A review of Danish integrated multi-energy system flexibility options for high wind power penetration

Wang, Jiawei; Zong, Yi; You, Shi; Træholt, Chresten

Published in:
Clean Energy

Link to article, DOI:
10.1093/ce/zkx002

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Clean Energy, 2017, 1–13

doi: 10.1093/ce/zkx002
Homepage: https://academic.oup.com/ce

Review Article

A review of Danish integrated multi-energy system flexibility options for high wind power penetration

Jiawei Wang, Yi Zong*, Shi You and Chresten Træholt

Center for Electric Power and Energy, CEE, Department of Electrical Engineering, Technical University of Denmark, Copenhagen, Denmark

*Corresponding author. E-mail: yizo@elektro.dtu.dk

Abstract

The current status of wind power and the energy infrastructure in Denmark is reviewed in this paper. The reasons for why Denmark is a world leader in wind power are outlined. The Danish government is aiming to achieve 100% renewable energy generation by 2050. A major challenge is balancing load and generation. In addition, the current and future solutions of enhancing wind power penetration through optimal use of cross-energy sector flexibility, so-called indirect electric energy storage options, are investigated. A conclusion is drawn with a summary of experiences and lessons learned in Denmark related to wind power development.

Key words: energy system flexibility; high wind power penetration; integrated multi-energy system; Danish wind energy

1 Current status of Danish wind power and energy system

Denmark is an international leader in the implementation of a renewable, secure and cost-efficient energy system using a high share of wind power. In 2016, Denmark achieved a wind power penetration of 38%; while supplying 99.996% of domestic electrical power throughout the year, resulting in one of the highest energy security levels in Europe [1]. The Danish economy since the 1980s has grown by around 80% while maintaining constant energy consumption and, at the same time, decreasing CO_2 emission by 34% [2]. Danish knowledge and development of green energy has also attracted foreign economic investment in renewable energy. In 2017, Apple announced the establishment of one of the largest international data centers in Western Denmark. The Apple data center will be powered by renewable energy and its surplus heating will be injected into the local district heating system [3].

In Denmark, the first commercial 30 kW wind turbine was installed in 1979. The first offshore wind farm in the world, 11 turbines of 450 kW each, was built near Vindeby, Denmark, in 1991, and recently retired [4]. In 2015, Denmark broke the world wind power production record and achieved around 14 TWh, providing 42.1% of the Danish gross electricity consumption. Denmark is the only European country that consists of two synchronous areas, Western Denmark (DK1) and Eastern Denmark (DK2), which are connected through the Great Belt Power Link (see Fig. 10). In 2015, DK1 and DK2 achieved a wind power penetration of 55 and 23%, respectively. Fig. 1 shows the Danish onshore and offshore wind power capacity and the penetration level of wind power in Danish electricity consumption between 2009 and 2016. The average capacity factor of Danish offshore wind turbines can achieve up to 48% [5].

Onshore wind farms still constitute a major percentage of the total wind farm installations; however, new onshore wind farms are limited in Denmark due to a lack of land. New onshore installations are now typically associated

Received: 31 July, 2017; **Accepted:** 30 October, 2017

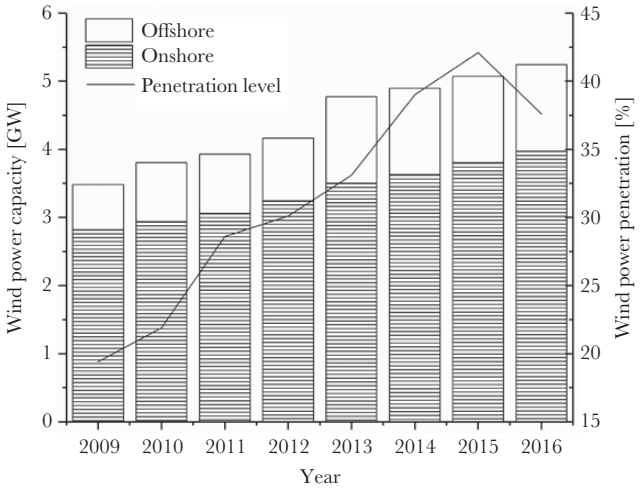

Fig. 1 Wind power capacity and penetration level in Denmark from 2009 to 2016 (data from [8, 9])

Fig. 2 Multi-rotor wind turbine at DTU Risø campus, Denmark

with an upgrade of old installations. The higher wind speed, more stable wind conditions on the sea and the relatively shallow water around Denmark make it more economically attractive to build offshore wind farms. In 2016, there were 13 offshore wind farms with a total capacity of 1.27 GW in Denmark [6]. Three new offshore wind farms are planned to be commissioned by 2021, namely Horns Rev3 with 406.7 MW, Nearshore 350 MW and Kriegers Flak 600 MW [4]. The power transmission from offshore to mainland options are being investigated due to the increasing installation capacity of offshore wind farms and the longer distance between the wind farms and the grid. One option being considered is providing voltage support to the grid through high-voltage direct current (HVDC) technology [7].

In 1981, Denmark introduced subsidies for the construction and operation of wind turbines to increase the competitiveness of renewable energy plants during the oil crisis [10]. The support schemes since then have been restructured several times to encourage the investment and operation of wind power with a lower levelized cost of energy (LCOE). In 2014, the Danish subsidy scheme for new onshore wind power was renewed. A nominal feed-in premium of 250 DKK/MWh is added to the spot price for the full load operation of the first 22 000 h [11].

New wind turbine concepts are currently being tested in Denmark in order to further reduce the LCOE of wind turbines. In 2012, a 3.6-MW two-bladed offshore wind turbine owned by a Chinese green energy company, Envision Energy, was built in Denmark for testing [12]. By having only two blades, the turbine is cheaper to transport and install in comparison with three-bladed turbines. The two-bladed wind turbine development by Envision Energy reduces the construction cost by 20% and increases operation reliability by using segmented blades and carbon fiber main shaft technologies [13]. Additionally, the segment design allows for customization of the blade length by changing the tip length to match the prevailing wind speed at specific sites. The transformers and converters are also located at the tower base which enables easier maintenance of offshore wind turbines [14]. Envision Energy in cooperation with the Technical University of Denmark (DTU) is also developing a superconducting wind generator which was successfully tested at DTU and is expected to be installed in Thyborøn, Denmark, by 2019 [15, 16]. The consequent-pole rotor with superconducting coils is capable of conducting electricity more efficiently in comparison with conventional copper coil, resulting in a higher torque density and 50% reduction in the number of windings. Therefore, a reduced generator volume and mass with the same power can be achieved resulting in a lower cost of transportation, installation and foundation of large wind turbines [17].

In 2016, the Danish wind turbine manufacture company, Vestas, installed a multi-rotor wind turbine prototype with four 225 kW nacelles on one tower at the Risø campus of DTU, as shown in Fig. 2 [18]. The aim of the prototype is to increase the wind power output with smaller and lighter size rotors. This new prototype, if successful, could reduce the cost of transport and installation of wind turbines. In addition, new technologies such as the rotor arm structure and turbine control system were tested with the Vestas multi-rotor turbine. The rotor arms are linked with steel cables in order to make the multi-rotor structure more stable. The wind turbine exhibits variable speed operation with a full-power converter and control mechanism for each turbine [19].

In 2016, a 9-MW offshore turbine was tested at the Danish national test center in Østerild for large wind turbines. The 9-MW turbine produced 216 MWh in 24 h, a new world record [20]. Large and powerful offshore wind turbines with optimized rotor-to-generator ratio enables less turbines with the same power output and higher energy efficiency, therefore decreasing the operational and maintenance costs. The Østerild large wind turbine test center is a DTU facility and annually receives 50 000 visitors [21]. Another element of Danish wind farms is community ownership with the Middelgrunden offshore wind farm; 50% is owned by 8700 Danish local residents [22] and the other 50% is owned by the local distribution

grid operator (DSO). The close collaborations between research and product, universities and companies, and the awareness and support from citizens provide strong incentives for wind power technology development in Denmark.

