Danish Energy Agency

Development and Role of Flexibility in the Danish Power System

Solutions for integrating 50% wind and solar, and potential, future solutions for the remaining 50%

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Danish Energy Agency

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Danish Energy Agency

Foreword

Kristoffer Böttzauw, Director General of the Danish Energy Agency

To deliver on the Paris agreement and ensure a sustainable world for future generations, we stand before a substantial, global transformation of the energy sector. As a key element of this green transformation, we need to replace carbon-emitting technologies with technologies based on renewable energy sources. This decarbonisation needs to happen fast and on a large scale, hence the deployment of renewable energy has never been more important.

To rapidly decarbonise our energy systems, electricity systems will play a central role. While the deployment of renewable energy sources is necessary, it cannot stand alone. Effective integration of these renewable energy sources is crucial to ensure a successful substitution of the technologies that are holding us back with those that will help us move forward.

Today and for many years, Denmark is the country with the world´s highest share of variable renewable energy in its electricity system, with more than half of our electricity demand currently being covered by wind and solar power. Our experience in integrating these technologies shows how we have succeeded in leading on variable renewable energy share in the electricity system while meeting the Danish electricity demand with affordable electricity prices and a world-class security of supply.

The experiences gathered over the last decades in Denmark on how to integrate ever-increasing shares of variable renewable energy while ensuring economic growth and affordable electricity prices are of high value, as countries around the world transition their own energy systems and face challenges similar to the ones experienced during the first stages of the Danish energy transition.

In this report we share the history of the structural transformation of our electricity sector, framed by its beginning with the opening of the power market as a way to ensure fair and equal access for all technologies to the electricity market and grid. In this context, the evolution of flexibility solutions is presented not as a goal by itself, but rather as a tool to facilitate the integration of variable renewable energy in a cost-effective way.

We, at the Danish Energy Agency, hope that these experiences will inspire countries around the world, which are constrained by a lack of flexibility in their electricity system, on how to further the transformation of their energy system so that we together can tackle the global challenge that is climate change.

Executive summary

Integrating 50% variable renewable energy: the role of flexibility in the Danish power sector

In 2020, 50% of the electricity consumed by the Danish power sector came from variable renewable energy (VRE) sources, making it the country with the highest VRE share in its power system. During some days, VRE production even exceeded demand, and as a result the power system ran on 100% VRE while the rest was exported. This is a big step up from an annual average of around 12% in 2000 and 22% in 2010 as shown in Figure 1.

This achievement builds on 20 years of experiences that have shown that it is possible to cost-effectively integrate large shares of VRE while maintaining a world-class security of supply – the 10-year average of security for power availability is 99.996% (Energinet, 2020). Central to the many challenges and barriers in transitioning from a power system based on thermal power plants to one with a large VRE supply, as shown in Figure 1, was the evolving need for flexibility to cope with uncertainty and variability of the production output while maintaining high security of supply at a reasonable cost.

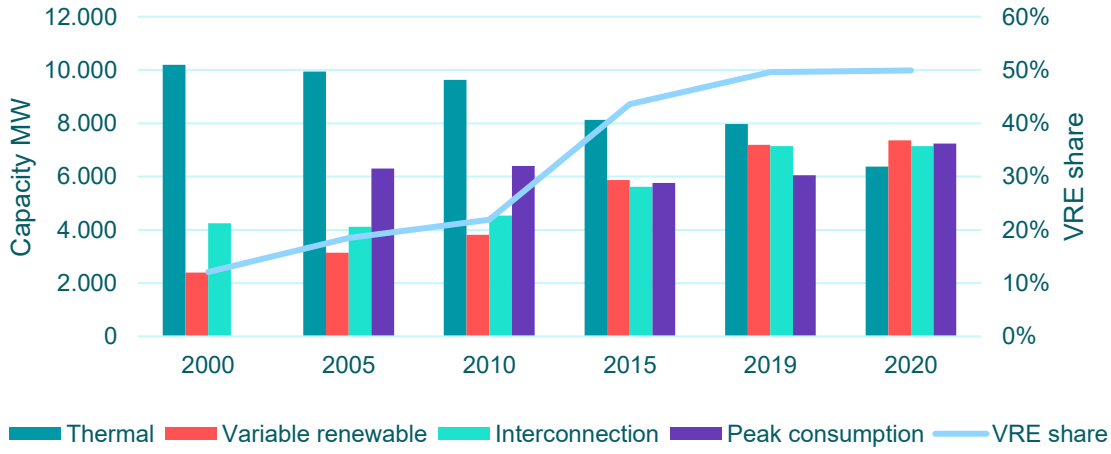

Figure 1 *Development in capacities for thermal power plants, VRE and interconnectors (DEA, 2019) in relation to peak consumption (Energinet). Thermal capacity entails all possible thermal power generation capacity including plants that may be mothballed.*

