging mode respectively. As can be seen the there is a big difference between the no transmission capacity and a transmission capacity of the actual size (1500 MW). The needed storage capacity is reduced by more than 100 GWh to 498 GWh and 2 TWh of excess wind energy is transmitted to Germany during the year under investigation. When doubling the transmission capacity to 3 GW there is only 600 GWh more energy than can be transmitted to Germany. With an unlimited transmission capacity the is almost no extra value than with just 3 GW.

The same can be observed with the energy storage needs. The needed capacity decreases a lot from zero transmission capacity to 1500 MW whereas there is not much difference when further increasing the TC. The maximum needed charging power stays the same in all investigated scenarios. This shows that during the maximum surplus of wind energy in West Denmark there is also a surplus of wind energy in Germany. On the other side the needed discharging power is decreasing little with increasing transmission capacity.

Table 12: Overview of results I

	Transmission capacity			
	None	1500 MW	3000 MW	Unlimited
Rejected Energy	4928 GWh	2928 GWh	2318 GWh	2280 GWh
Transmittable Energy	0	2000 GWh	2609 GWh	2648 GWh

Table 13: Overview of results II

Transmission capacity	none	1500 MW	3000 MW	unlimited
E_{stored}	4302 GWh	3284 GWh	3142 GWh	3139 GWh
$E_{provided}$	3004 GWh	2305 GWh	2221 GWh	2220 GWh
E_{max}	600 GWh	498 GWh	446 GWh	442 GWh
$P_{max, charging}$	3.90 GW	3.90 GW	3.90 GW	3.90 GW
$P_{max, discharging}$	3.12 GW	3.03 GW	2.85 GW	2.81 GW

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9 Summary and Conclusion

The aim of this report is to determine the need for bulk energy storage capacity in West Denmark by investigating future development plans for the year 2020 and also an 80 % renewable energy share penetration. Furthermore, this report considers the impact of the heating sector and transmission capacity to Germany. For that purpose an algorithm was developed at HSU to determine these storage needs. In this report about Denmark followed three main steps: West Denmark as an isolated system (chapter 8.2), the integration of the heating sector (chapter 8.3) and the investigation of the influence of the transmission capacity to Germany (chapter 8.4).

In general it has been shown that there will be a need of energy storage in Denmark and especially in Western Denmark even when taking the heating sector into account and considering an unlimited transmission capacity to Germany.

To get to this result, at first West Denmark as an isolated system was investigated. The maximum used charging power in scenario 2020 A was 2.33 GW whereas the maximum discharging power was 2.36 GW. The maximum needed capacity (maximum size of the reservoir) was 55.22 GWh. For the 80 % scenarios the storage needs increased a lot. The maximum needed charging and discharging power was 4.85 GW and 3.25 GW respectively. The needed capacity to integrated all energy from renewable sources increased the most to a final need of 600 GWh. The outcomes of all simulations are summarized in table 14 as the numbers in brackets.

Second the heating sector was taken into account. Future development scenarios for electric boilers and heat pumps were integrated into the computation algorithm. Based on these scenarios the influence of the heating sector was investigated. As a result it can be stated that the electric boilers and heat pumps can take much of the surpluses produced by wind energy but still not enough to have no more excess wind energy. Especially in the 80 % scenario there is still a very high need for energy storage, see table 14.

Table 14: Overview of the impact of heat pumps and electric boilers on total energy storage needs. Values in brackets are without heating sector, see chapter 8.2

2020 Scenarios	Stored Energy [GWh]	Provided Energy [GWh]	Capacity Factor			Max. Used Power [GW]		Max. needed energy [GWh]
			Charge	Disch.	Total	Charge	Disch.	
A	2092.04 (2170.58)	1682.66 (1743.08)	13.12 % (10.6 %)	9,70 % (8.43 %)	22,82 % (19.03 %)	1.82 (2.33)	1.98 (2.36)	45.89 (55.22)
B	2036.65 (2096.92)	1645.38 (1691.62)	13.43 % (10.6 %)	10,73 % (8.51 %)	24,16 % (19.11 %)	1.73 (2.26)	1.75 (2.27)	40.2 (46.71)
C	1983.49 (2032.20)	1606.63 (1647.61)	13.47 % (10.6 %)	11.25 % (8.63 %)	24.72 % (19.23 %)	1.68 (2.19)	1.63 (2.18)	32.5 (38.68)
80 % Scenario								
A	4301.93 (4592.37)	3004.27 (3224.58)	12.6 % (10.8 %)	11 % (11.3 %)	23.6 % (22.1 %)	3.90 (4.85)	3.12 (3.25)	600 (660.75)

Finally the outcomes of the previous sections where summarized and analyzed in combination with various transmission capacities to Germany to determine the influence an export of excess wind energy can have on the energy storage needs. For that purpose four different transmission capacities were investigated, no TC, 1500 MW (actual transmission capacity), 3000 MW and an unlimited transmission capacity.

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It has been shown that when reaching an 80 % share of renewable energies on the net electricity consumption in both counties, building new transmission lines will not consequently lead to a decrease in rejected energy and to a decrease of the storage needs. This can be observed again in table 15. With a transmission capacity of more than 1500 MW the transmittable energy as well as maximum needed capacity of the ESS do not change significantly.

Table 15: Overview of transmission capacity investigation

	Transmission capacity			
	None	1500 MW	3000 MW	Unlimited
Rejected Energy	4928 GWh	2928 GWh	2318 GWh	2280 GWh
Transmittable Energy	0	2000 GWh	2609 GWh	2648 GWh
E_{stored}	4302 GWh	3284 GWh	3142 GWh	3139 GWh
$E_{provided}$	3004 GWh	2305 GWh	2221 GWh	2220 GWh
E_{max}	600 GWh	498 GWh	446 GWh	442 GWh
$P_{max, charging}$	3.90 GW	3.90 GW	3.90 GW	3.90 GW
$P_{max, discharging}$	3.12 GW	3.03 GW	2.85 GW	2.81 GW

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[1] http://www.lorc.dk/offshore-wind-farms-map/statistics/production/annual

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