Wind power is characterized by its uncertainty and limited prediction, which leads to the inadequacy of generation and imbalance between power generation and consumption in the grid. In order to integrate more wind power into the power system Denmark has developed efficient measures to ensure it is secured and balanced. Flexibility allows the management of a power system to maintain a reliable operation and power balance on different time scales, even with variable and uncertain generation and consumption [23]. In order to significantly increase wind power production, further flexibility to keep the system secure and balanced all the time will be required.

The flexibility provided by interconnectors to neighboring countries helps Denmark to integrate a high penetration of wind power. Fig. 3 shows the current capacities of interconnectors between DK1 and DK2 to Norway, Sweden and Germany, respectively. DK1 has a higher capacity of interconnectors than DK2 for more wind power penetration. Due to the annual peak load of less than 6.5 GW in Denmark, the capacity of the interconnectors is sufficient to allow for a high fluctuation in wind power and to enable the system to balance.

The flexible power generation from conventional power plants is another important way of balancing wind power. High wind power fluctuations require high ramp rates and low minimum loads by conventional power plants in order to balance the sudden surplus or deficit of power generation, i.e. the net load, which defines the demand minus the renewable power generation [24]. A typical Danish coal-fired or biomass fuel power plant can currently provide a ramp rate of 4%/min (percentage of full capacity in a minute) and a minimum load of 18% (percentage of full capacity) [25].

The Danish power system also has a close connection with the heating sector through combined heat and power (CHP) plants. The use of CHP plants offers a potential option for flexibility in integrating wind power in the power system by coupling to the heating system. Furthermore, CHP plays an important role in the Danish district heating (DH) network, where around 70% of DH generation is from CHP. Together with heat storage, CHP can provide optimal dispatch of their cogeneration of electricity and heat into the electricity market, e.g. during a period of high wind power and low electricity prices. CHP can decrease the need for power generation and meet heat demand through heat storage [26]. Additionally, in 2013, the electricity tax was significantly reduced, resulting in an incentive to generate heat through electric boilers and heat pumps (HPs) [27]. The increasing flexibility from the heating sector provides a good opportunity for Denmark to accommodate more wind power [28]. In 2017, the new highly energy efficient waste-to-energy plant Amager Bakke (Amager Hill/Slope) began operation. The plant can provide 310-MW power and heat with low emissions. The unique architecture of the power plant follows a long Danish tradition attempting to create esthetic integration with local landmarks. The new waste-to-energy power plant is shown in Fig. 4 [29]. Other examples are the Avedøre power plant south of Copenhagen and the Energy tower (waste-to-energy plant) near the city of Roskilde.

High wind power penetration is driven economically by the mature electricity market, Nord Pool, and ancillary services procured by the Danish Transmission System Operator (TSO). The day-ahead spot market Elspot offers electricity trading in Nordic and Baltic countries and prioritizes power generation at the lowest cost [30]. Therefore, when there is an excess of wind power, Denmark is able to sell the electricity to neighboring countries via interconnectors. Similarly, when the wind speed is low, inexpensive hydro power can be imported from Norway to ensure a reliable operation

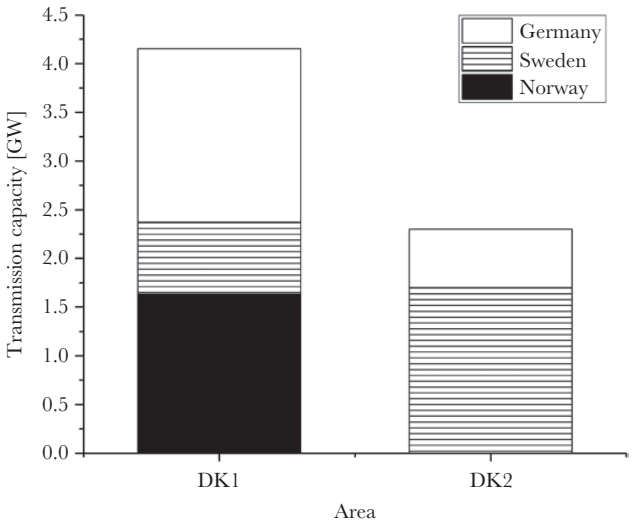

Fig. 3 Capacity of interconnectors between Denmark and neighbors (data from [9])

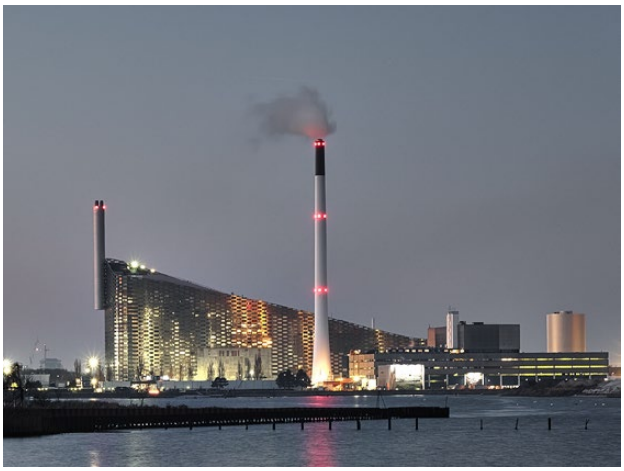

Fig. 4 The waste-to-energy plant Amager Bakke (Amager Hill/Slope) (photo by Christoffer Regild [35])

of the Danish grid. Ancillary services are procured by the Danish TSO in order to keep the grid balanced, e.g. reserves which drive the flexibility provided by interconnectors and voltage control which drives the flexibility provided by central power plants [31, 32]. Furthermore, as wind power generation is increasing so are ancillary services from wind turbines through control strategies [33]. In Denmark, the ongoing project RePlan aims for integration of more wind power into the future Danish power system. The RePlan project researchers are investigating the coordination of ancillary services provided by wind power, such as frequency reserve and voltage control [34]. The provision of ancillary services from wind power could benefit both the TSO with a more secure energy supply and the wind farm owner/operators economically [33].

The success of Danish high wind power penetration depends on the accurate forecast of power generation. An accurate forecast can help the generation units to offer profitable bids in the day-ahead market and also help the TSO to schedule reserves to balance the power system. Forecast methodology was studied in Denmark from the early 1990s and an 'Operational Planning Tool' was developed by the Danish TSO to forecast wind power generation, as well as CHP generation and heat demand [36, 37]. A wind resource simulation tool, WasP, was also developed at the planning stage by DTU for estimating the potential wind power resources of prospective new wind turbine installations [38]. Additionally, using the two-price regulation in the balancing market penalizes the forecast error, which can result in a system imbalance [39]. All these measures work as incentives to keep the power system balanced with high wind power generation.

2 Potential challenges of wind power in Denmark

The ongoing development of the Danish wind power sector is challenging. An increasing share of wind power potentially may increase the imbalance between power generation and consumption with the result of lower electricity prices. The Danish government energy strategy aims to achieve 50% of electricity consumption by wind power in 2020; coal and oil burners phased out of the power system by 2030 and electricity and heat supply from renewable energy sources by 2035. If all these steps are accomplished, the Danish government expects to have a secure, stable and affordable energy system completely independent from fossil fuels by 2050 [40].

The increasing wind power penetration in the power system may lead to increasing challenges in three cases, namely lower wind power than consumption (e.g. deficit shown in Fig. 5), higher wind power than consumption (e.g. surplus shown in Fig. 5) and system balancing during real time (e.g. up- and down-regulating power shown in Fig. 5).

The first challenge is to ensure enough production when there is little wind. Fig. 1 shows that 2016 wind power capacity increased while the wind power penetration was the lowest since 2014, because 2016 was a low wind speed year. During the low wind power period, power balancing from interconnectors and conventional power plants is of great importance. Fig. 6 shows the peak generation of power plants in Denmark between 2009 and 2016. The weak wind resources in 2016 resulted in peak power generation from conventional power plants operating at their maximum level since 2014. As a result, the lowest cost dispatch in the electricity market also pushes the conventional power plant from a base load to intermediate or peak load generation resulting in lower revenues for the conventional power plants [28]. An enhanced flexibility from conventional power plants, interconnectors and demand response measures can be used to ensure sufficient generation as a response to a low wind power period.