Electricity market as the key driver for flexibility

The development of flexibility in the Danish case is closely linked to the opening of the electricity market in 2000 and the unbundling of the previously vertically integrated energy utilities. Central to the market idea is that the market is designed to reflect the system's need for flexibility through price signals which provide market players with an economic incentive to act accordingly.

In the Danish case, the market design, such as an intra-day market and hourly electricity prices,

therefore, plays a key role in cost-effectively unlocking flexibility. Historically, key market players have been power plant operators who, through price signals, have been incentivised to be active in the power market and increase flexibility in their operation in order to maximise profits under varying electricity prices.

Lessons from a chronological review of flexibility solutions 2000-2020

As the VRE share has changed significantly over the past 20 years, so has the need for flexibility. Hence, chronologically reviewing the technical and institutional flexibility solutions in the Danish power system 2000-2020, not only provides insight into its stepwise development, it also illustrates which flexibility solutions are needed for different VRE shares. Some lessons from this review are shared below.

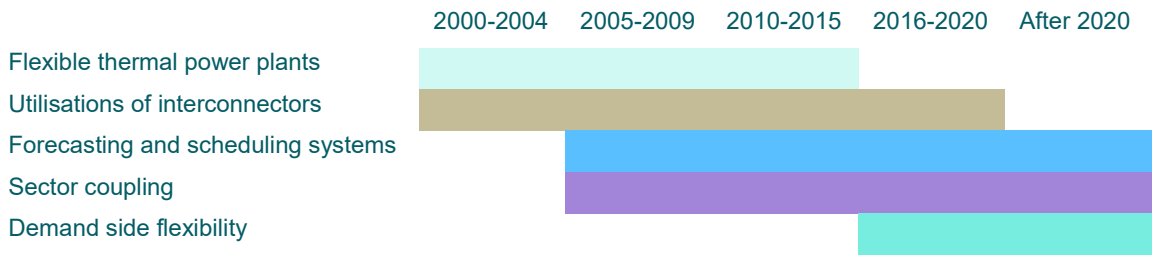

Figure 2 Illustration of primary flexibility measures in different periods. For further explanation of the categories, see textbox with Figure 7

2000-2009 (VRE shares <20%): the market incentivised better use of interconnectors and more flexible operation of existing power plants with only little investment in flexibility

The review reveals that at low VRE shares only relatively few investments in flexibility were needed as the need for flexibility could be met through more flexible operation of existing thermal power plants and better use of interconnectors to neighbouring countries. As shown in Figure 2, until 2009 with VRE below 20%, the primary, but not exclusive, sources of flexibility were flexible thermal power plants, utilisation of interconnectors, forecasting and scheduling systems. Forecasting and scheduling systems were important to reduce the need for flexibility and are becoming increasingly more important with higher shares of VRE.

Flexible operation of combined heat and power plants was promoted by exposing them to price fluctuations in the electricity market with hourly price formations as opposed to a previous three-part tariff scheme. In 2009, negative spot prices were introduced which created incentives to significantly reduce power production during high VRE production through enhanced flexibility in thermal power plants. Combined heat and power units also allowed for using the sector coupling of heat and power to vary electricity output by for example changing the power-to-heat generation ratio.

2010-2015 (VRE shares 20-44%): higher VRE share required larger investments in flexibility measures in existing technologies and new ways of operating power plants and the grid

In 2010-2015, the VRE share grew to 44% necessitating larger investments in flexibility across most of the power sector value chain. This included technical solutions such as complete turbine bypass and electric boilers or heat pumps to decouple heat and electricity production altogether.