Another challenge is to ensure wind power profitability during higher wind speed periods. Factors influencing profitability include the increasing installation capacity of wind

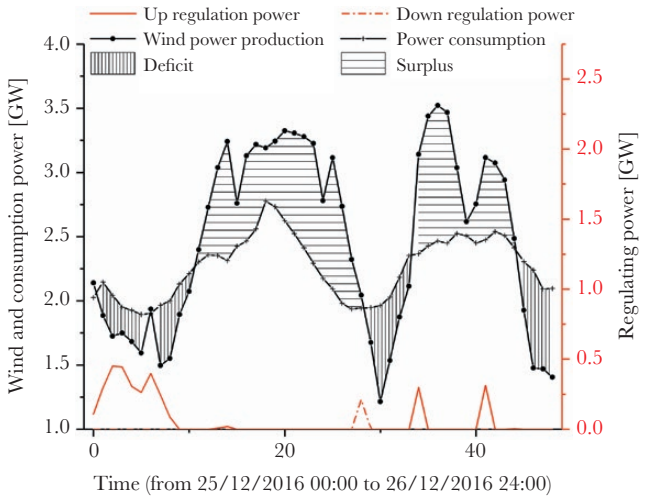

Fig. 5 Wind power, consumption and regulating power of two typical days in DK1 (data from [9])

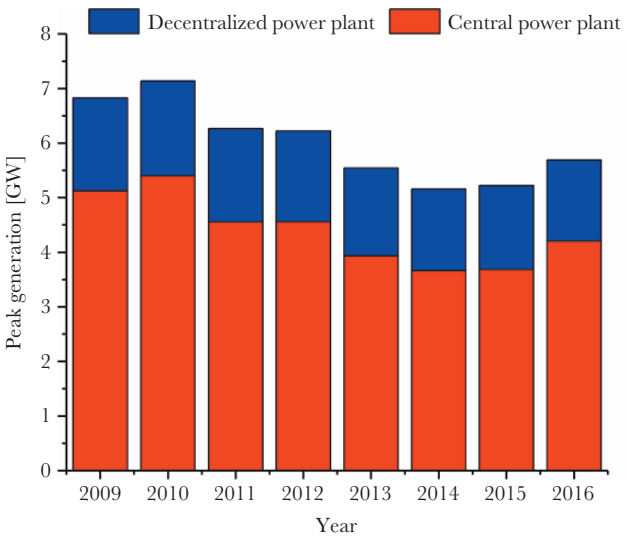

Fig. 6 Peak generation of Danish power plants (data from [9])

power in North Germany and the resulting internal congestion problem in the German grid. Electricity exports from DK1 to Germany via the interconnector decreased to an average of around 200 MW in 2016 [9, 41]. Fig. 7 shows periods with export power less than half of the transmission capacity.

The excess of electricity is a technical and economic problem which can result in low or negative spot prices for electricity. The spot price could be decreased by the increased production of renewable power which has a low marginal price, e.g. wind power [42]. Fig. 8 illustrates the wind power and power plant generation, consumption and spot price during two typical days in Denmark (25 and 26 December in 2016) with a minimum negative spot price of –47.03 USD/MWh. The main reasons for the negative spot price were the high wind speed, low power consumption and higher cost for conventional power plants to stop operation or change to heat-only production [43]. The current regulation and market for CHP plants limit its flexibility by first requiring CHP plants to meet the primary heat demand with electricity considered as a byproduct [44]. Therefore, it is challenging to make wind power profitable during high wind speed and low consumption periods.

The last challenge of increasing wind power penetration is fast system balancing during real time, i.e. ancillary services. Wind power forecasts are well studied in Denmark; however, the wind power production is still variable in real time. The load and generation imbalance may result in frequency deviations and consequently system insecurity. A faster ramp rate from conventional power plants, increasing capacity of interconnectors, flexible power consumption and ancillary services from wind farms can further provide real-time balancing for the grid.

3 Current flexibility measures of the Danish energy system

In recent years, the investigation of the flexibility from the cross-sectoral energy system, also known as indirect electric energy storage, was undertaken to meet the above-mentioned challenges. The forecast error and fluctuation of wind power require the flexibility to accommodate a larger share of wind power. The current measures have been implemented to ensure flexibility at a high level from interconnectors, conventional power plants and integration of the heating sector, and are discussed below. The current Danish solution includes the flexibility from both cross-sectoral energy systems and power generation of neighboring countries.

3.1 Flexibility from interconnectors

One major reason for successful large scale integration of wind power in Denmark is the grid connection to neighboring countries, i.e. interconnectors, which provides adequate capacity to meet Danish energy needs. Denmark's key advantage is flexibility with its location between other Nordic countries and continental Europe, where DK1 and DK2 are

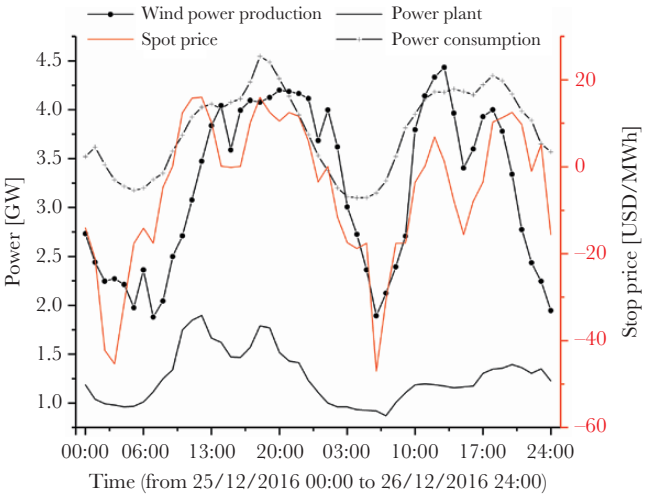

Fig. 8 Power generation, consumption and spot price in Denmark on two typical days in 2016 (data from [9])

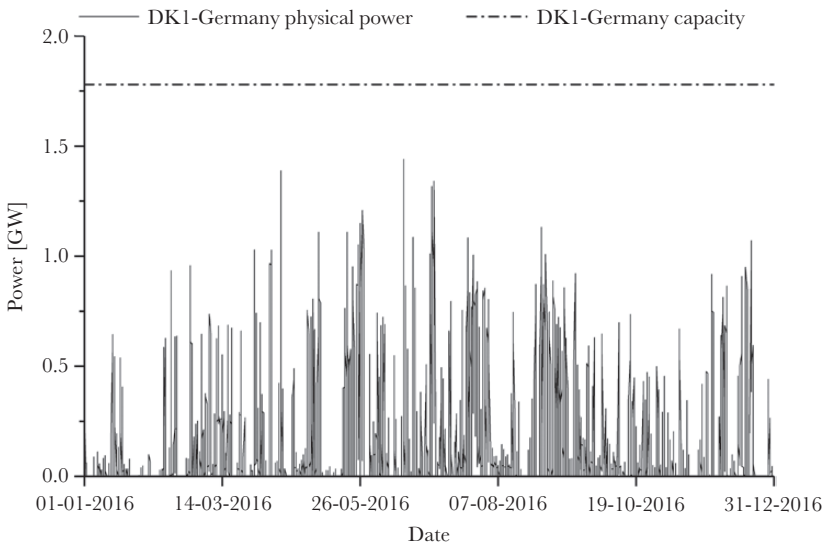

Fig. 7 DK1 power export to Germany and transmission capacity (data from [9])

connected, respectively. Fig. 9 shows that, from 2014, the total capacity of interconnectors has exceeded the Danish peak load, leading to adequate capacity for the Danish load.

The link to neighboring power systems provides Denmark with more energy security and contributes to a cost-effective utilization of excess wind power through the electricity market Nord Pool [45]. As illustrated in Fig. 10, there are six interconnectors currently used for electricity exchange between Denmark and its neighbors, i.e. Norway (1), Sweden (3) and Germany (2). The six interconnectors are controlled by TSOs in these countries, namely Energinet.dk (Denmark), Statnett SF (Norway), Svenska Kraftnät (Sweden), TenneT TSO GmbH and 50 Hertz (Germany) [46, 47]. Further information about the live power exchange between Denmark and other countries through the interconnectors is available in reference [48].

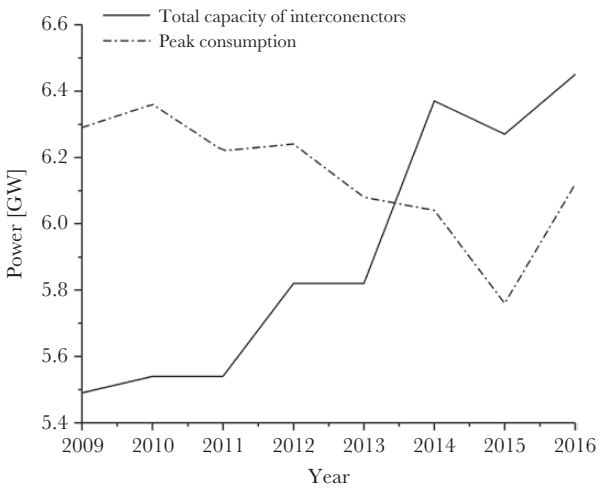

Fig. 9 Total capacity of interconnectors and the Danish peak load between 2009 and 2016 (data from [9])

The physical exchange across the interconnectors is driven by market integration, i.e. Nord Pool. DK1 and DK2 joined Nord Pool in 1999 and 2000, respectively [49]. The cross-border tariff between Sweden and Denmark ended in 2002. Since then, there has been a free electricity market between Nordic countries [50].

The interconnectors between Denmark, Germany and Sweden utilize both HVDC and high-voltage alternating current (HVAC) technologies; between Denmark and Norway, only HVDC technology is used. Several technologies are deployed to increase the interconnector's capacity to provide a more flexible transmission system, including voltage source converter (VSC)-based HVDC lines. These technologies can independently control voltage and power as well as reduce the harmonics [51]. The cost of insulated-gate bipolar transistors, which is the key component of VSC, has decreased by 67% during the last 9 years [52]. Skagerrak 4, the most recently installed interconnector between DK1 and Norway, uses the VSC-based HVDC technology and is also capable of performing black starts.

3.2 Flexibility from conventional power plants

The increasing Danish wind power penetration requires a more flexible backup generation from conventional power plants to keep a consistent load generation balance with the power surplus and deficit. The flexibility of Danish

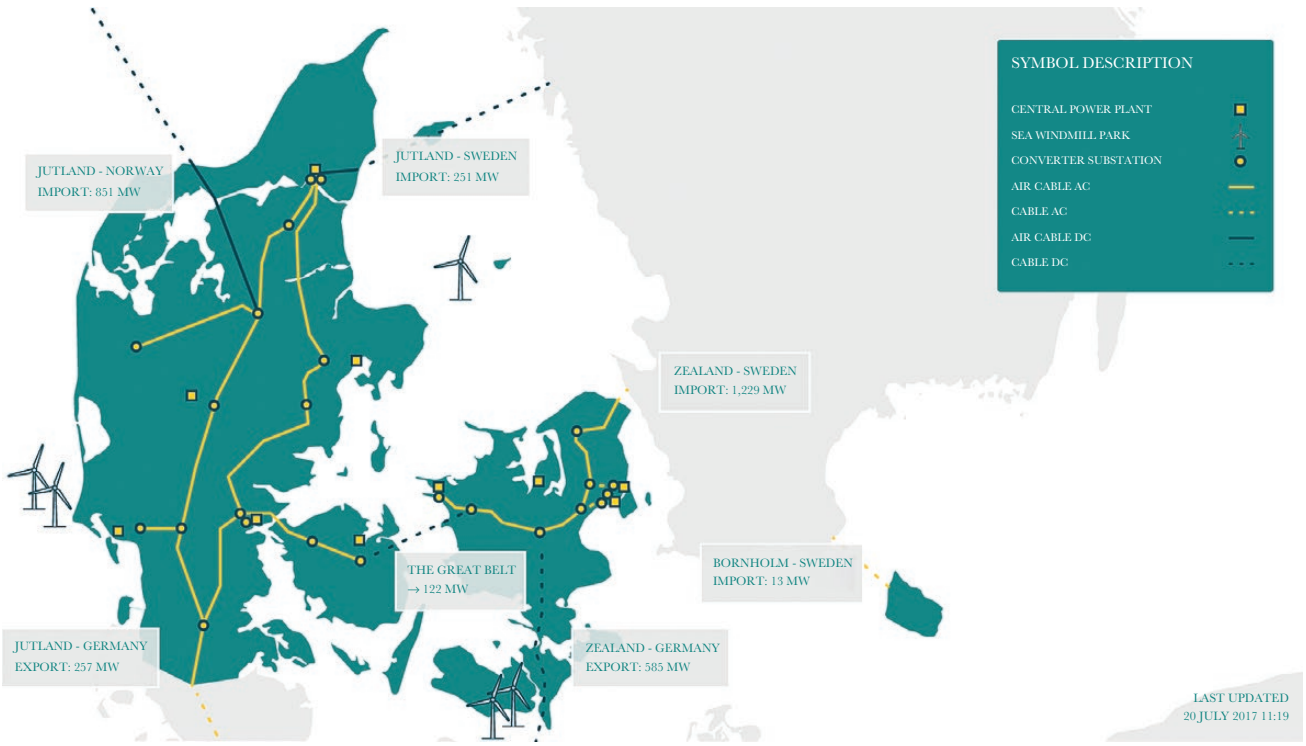

Fig. 10 Live illustration of the Danish power exchange with neighbors (figure from [48])

Table 1 Comparison of operational characteristics of central power plants (data from [9])

Year	Base load generation [GW]	Base load period [h]	Peak generation [GW]	Minimum generation [GW]	Minimum generation period [h]	Annual generation [GWh]
2010	1.5	416	2.98	0.33	16	13062
2016	0.91	409	2	0.023	28	5502

power plants has been optimized for more than 20 years, e.g. ramp rate and minimum load. This flexibility is a result of responding to the increasing wind power penetration and to the different market regulations. As a result of the 100% renewable energy goal, fossil fuel is being replaced by renewable fuels such as biomass for power plants. An example of this is the largest Danish coal fired power plant Avedøre Power Station which has converted from coal to sustainable wood pellets. It has a total generation capacity of 797 MW electric power and 932 MJ/s heat [53].

The increasing flexibility from power plants is shown in Table 1. The table compares operational characteristics of central power plants of DK1 in 2010 and 2016. During that period, there was a decrease in total base load generation, a lower total peak generation, a shorter total base load period, a lower total minimum generation, a longer total minimum generation period and a lower total annual generation. Additionally, a steep negative ramp rate is required when a sudden surplus of wind power occurs; while also requiring a steep positive ramp rate when a deficit in power occurs as shown in Fig. 5. The current Danish standard ramp rate for coal fired power plants is 4% (percentage of full capacity in a minute), for open cycle gas turbines 3% and for gas fired power plants 9% [54].

Danish coal fired power plants reduce the minimum load by decreasing supplemental firing that is associated with using expensive auxiliary fuel to stabilize the flame in the boiler during the start up [55]. Typically, the boiler maximum continuous rating (BMCR) can be as low as 15–25%. The high ramp rate is often limited by the combustion dynamics that can damage equipment. The ramp rate can be improved through control systems that control the rate of change of energy and vary fuel-to-air ratio [55].

3.3 Flexibility from integration with the heating sector

The flexibility from the heating sector is currently related to the cogeneration of heat and power in CHP plants. The capacity of centralized CHP plants covers around 85% of the centralized power plants [56]. Additionally, both the electrical and heating sectors are aiming at transferring to renewable energy based fuel by 2035. The strong coupling between the electric power and the heating sector offers a good opportunity to increase wind power penetration.

The flexible production from CHP plants can be achieved by optimization of cogeneration through the utilization of heat storage. One challenge from increasing wind power penetration is the surplus of production as shown in Fig. 5. Electricity production can be decreased while the heating demand can be satisfied with heat-only production from heat storage. During a period when there is a higher heat production than demand, heat accumulation can occur. Danish CHP plants currently in the central and decentralized DH areas are equipped with a total heat storage of 65 GWh [57, 58]. The heat storage can only operate for a short period of up to 8 h of demand in winter due to its limited size [28]. An alternative to cogeneration could be the use of seasonal heat storage from solar collectors that has been used in four DH plants in Denmark [59].