While Denmark historically has been highly interconnected to neighbouring countries' power systems, the utilisation was improved when the entire interconnector capacity was made available on the market. Joining the Nordic power exchange Nord Pool in 2000 facilitated cross-border trading with neighbouring countries providing an important source of flexibility, both in terms of up and down regulation of power. Around 2015, a European harmonised day-ahead market was implemented providing access to a wider balancing area and cheaper sources of flexibility.

Furthermore, the ability for VRE to self-balance intraday deviations in production was improved with the European cross border intraday market launched in 2018 as the large number of buyers and sellers promoted competition and increased the liquidity of the market making intraday trading more efficient across Europe.

Besides the production and transmission side, the operation of the Danish power system also underwent a transition so that by 2017 central thermal power plants were no longer required to run. Studies provided insights into the fact that components in both the system backbone such as AC interconnectors or synchronous generators were providing sufficient properties required to maintain system stability in the Danish power system. As a consequence, the Danish power system started to run several hours per year and extended periods without central thermal plants.

2016-2020 (VRE shares 44-50%) and beyond 50%: focus has shifted towards increased sector coupling and demand-side flexibility

Demand-side flexibility started to be promoted through for example aggregators to actively participate in the balancing of the system as part of a transition from passive to active consumers.

The "low hanging fruits" of flexibility have already been implemented and the solution which has enabled integration of the first 50% of VRE in Denmark will not be able to meet future demand of flexibility. The focus is generally shifting towards increased sector coupling and demand-side flexibility through new technologies, innovative use of existing technologies, digitalisation and data-driven business models. The market is expected to remain the main driver of flexibility and its design will continuously be developed to promote increased levels of flexibility to enable a 100% renewable Danish power system by 2030.

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Abbreviations

BRP	Balancing Responsible Party
CEER	Council of European Energy Regulators
CEM	Clean Energy Ministerial
CHP	Combined Heat and Power
COP	Coefficient of Performance
CCUS	Carbon Capture Utilisation and Storage
DAM	Day-Ahead Market
DEA	Danish Energy Agency
DSF	Demand Side Flexibility
DSO	Distribution System Operator
EU	European Union
EV	Electric Vehicle
HVDC	High Voltage Direct Current
LCC	Line-Commutated Converter
mFFR	Manual Frequency Restoration Reserves
NDC	Nationally Determined Contribution
RfG	Requirements for Generators (EU network code)
TSO	Transmission System Operator
VRE	Variable Renewable Energy (refers to non-dispatchable renewable energy sources, specifically wind and solar power generation in this report)
VSC	Voltage Source Converter
PtX	Power-to-X

1. Introduction to the development of the Danish power system and role of flexibility

Messages in this chapter

- The share of VRE in the Danish power system has grown from 12% in 2000 to 50% in 2020.
- Today, the thermal capacity, interconnector capacity and VRE capacity are on similar levels (each around 7-8 GW) and peak consumption is around 6 GW.
- In this report, flexibility is defined as *"the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons"* (Ma, 2013).
- The electricity market was the main driver for flexibility – the market opening ensured a cost-efficient integration of VRE

The aim of this report is to share the past 20 years of Danish experiences of successfully integrating increasingly larger shares of variable renewable energy (VRE) into the power system. In this report, VRE covers primarily wind while solar only makes up a minority of the power generated.

This introductory chapter begins with a high-level introduction to why Denmark's experiences are considered to be valuable to the energy transition of other countries. This is followed by an introduction to flexibility as a key concept in integration of VRE and how this report defines the concept of flexibility. It ends by introducing the report structure, which is a chronological introduction to the flexibility of the Danish power system from 2000-2020 and in the future, and the motivation for choosing this structure.

The Danish power system: from 12% VRE to 50% in 20 years

Since the late 1980s, the Danish power system has been undergoing, and still is, a radical transition from a system based on large central coal-fired power plants to one based on VRE sources, CHP plants and strong interconnectors. Today, the Danish power system consists of roughly 7.2 GW of VRE (of which 6.1 GW are wind) and 8 GW of thermal power capacity as shown in Figure 3 (DEA, 2019).

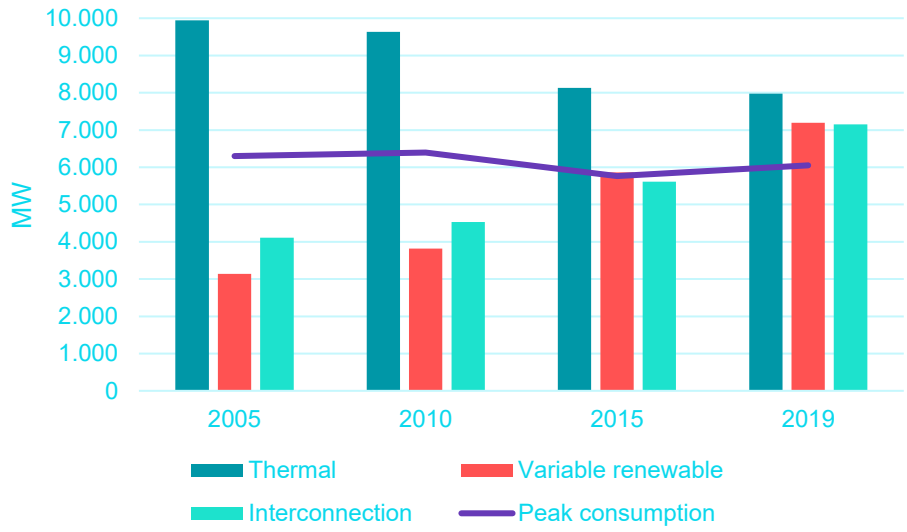

Figure 3 *Development in capacities for thermal power plants, VRE and interconnectors (DEA, 2019) in relation to peak consumption (Energinet). Thermal capacity entails all possible thermal power generation capacity including plants that may be mothballed or that are "conditionally operational" and may have start-up times of weeks or months. Decommissions are not included.*

The VRE share is equally reflected in the Danish power production, where in 2020 for the second year in a row, the VRE production share was 50% of the power demand as shown in Figure 4 (Energinet, 2021). This is a significant increase up from 12% in 2000 owing to the rapid deployment of VRE sources (DEA, 2019) which is expected to continue to meet the goal of a 100% renewable power system before 2030 (DEA, 2020).

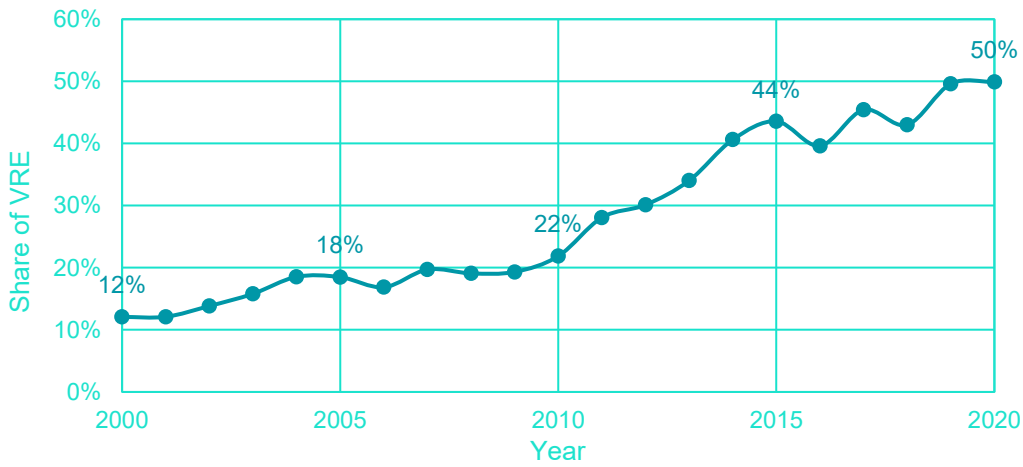

Figure 4 *Development in the share of VRE produced in the Danish power system in relation to power demand (DEA, 2019). Fluctuations between years are mainly owed to differences in annual wind generation due to varying wind speeds.*

This achievement has established Denmark as a leader in the integration of VRE. However,

achieving such a high level of VRE integration was not without effort, as the prospects for increasing VRE in the Danish system met institutional barriers at each step along the way. At every progress in VRE share, it was considered to be impossible to raise the share of VRE any higher. As VRE sources started being connected to the power grid, experts were sceptical of the possibility of integrating 10% of VRE in the Danish system. Once a 10% VRE share was reached, it was said to be impossible to reach a 20% VRE share without compromising the power system stability. Nonetheless, the boundary was continuously pushed as major institutions learned to adapt to these new VRE realities along the way. A central, enabling institution was the Danish Transmission System Operator (TSO) Energinet, which went from thinking "*we know best what our system can do because we are engineers*" to "*because we are engineers we have to develop innovative solutions for what society wants*" (Ackermann, 2006; Wittrup, 2018).