In 1992, a subsidy was implemented for electricity production from natural gas and renewable fueled CHP plants, which resulted in more investment in renewable power in the heat and electric power system [60]. However, the fixed feed-in tariffs discourage CHP plants generating electricity as they must first meet heat demand. The regulatory framework for CHP generation will change in 2018 from being supported by feed-in tariffs to reliance solely on the electricity market. All centralized CHP plants and most decentralized CHP plants are currently part of the electricity market, Nord Pool and can sell their electricity generation. This incentive stimulates CHP plants to optimize their power and heat dispatch according to the variation on the spot price [61]. Additionally, in 2013, the electricity tax was significantly reduced, which encouraged the electrification of DH generation, i.e. replacing oil and natural gas boilers with HPs and electric boilers [62]. Denmark currently integrates only around 400 MW electric boilers and 20 MW HPs for DH supply with the main economic driver being the ancillary services for the Danish TSO. The capacities of electric boilers and HPs are expected to be 1500 and 900 MW, respectively, in 2020 [54, 63].

Danish CHP plants are built with separate high pressure and intermediate pressure casings with individual bearings and designed for short startup time and quick ramp rate. Additionally, the CHP plants are equipped with asymmetric intermediate-pressure (IP) turbine sections in order to extract heat that enables some decoupling of heat and power generation with a wide output range [28].

4 Future flexibility measures of the energy system

Wind power will continue to increase in the short term and cover 50% of domestic electricity consumption in order to achieve the long-term goal of 100% renewable energy. The increasing fluctuation of wind power generation will challenge the system balancing and security. Therefore, it is important to enhance the current and future flexibility of the power system. Denmark is undertaking several studies and implementing projects to improve power system flexibility.

The EnergyLab Nordhavn project started to test the flexibility of the electric power system through electrical energy storage as a demand response in 2017. The project includes a 460-kWh (630 kW converter) grid connected battery with a goal of providing balancing services for a Danish residential area in the future [64].

The vehicle to grid (V2G) of electric vehicles (EVs) has also been studied [65–67]. In 2016, the world's first real live test of V2G was achieved by using 10 grid-connected EVs in the Frederiksberg municipality in Copenhagen. The EVs were able to inject back power from the battery of the cars to the grid and provided balancing support to the grid, which was demonstrated in the ongoing Parker project [68, 69].

4.1 Enhancing flexibility from interconnectors

To respond to the increasing fluctuation from wind power, there is an investigation into increasing the capacity of interconnectors to neighboring countries. The Danish TSO, Energinet, is planning to build new interconnectors to the Netherlands, the UK and Germany together with the TSOs in each country [70]. The COBRAcable, a 325-km-long 0.7 GW interconnector between DK1 and the Netherlands, is expected to be completed in 2018. The new transmission line will contribute to a stronger grid connection between DK1 and continental Europe. It will balance the variable supply of wind power, provide a backup power in case of the failure of other interconnectors and further integrate the European electricity market [71]. The Viking Link, a 760-km-long 1.4 GW interconnector between Denmark and the UK, is expected to be operational by 2022. This will improve the security and balancing capability of the Danish grid and benefit the UK grid by connecting it to cheaper electricity production in Nordic countries [72]. Options are also being developed to overcome the decreasing power exchange between Germany and DK1. By 2020, the minimum capacity of its power exchange in a day-ahead market will be raised to 1.1 GW and the current interconnector will be extended further inside Northern Germany [73]. Thus, the total capacity of interconnectors to neighboring countries is planned to be expanded by around 3.2 GW in the near future. This expansion will further reinforce the ability to absorb and integrate more wind power in the Danish grid.

The demand for HVDC transmission lines will increase in the near future. In comparison to HVAC, HVDC has no problem with reactive power or synchronization of voltage and frequency. The cost of an HVDC link is also lower than an HVAC link. Based on current technologies, the cost of HVDC is lower when the distance is longer than 600 km [74], such as the Viking Link. The HVDC system tends to become more cost-effective with higher voltage and capacities [75]. The Krigers Flak multi-terminal VSC technology is currently under development as a pilot project utilizing multi-terminal VSC-based HVDC link to connect the asynchronous area between DK2 and Germany with offshore wind power integration [76].

4.2 Enhancing flexibility from conventional power plants

Due to the increased amount of wind power, conventional power plants will be required to further improve on parameters such as minimum load and ramp rate. According to DONG Energy, a Danish energy company, the lower minimum load and quicker ramp rate can be achieved by a stepwise optimization approach. The load is reduced slowly stepwise until the technical limitation is reached. It will require that the power plant is completely protected by alarms and warning sensors [77]. The operation of conventional power plants tends to shift from base load to intermediate and peak load.

4.3 Enhancing flexibility from the heating and power sector

In order to meet the year-round heat demand covering both the space heating and the domestic hot water sector, CHP plants may lead to inflexible power production, especially during the surplus period as shown in Fig. 5. In this situation, the utilization and bypassing of power turbines will enable CHP plants to work at a heat-only mode. Increasing energy capacity of heat storage at CHP plants will enable flexible power generation and increase flexibility into the power system. In addition to the CHP plants, electrical-driven heating, such as electric boilers, electric heaters and HPs, will all play a more important role in the future DH system. In this manner, a significant amount of future heating supply will come from wind power and in return address the challenge of surplus wind power generation [61].

The electrification of heating is also being studied in Denmark. Zong *et al.* [78] investigated and tested an economic model predictive control strategy for electrical heaters in Danish residential buildings [79]. The results indicated that as a flexible demand, control of electrical heaters could enable wind power integration. Cai *et al.* [80] proposed a framework for integration of electric heaters in the demand side of the electric power and heating sectors. Examples of different situations that can be addressed by this framework are frequency excursion and volatile electricity market prices caused by renewable generation. A coordinated optimization of heat and power through HPs and CHP plants has demonstrated a reduction in wind power curtailment [81]. The electrification of domestic consumption during a surplus period technically provides flexibility and also increases the value of wind power, e.g. decrease the period with a low electricity price [82].

4.4 Enhancing flexibility from the gas and power sector

The main focus of this section is on the potential flexibility of a power system, including power to gas (P2G) technology and gas storage. P2G is an emerging technology that converts electricity into hydrogen by means of electrolysis.

Table 2 Ongoing Danish projects on enhancing wind power penetration through system flexibility [86–88]

Project name	EnergyLab Nordhavn	EcoGrid 2.0	EPIMES
Flexibility provider	HPs, electric boilers and DH system	HPs, electric radiators and electricity market	P2G and DH system
Demonstration location	Copenhagen Nordhavn	Danish island Bornholm	Zhangjiakou and Beijing, China

The hydrogen generated could be further converted to methane by using methanation reaction and gas upgrade. Electricity supplied from renewable energy, such as wind power, could be converted into methane through this process with the product considered as a biomethane equivalent in quality to natural gas. The biogas can be further stored in gas storage in the long term. The P2G technology has a large potential in helping to absorb the surplus wind power generation and providing long-term indirect electrical energy storage. This multi-energy system is where the electric power sector, the heating sector and natural gas system is coupled. Li *et al.* [83] conducted a study on optimal power dispatch of P2G in combination with CHP plants and storage in a multi-energy system. The CO_2 for methanation is recycled from the CHP plant and used to generate biogas together with the P2G technology. The results show that the P2G system can operate during a low consumption period with surplus wind power, e.g. 0–7 h, and decrease the CO_2 emission level by capturing the emissions from CHP plants.

In Denmark, the newly finished BioCat project demonstrated the generation of biogas as well as injection into a local gas distribution and storage network. The electrolyzer is capable of drawing electricity during the low spot price periods, which indicates a surplus of wind power. Moreover, it provides an ancillary service through frequency regulation to the power system due to its fast response time [84]. The ongoing European QualyGridS project is also expected to establish a standard test for electrolyzer to perform electrical grid services such as frequency regulation and voltage support for both TSO and DSO [85].

4.5 Ongoing Danish projects for cross-energy sector flexibility

Table 2 highlights selected Danish projects enhancing wind power penetration through using flexibility from an integrated multi-energy system.

The EnergyLab Nordhavn project aims to establish a real-life integrated energy laboratory in the Copenhagen Nordhavn, a city development area. The project includes a large share of renewable energy and an optimal integration of district heating and power through the utilization of centralized and decentralized HPs, heat storage and heat boosters [86, 89]. DTU as part of this project has developed prototypes of heat boosters, HPs and heat storages which serve as sampled measurements transferred to a data warehouse. The EcoGrid 2.0 project demonstrates an electricity market for flexible power consumption in private homes. It will control 1000 HPs and electric radiators to optimize the electricity consumption on the Danish island of Bornholm. It will demonstrate aggregators to link the flexibility provided by residential electrical heating. The project also aims at coupling the demand response to the electricity market to keep the load and generation balanced at all times [90]. The EPIMES (Enhancing wind Power Integration through optimal use of cross-sectoral flexibility in an integrated multi-energy system) project is a joint bilateral research project between China and Denmark. The aim of the research was to utilize cross-sectoral flexibility to address wind power integration challenges in China through strong academia–industry collaboration. These activities include the development of P2G solutions for the city of Zhangjiakou where the 2022 winter Olympics will be hosted. The research project will also address local 'wind energy curtailment' issues, and develop power to heat solutions in an existing smart grid demo site near Beijing [91].

5 Conclusion

Internationally, wind power integration in Denmark is recognized as world-class with further research ensuring that status continues. Danish wind power technology development has received considerable support over many years from local government, industries, research institutes and the wider community. The increased uncertainty and limited predictability of wind power has induced new requirements and challenges with power system flexibility. The current flexibility solutions rely on a combination of adequate capacity of interconnectors, optimal dispatch from the heating and power sector, flexible operation of conventional power plants and a mature electricity market. To achieve the 100% renewable energy goal, the current flexibility from integrated multi-energy systems will need further development and research advances. A stronger connection with neighboring countries is being developed. The flexibility of conventional power plants such as the minimum load and the ramp rate need to be further improved. The electrification of heat generation will also play an important role in balancing wind power fluctuation and realizing the 100% green target for the power and heating systems. Emerging technology with gas systems will establish in the long-term electrical energy storage and future ancillary services provide power balancing. The Danish experience and lessons from their past and

current research projects can be applied elsewhere and further improve the development and utilization of wind power.

References

[1] Energinet. *Security of Electricity Supply Report [Online]*. 2017. https://en.energinet.dk/About-our-reports/Reports/Security-of-Electricity-Supply-Report-2017 (26 July 2017, date last accessed).

[2] State of Green. *The History Behind Denmark's Green Transition [Online]*. 2017. https://stateofgreen.com/en/pages/denmark-becoming-the-state-of-green (28 July 2017, date last accessed).

[3] Kjar P, Vizard DB. *Apple Established One of the World's Largest Data Center in Denmark [Online]*. February 2015. http://www.investindk.com/News-and-events/News/2015/Apple-establishes-in-Denmark (31 July 2017, date last accessed).

[4] Kjaer E. *Danish Experiences from Offshore Wind Development [Online]*. March 2017. https://ens.dk/sites/ens.dk/files/Globalcooperation/offshore_wind_development_0.pdf (1 August 2017, date last accessed).

[5] IEA Wind TCP. *IEA Wind 2015 Annual report [Online]*. August 2016. https://www.ieawind.org/annual_reports_PDF/2015/2015%20IEA%20Wind%20AR_small.pdf (14 July 2017, date last accessed).

[6] Nielsen S, Sørensen KH. *Energy Policy Toolkit on Physical Planning of Wind Power, Experiences from Denmark [Online]*. 2015. https://ens.dk/sites/ens.dk/files/Globalcooperation/physical_planning_of_wind_power.pdf (26 July 2017, date last accessed).

[7] Megavind. *Denmark—Supplier of Competitive Offshore Wind Solutions [Online]*. December 2010. https://www.windpower.org/download/952/uk_megavind_report_okpdf (26 July 2017, date last accessed).

[8] Danmarks vindmøllerforening. *Kapacitet-historisk [Online]*. 2017. http://dkvind.dk/html/nogletal/kapacitet-historisk.html (13 July 2017, date last accessed).

[9] Energinet. *Market Data [Online]*. 2017. https://en.energinet.dk/Electricity/Energy-data (13 July 2017, date last accessed).

[10] Shukla S, Sawyer S, Fichaux N, et al. *30 Years of Policies for Wind Energy, Lessons from 12 Wind Energy Markets [Online]*. 2012. https://www.irena.org/DocumentDownloads/Publications/IRENA_GWEC_WindReport_ Full.pdf (25 July 2017, date last accessed).

[11] Bøndergaard MR. *The Future of Wind Energy in Denmark—Reducing the Cost and Increasing the Value of Wind [Online]*. June 2015. https://www.windpower.org/download/2530/7_the_future_of_wind_energy_in_denmark-pdf (27 July 2017, date last accessed).

[12] Envision. *Close up – Envision's 3.6 MW Offshore Machine [Online]*. February 2012. http://www.windpowermonthly.com/article/1115270/close---envisions-36mw-offshore-machine (13 July 2017, date last accessed).

[13] *Envision. 3.6MW: the Offshore "Game Changer" [Online]*. http://www.envisioncn.com/en/smart_windpower.aspx# (13 July 2017, date last accessed).

[14] Dvorak P. *Envision Energy 3.6 MW two-blade offshore turbine [Online]*. June 2016. http://www.windpowerengineering.com/featured/envision-energy-3-6-mw-two-blade-offshore-turbine/ (15 September 2017, date last accessed).

[15] EcoSwing. *Project [Online]*. 2015. https://ecoswing.eu/project (26 July 2017, date last accessed).

[16] Song X, Mijatovic N, Kellers J, et al. A pole pair segment of a 2-MW high-temperature superconducting wind turbine generator. *IEEE Trans. Appl. Supercond*. 2017; 27:5201205.

[17] Song X, Mijatovic N, Kellers J, et al. A full-size high-temperature superconducting coil employed in a wind turbine generator setup. *IEEE Trans. Appl. Supercond*. 2017; 27:5201105.

[18] Zarin M. *Vestas Challenges Scaling Rules with Multi-rotor Concept Demonstration Turbine [Online]*. April 2016. https://www.vestas.com/en/media/~/media/e8ac3f-1cafea47b7b11b13901de86fa9.ashx (13 July 2017, date last accessed).

[19] Vries E. *Exclusive: Vestas Tests Four-rotor Concept Turbine [Online]*. April 2016. http://www.windpowermonthly.com/article/1391775/exclusive-vestas-tests-four-rotor-concept-turbine (15 September 2017, date last accessed).

[20] Mulin S. *World's Most Powerful Wind Turbine Once Again Smashes 24 Hour Power Generation Record as 9 MW Wind Turbine is Launched [Online]*. January 2017. http://www.mhivestasoffshore.com/new-24-hour-record/ (15 September 2017, date last accessed).

[21] Slente HP, Alexandersen P, Bizet B, et al. *Wind Energy Moving Ahead, How Wind Energy has Changed the Danish Energy System [Online]*. May 2017. https://stateofgreen.com/files/download/11875 (18 August 2017, date last accessed).

[22] State of Green. *Wind Energy Moving Ahead, How Denmark Utilize Wind in the Energy Sector [Online]*. October 2015. https://stateofgreen.com/files/download/6955 (20 August 2017, date last accessed).

[23] Ma J, Silva V, Belhomme R, et al. Evaluating and planning flexibility in sustainable power systems. *IEEE Trans. Sustain. Energy* 2013; 4:200–09.

[24] Cochran J, Miller M, Zinaman O, et al. *Flexibility in 21st Century Power Systems [Online]*. May 2014. http://www.nrel.gov/docs/fy14osti/61721.pdf (28 July 2017, date last accessed).

[25] Danish Energy Agency and Energinet. *Technology Data for Energy Plants Technology Data for Energy Plants [Online]*. August 2016. https://ens.dk/sites/ens.dk/files/Analyser/update_-_technology_data_catalogue_for_energy_plants_-_aug_2016.pdf (28 July 2017, date last accessed).