An important accomplishment in this transition is that Denmark has maintained one of the highest securities of power supply in Europe (CEER, 2018) due to a continuous hunt for good and innovative solutions and the implementation thereof. Not only has Denmark not lacked power generation adequacy in at least the last 30 years, but the fault rate is also extremely low. As a consequence, Danish power consumers have on a 10-year average had a 99.996% security for power availability, meaning the average consumer has been without power for roughly 20 minutes a year, accounting for all types of faults in the entire power grid (Energinet, 2020).

The stability of the power system and the generation adequacy should not be seen entirely as a product of the development of the Danish power system alone, but also as the result of the Danish power grid being strongly connected to neighbouring countries. In brief, the many grid connections provide stability through inertia and frequency stability via the AC interconnectors and opportunities for balancing across large land areas with different generation mixes and sources.

VRE Integration: Sharing Danish experiences to help accelerate other countries' energy transition

To understand the evolving needs of the Danish power system to successfully integrate increasing shares of VRE as shown in Figure 4, the IEA's 6 phases of the VRE integration framework offer a helpful structure. The IEA divides the characteristics and challenges of VRE integration into six phases according to the amount of VRE already existing in the system, as illustrated in Figure 5. In 2020, Denmark is at phase 4, which is only shared by the Iberian Peninsula, Ireland and the state of South Australia. Based on IEA's assessment, no country has yet found itself in phase 5, which requires advanced technical options to ensure system stability. In comparison, countries such as India, China and the US are all considered in phase 2 where existing flexibility measures in the system are considered to be sufficient (IEA, 2018).

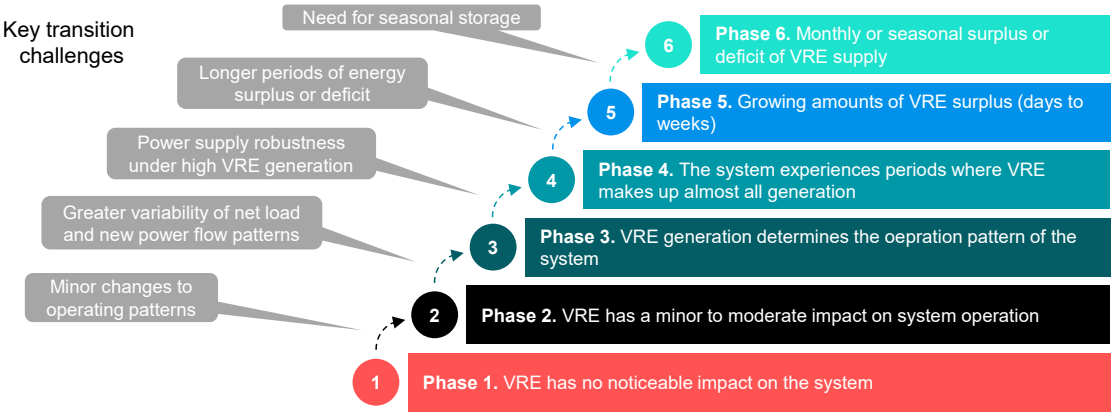

Figure 5 *Characteristics and key transition challenges in different phases of integration of renewables (IEA, 2018).*

In relation to IEA's phases of system integration, the Danish government's goal is to have the power system operating on 100% renewable power sources (including biomass firing), which as a consequence should put Denmark in phase 6.

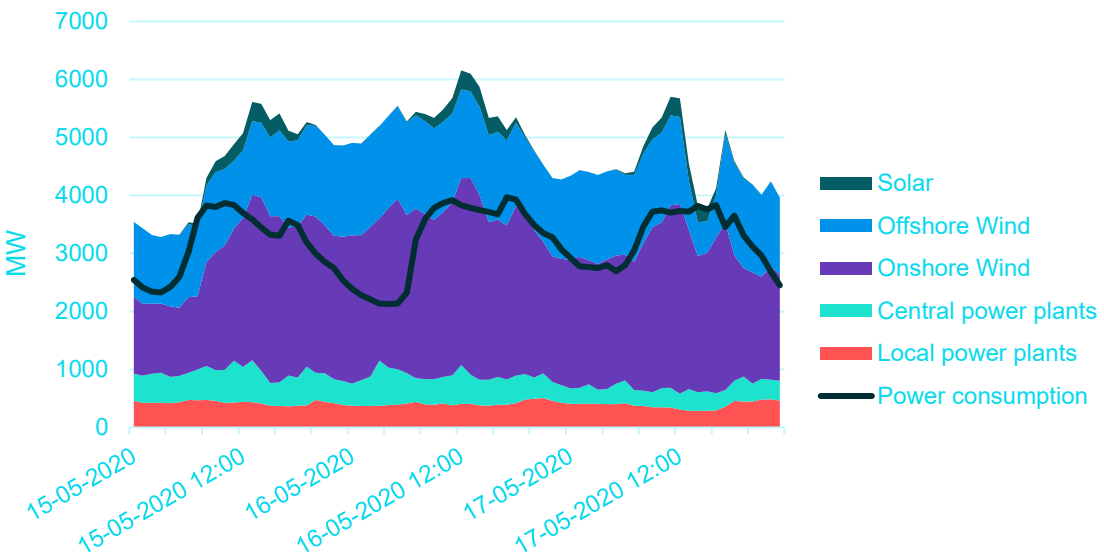

Figure 6 *Power consumption and generation from main sources in the whole of Denmark on 15th-17th of May 2020. Generation that surpasses consumption was exported.*

While the Danish integration of renewables has been long underway, the current state of the climate demands that countries with a lower renewable share progress even faster than Denmark; a fast transition is imperative to meet the challenges of the Paris agreement. However, countries located in phase 1-3 could adopt a steeper learning curve by looking at Danish experiences and leapfrogging in their development. This framework illustrates how the approach to VRE integration evolves with an increasing share of VRE as new solutions for grid stability and flexibility are

required.

VRE sources contain variability and uncertainty in their generation

Generation from VRE sources is dependent on many meteorological factors, such as wind speed or solar irradiance, temperature, precipitation, humidity and cloud cover, which means generation will be varying and stochastic on all timescales from seconds to minutes and hours, days, months and years. As an example, a change of 1 m/s in wind speed can cause a change of more than 500 MW in power production in a power system with more than 5 GW installed wind capacity. In other words, if the power system is not flexible enough, such large changes in power production can lead to grid congestion, wind power curtailment and imbalances (DEA, 2020; IEA, 2018).

The inherent non-dispatchable nature of VRE entails that other units in the power system are capable of quickly responding to changes in order to balance the system. Stability and balancing are vital for operating a power grid especially as VRE sources supply the majority of power demand. Particularly for balancing, the key is having components on all side of the power system able to respond to fluctuations from VRE, but also disturbances from other components. This means that flexibility in the power system is crucial.

Flexibility: a key concept in VRE integration

In this report, the term flexibility is adopted according to the definition by "Evaluating and Planning Flexibility in Sustainable Power Systems" as *"the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons"* (Ma, 2013).

Flexibility in the Danish power system has not been provided by a single measure but as a combination of several technical and institutional instruments, which will be presented in the following sections. To structure the topics in this report, the measures are divided into the following categories:

- Flexible thermal power plants
- Utilisation of interconnectors
- Forecasting and scheduling system
- Sector coupling
- Demand-side flexibility

The term flexibility should not be confused with the term reserves. Reserves are mainly used to compensate for the uncertainty in the power balance. Imbalances can be caused by a large disturbance, stochastic variation, forecast error or hour shift problems etc. Reserves provide flexibility to the system. However, flexibility also covers the ability of the system to adapt to the

normal variation in net load during the day and throughout the year (DEA, 2015).

Flexibility can be achieved through the generation side, demand side, interconnectors or storage. With weather dependent renewable energy sources, like solar and wind, the available generation also exhibits variability. The objective is therefore to balance the net load, i.e. the difference between the non-dispatchable generation and the non-dispatchable load (DEA, 2015). There is a big difference between the flexibility which is needed to have reserves for a generator trip and the flexibility required to cope with a dry year with shortage of hydropower. Overall, we need flexibility in the power system in the short term meaning seconds, minutes, quarter- and half-hours as well as over longer time periods such as days, weeks or years (DEA, 2015).