[26] Danish Energy Agency, State of Green and DBDH. *District Heating – Danish Experience [Online]*. August 2016. http://dbdh.dk/download/DH%20Danish%20Experiences%20august%202015.pdf (28 July 2017, date last accessed).

[27] Dansk Energi. *Mulighederne for Den Fremtidige Fjernvarmeproduction i Decentrale Områder, Analyse nr. 9 [Online]*. December 2013. https://www.danskenergi.

dk/Analyse/Analyser/09_MulighederFjernvarmeDecentraleOmraader.aspx (28 July 2017, date last accessed).
[28] Danish Energy Agency. *Flexibility in the Power System – Danish and European Experiences [Online]*. October 2015. https://ens.dk/sites/ens.dk/files/Globalcooperation/flexibility_in_the_power_system_v23-lri.pdf (28 July 2017, date last accessed).
[29] Babcock & Wilcox Vølund A/S. *Waste-to-energy plant – Amager Bakke/Copenhill Copenhagen, Denmark [Online]*. 2013. http://www.volund.dk/~/media/Downloads/Brochures_-_WTE/Amager_Bakke_-_Copenhagen_-_Denmar k.pdf (28 July 2017, date last accessed).
[30] Stavseth E. *The Nordic/Baltic Power Market – Nord Pool Spot [Online]*. June 2013. http://www.nasdaqomx.com/digitalAssets/86/86050_npspotjune112013.pdf (28 July 2017, date last accessed).
[31] Market Development. *Ancillary Services to be Delivered in Denmark – Tender Conditions*. Energinet.dk, Fredericia, Rep. 8871/11 v3, Case 10/2932, October 2012.
[32] Merino J, Gómez I, Turienzo E, et al. *Ancillary Service Provision by RES and DSM Connected at Distribution Level in the Future Power System [Online]*. December 2016. http://smartnet-project.eu/wp-content/uploads/2016/12/D1-1_20161220_V1.0.pdf (15 September 2017, date last accessed).
[33] Aho J, Buckspan A, Laks J, et al. A tutorial of wind turbine control for supporting grid frequency through active power control. In: *2012 American Control Conference (ACC)*, Montreal, QC, 2012, 3120–31.
[34] Altin M, Han X, Hansen AD, et al. *Technical Feasibility of Ancillary Services provided by ReGen Plants DTU*. Wind Energy E, No. 0099, 2015.
[35] Regild C. *Construction Photos [Online]*. 2017. https://www.a-r-c.dk/media/417373/Regild-juni-2017.pdf (23 September 2017, date last accessed).
[36] Sørensen KH. *Energy Policy Toolkit on System Integration of Wind Power, Experiences from Denmark [Online]*. 2015. https://ens.dk/sites/ens.dk/files/Globalcooperation/system_integration_of_wp.pdf (17 July 2017, date last accessed).
[37] Pinson P, Giebel G, Madsen H. Forecasting of wind generation – The wind power of tomorrow on your screen today! *WindTech Int*. 2008; 4:32–5.
[38] Jacobsen HS. *Wind Resource Assessment, Siting & Energy Yield Calculations [Online]*. September 2016. http://www.wasp.dk/wasp (23 September 2017, date last accessed).
[39] Pinson P, Mitridati L, Ordoudis C, et al. Towards fully renewable energy systems - Experience and trends in Denmark. *CSEE J. Power Energy Syst*. 2016; 3:26–35.
[40] The Danish Government. *Energy Strategy 2050 – from Coal, Oil and Gas to Green Energy [Online]*. February 2011. http://dfcgreenfellows.net/Documents/EnergyStrategy2050_Summary.pdf (22 July 2017, date last accessed).
[41] Klasman B, Leymann J, Granström SC. *Capacity Limitations Between the Nordic Countries and Germany [Online]*. 2015. http://ei.se/Documents/Publikationer/rapporter_och_pm/Rapporter%202015/Ei_R2015_12.pdf (23 September 2017, date last accessed).
[42] Zong Y, Kullmann D, Thavlov A, et al. Application of model predictive control for active load management in a distributed power system with high wind penetration. *IEEE Trans. Smart Grid* 2012; 3:1055–62.
[43] Götz P, Lenz K. *Negative Electricity Prices: Causes and Effects, an Analysis of Recent Developments and a Proposal for a Flexibility Law [Online]*. August 2014. https://www.agora-energiewende.de/fileadmin/Projekte/2013/Agora_Negative_Electricity_Prices_Web.pdf (28 July 2017, date last accessed).
[44] *Varmelast.dk. Heating plans [Online]*. http://www.varmelast.dk/en/heat-plans/heating-plans (18 July 2017, date last accessed).
[45] Danish Energy Agency. *Security of Electricity Supply in Denmark [Online]*. 2015. https://ens.dk/sites/ens.dk/files/Globalcooperation/security_of_electricity_supply_in_denmark.pdf (28 July 2017, date last accessed).
[46] ENTSOE. *Allocation Rules for Forward Capacity Allocation [Online]*. June 2016. https://www.entsoe.eu/Documents/Network%20codes%20documents/NC%20FCA/160629_HAR_EU_MainBody_2017.pdf (28 July 2017, date last accessed).
[47] Andreasen PØ, Ruusunen J, Lont A, et al. *Nordic Grid Development Plan [Online]*. August 2014. http://www.statnett.no/Global/Dokumenter/Media/Nyheter%202014/Nordic%20Grid%20Development%20Plan.pdf (28 July 2017, date last accessed).
[48] Energinet. *The Electricity Net Right Now [Online]*. 2017. https://en.energinet.dk/ (20 July 2017, date last accessed).
[49] Gommesen H, Söderlund E, Willumsen MØ, et al. *Nordic Market Report 2010 [Online]*. July 2010. http://www.nordicenergyregulators.org/wp-content/uploads/2013/02/Nordic_Market_Report2010.pdf (28 July 2017, date last accessed).
[50] Hoelsæter OH, Styrbro G, Gjerde O, et al. *Nordel Annual Report 2001 [Online]*. 2002. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/annualreport/Annual%20report%202001.pdf (28 July 2017, date last accessed).
[51] Reed G, Pape R, Takeda M. Advantages of voltage sourced converter (VSC) based design concepts for FACTS and HVDC-link applications. In: *2003 IEEE Power Engineering Society General Meeting*, Toronto, 2003, pp. 1816–1821.
[52] International Energy Agency. *Large-scale Electricity Interconnection, Technology and Prospects for Cross-regional Networks [Online]*. 2016. https://www.iea.org/publications/freepublications/publication/Interconnection.pdf (15 September 2017, date last accessed).
[53] Kjær CB. *Avedøre Power Station Getting Ready to Use Wood Pellets as Fuel [Online]*. 16 June 2016. http://www.dongenergy.com/en/media/newsroom/news/articles/aved%C3%B8re-power-station-getting-ready-to-use-wood-pellets-as-fuel (15 September 2017, date last accessed).
[54] Kofoed-Wiuff A, Hethey J, Togeby M, et al. *The Danish Experience With Integrating Variable Renewable Energy, Lessons Learned and Options for Improvement [Online]*. September 2015. https://www.agora-energiewende.de/

fileadmin/Projekte/2015/integration-variabler-erneuerbarer-energien-daenemark/Agora_082_Deutsch-Daen_Dialog_final_WEB.pdf (15 September 2017, date last accessed).

[55] Ess F, Peter F, Klummp F. *Flexibility in Thermal Power Plants, With a Focus on Existing Coal-fired Power Plants [Online]*. June 2017. https://www.agora-energiewende.de/fileadmin/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf (15 September 2017, date last accessed).

[56] Danish Energy Agency. *Energy Statistics 2014 [Online]*. April 2016. https://ens.dk/sites/ens.dk/files/Statistik/energystatistics2014.pdf (1 August 2017, date last accessed).

[57] Danish Energy Agency and DBDH. *District Heating – Danish and Chinese Experience [Online]*. https://ens.dk/sites/ens.dk/files/energistyrelsen/Nyheder/district_heating_danish-chinese_experiences.pdf (15 September 2017, date last accessed).