A chronological review of flexibility measures and their drivers in the Danish power system

The following chapters describe the historical development of the flexibility measures and the variable renewable share of the power mix in Denmark. A chronological order is chosen as it illustrates how flexibility strategies changed as the VRE share grew, and how these were largely driven by different market mechanisms as the Danish power system is operated based on market dispatch. To some extent, this also meant that the least cost flexibility measures were the first to be implemented as the power producing companies were the implementers.

In Denmark and Europe in general, the market dispatch operation drove flexibility measures forward by letting the need of the market be reflected through economic incentives to operate current plants more flexibly or change their characteristics. While flexibility measures may also be promoted through other incentives than market operation, letting the market showcase the need through price signals and letting the suppliers fulfil that need means the least expensive measures will be deployed first. However, this will only be the case for a well-functioning market where regulation, incentives and market structures have been designed to best reflect the system needs and where market players operate under an economically rational behaviour, meaning according to the price signal they are presented for. Something that will also be evident through this report is that regulation such as network codes, (also known as grid codes) which entail requirements to connecting newer plants, are essential for ensuring power system security while providing flexibility.

During the period of implementing market-based flexibility measures from 2000 until today, several types of flexibility methods were further developed, with different priorities through the years. In general, the less expensive and simpler measures were implemented first, such as flexibilisation of power plants, interconnector related measures and continuous method development of forecasting of renewable generation as generally illustrated in the text box below.

Overall timeline and development within main types of flexibility

In general, all of the categories of power system flexibility have had huge importance for integrating renewables, yet some had a more important role in certain periods than others.

Figure 7 illustrates which types of flexibility were in focus and were a significant source of flexibility in a given period.

Flexible thermal power plants were initially the most important sources of flexibility, hence in Figure 7 it is marked as having a large impact in the first three periods. This merely means, that the most significant developments of thermal power plant flexibility were implemented in these periods, while the effects are still seen today.

It should also be understood from Figure 7 that the generation side has been the main source of flexibility until 2020, but that these measures alone will not economically nor technically be sufficient for Denmark to integrate increasingly larger amounts of VRE in the future. Instead, sector coupling, demand-side flexibility and other sources of flexibility are being brought into play.

However, the focus and primary sources of flexibility within each category have also changed over time. For instance, sector coupling initially was about coupling power and heating generation closer together to use excess heat from power generation in district heating. Yet, the focus in later years has been on technologies that make use of surplus electricity in times of high renewable generation such as the promotion of heat pumps and electric boilers. Likewise, in these years PtX is a popular topic for future sector coupling for decarbonising sectors that are difficult to electrify and the possible flexibility of these technologies.

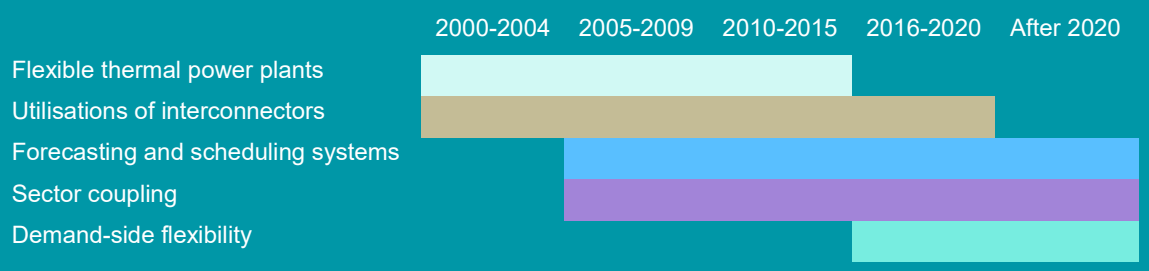

Figure 7 Illustration of periods in which particularly categories of flexibility generally had the most significant impact on power system flexibility and thereby renewable integration.

The following chapters refer to these categories of flexibility. Some flexibility measures, however, may fall under several categories, such as flexible CHP plants, which can be described as both flexible thermal power plants and sector coupling. As a consequence, it could be argued that

some measures should pertain to other categories, nonetheless, in order to simplify the messages and report structure, we have chosen this setup. Moreover, the flexibility measures in the following are described as seen from an overall system perspective, meaning the report does not go into detail with the exact technical alterations to specific thermal power plants or grid components. If this is of interest, information on this can be found in the references or other DEA publications[1].