[58] Mathiesen BV, Lund RS, Connolly I, et al. *Copenhagen Energy Vision: A Sustainable Vision for Bringing a Capital to 100% Renewable Energy [Online]*. March 2015. http://vbn.aau.dk/files/209592938/Copenhagen_Energy_Vision_2050_report.pdf (15 September 2017, date last accessed).

[59] PlanEnergi. *Long Term Storage and Solar District Heating, a Presentation of the Danish Pit and Borehole Thermal Energy Storages in Brædstrup, Marstal, Dronninglund and Gram [Online]*. https://ens.dk/sites/ens.dk/files/Forskning_og_udvikling/sol_til_fjernvarme_brochure_endelig.pdf (15 September 2017, date last accessed).

[60] Auken S. *Combined Heat and Power in Denmark [Online]*. August 1998. http://www.statensnet.dk/pligtarkiv/fremvis.pl?vaerkid=329&reprid=0&filid=7&iarkiv=1 (15 September 2017, date last accessed).

[61] Danish Energy Agency. *Regulation and Planning of District Heating in Denmark [Online]*. June 2017. https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf (14 July 2017, date last accessed).

[62] Det Økologiske Råd. *Environmental Taxation in Denmark – Changes Since 2009 [Online]*. July 2013. https://www.ecocouncil.dk/en/documents/temasider/1601-140829environment-taxation-changes-since-2009/file (28 July 2017, date last accessed).

[63] Jessen K. *District Heating in the Danish Energy System [Online]*. http://www.northsearegion.eu/media/1531/the-danish-energy-system-case-dh.pdf (28 July 2017, date last accessed).

[64] Træholt C. *Giant Battery to Charge Nordhavn [Online]*. 3 March 2017. http://www.dtu.dk/english/news/2017/04/dynamo-giant-battery-to-charge-nordhavn?id=aecdfa56-6888-4868-b9f0-a8345a1ddee4 (27 July 2017, date last accessed).

[65] You S, Hu J, Pedersen AB, et al. Numerical comparison of optimal charging schemes for electric vehicles. In: *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2012, pp. 1–6.

[66] Hu J, You S, Lind M, et al. Coordinated charging of electric vehicles for congestion prevention in the distribution grid. *IEEE Trans. Smart Grid* 2014; 5:703–11.

[67] Knezović K, Marinelli M, Møller RJ, et al. Analysis of voltage support by electric vehicles and photovoltaic in a real Danish low voltage network. In: *49th International Universities Power Engineering Conference (UPEC)*, Cluj-Napoca, 2014, pp. 1–6.

[68] Andersen PB, Sørensen TM, Wagner SL. *World's First Real Life Test of Vehicle to Grid is a Reality [Online]*. 1 September 2016. http://www.dtu.dk/english/collaboration/collaboration-news/nyhed?id=665C7B96-8394-429F-82F8-239D08BB595A (27 July 2017, date last accessed).

[69] Parker. *Danish Project Defines the Electric Vehicle of the Future [Online]*. 2 March 2017. http://parker-project.com/danish-project-defines-the-electric-vehicle-of-the-future/ (27 July 2017, date last accessed).

[70] Andersen K, Andersen PØ. *Sustainable Energy Together, Annual Report 2016 [Online]*. March 2017. https://en.energinet.dk/About-our-reports/Reports/Annual-Report-2016 (27 July 2017, date last accessed).

[71] Tenne T. *Energinet.dk and COBRAcable, COBRAcable, from Concept to Connection [Online]*. http://www.cobracable.eu/Dokumenter/COBRAcable-leaflet.pdf (27 July 2017, date last accessed).

[72] VikingLink and National Grid. *Strategic Options Report [Online]*. April 2016. http://viking-link.com/media/1054/viking-link-strategic-options-report_in-house-style-v2_final.pdf (27 July 2017, date last accessed).

[73] Hörchens U, Rasmussen JN. *Capacity on Germany-Denmark West Border will Increase to 1100 MW [Online]*. 14 June 2017. https://en.energinet.dk/About-our-news/News/2017/06/14/Capacity-on-Germany-Denmark-West-border-will-increase-to-1100-MW (27 July 2017, date last accessed).

[74] Kalair A, Abas N, Khan N. Comparative study of HVAC and HVDC transmission systems. *Renew. Sustain. Energy Rev.* 2016; 59:1653–75.

[75] ABB AB, Grid systems – HVDC. *Introducing HVDC [Online]*. 2014. http://www04.abb.com/global/seitp/seitp202.nsf/c71c66c1f02e6575c125711f004660e6/d8e7ec7508118cf7c1257c670040069e/$FILE/Introducing+HVDC.pdf (15 September 2017, date last accessed).

[76] European Commission. *Offshore Wind Baltic-Kriegers Flak: Combined Grid Solution [Online]*. October 2013. http://ec.europa.eu/energy/eepr/projects/files/offshore-wind-energy/baltic-kriegers-flak_en.pdf (27 July 2017, date last accessed).

[77] Blum R, Christensen T. *High Flexibility Power Plants, 25 Years of Danish Experience [Online]*. December 2013. http://www.cnrec.org.cn/english/publication/others/2013-12-05-401.html (27 July 2017, date last accessed).

[78] Zong Y, Böning GM, Santos RM, et al. Challenges of implementing economic model predictive control

strategy for buildings interacting with smart energy systems. *Appl. Thermal Eng.* 2017; 114:1476–86.

[79] Binder HW. *PowerFlexHouse [Online]*. Nov. 15, 2016. http://www.powerlab.dk/Facilities/PowerFlexHouses (15 September 2017, date last accessed).

[80] Cai H, You S, Bindner HW, et al. Load Situation Awareness Design for Integration in Multi-Energy System. In: *2017 IEEE International Conference on Energy Internet (ICEI)*, Beijing, China, 2017, pp. 42–7.

[81] Li J, Fang J, Zeng Q, et al. Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources. *Appl. Energy* 2016; 167:244–54.

[82] Meibom P, Kiviluoma J, Barth R, et al. Value of electric heat boilers and heat pumps for wind power integration. *Wind Energy* 2007; 10:321–37.

[83] Li Y, Zou Y, Tian Y, et al. Optimal stochastic operation of integrated low-carbon electric power, natural gas and heat delivery system. *IEEE Trans. Sustain. Energy*, 2017; pp. 1–1.

[84] BioCatProject. *Technology Components [Online]*. 2014. http://biocat-project.com/about-the-project/technology-components/ (28 July 2017, date last accessed).

[85] Reissner R. *QualyGridS [Online]*. 2016. http://www.fch.europa.eu/project/standardized-qualifying-tests-electrolysers-grid-services (28 July 2017, date last accessed).

[86] Lunau C. *Future Smart Energy Solutions [Online]*. http://www.energylabnordhavn.dk/ (28 July 2017, date last accessed).

[87] Østergaard J. *EcoGrid 2.0 Kick-off—Flexibility for Users is Key to Success [Online]*. 11 April 2016. http://www.dtu.dk/english/collaboration/collaboration-news/nyhed?id=C31B31ED-BBB7-4AD2-B640-345CC0EE3250 (28 July 2017, date last accessed).

[88] Binder HW. *DTU Collaboration with China could Save Thousands of Tonnes of Carbon Emissions [Online]*. 3 October 2016. http://www.dtu.dk/english/news/2016/10/dtu-collaboration-with-china-could-save-the-world-thousands-of-tonnes-of-carbon-emissions?id=1e387552-3d06-4f2c-ab2b-f1b602e8e27a (15 September 2017, date last accessed).

[89] Ledgaard K, Ingemann Mogensen J, Heller A, et al. *Energy Lab Nordhavn: sustainability defined by certification [Sound/Visual production (digital)]*, SMART CITIES, Stockholm, Sweden, 20 October 2015.

[90] EcoGrid 2.0. *Fact Sheet [Online]*. http://www.ecogrid.dk/en/home_uk#new-downloads (15 September 2017, date last accessed).

[91] Binder HW. *EPIMES - Enhancing wind Power Integration through Optimal use of Cross-sectoral Flexibility in an Integrated Multi-Energy System [Online]*. 2016. https://energiforskning.dk/en/node/8790 (15 September 2017, date last accessed).