[1] DEA publications may be found at https://ens.dk/en/our-responsibilities/global-cooperation/tools-and-publications

2. 2000-2004: Market opening in the power sector provided first incentives for flexible operation and interconnector capacity was fully made available to the market – 12-19% VRE share

Messages from this period

- Ownership of the grid was unbundled from commercial activities to ensure fair and equal market access for all technologies incl. RE.
- The market opening incentivised thermal power plant owners to flexibly operate their power plants which had initially been commissioned as base loads.
- The power system benefitted from increased interconnector capacity by having large geographic areas to balance against with different mix of production technologies and consumption profiles.

To explain how flexibility in the Danish power system has developed it is important to understand the main driver behind its development. For Denmark, the main driver was the desire to provide fair and equal access to the electricity market for all technologies allowing the most cost-effective to prevail.

The first step came when the EU in the 1990s proposed directives for how the electricity market across Europe should be shaped in the future. During the late 1990s, the EU's directives were adopted, leading to gradual market openings in several phases (DEA, 2020). In short, the purpose was to ensure no conflicts of interest and a fair and equal market whereby companies were not allowed to own both power grids and generation assets.

This market opening introduced competition in power generation and trade, and the previous vertically integrated energy utilities were unbundled. When Denmark joined the Nordic power exchange Nord Pool in 2000, competition on the market grew further and began to provide economic incentives to plant owners to be active in the power market and increase flexibility in their operation in order to maximise profits under varying electricity prices (DEA, 2020).

Market design – From fixed tariffs to hourly electricity prices

Before the market opening, a three-part tariff was the basis for the wholesale settlement of electricity production. However, since the market opening, settlement on the wholesale market has been subject to hourly electricity prices. Unlike the hourly intervals of the present settlement the three-part tariff only divided the day into three separate price periods; low load,

high load and peak load. The system operator's payment to supply companies was based on long term marginal cost to produce and transport electricity incl. fuel cost and CAPEX, and production was optimally dispatched by the system operator accordingly. As a result, the three-part tariff failed to incentivise flexibility from the power plants as these were set administratively and exogenously, thus not reflecting the actual supply and demand conditions.

With the market opening and the introduction of a DAM with 24-hour intervals, competition between all producers on a daily auction now ensured that the hourly electricity price would reflect the short-run marginal costs of generating electricity in each bidding zone of that hour. The fragmentation into twenty-four instead of only three intervals per day, better fits the dynamics of fluctuating energy sources thus providing power producers with signals more reflective of the state of the system as can be interpreted from Figure 8.

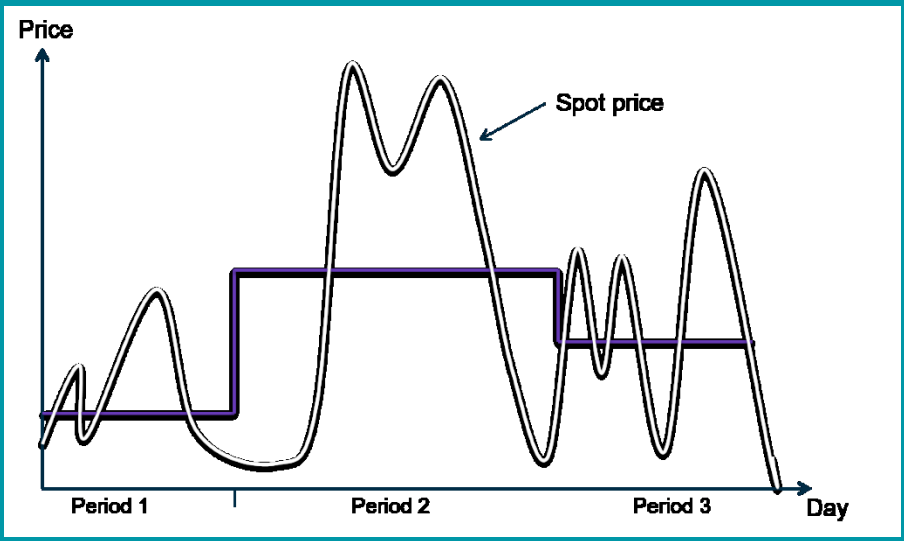

Figure 8 Illustration of difference between three-part tariff pricing and spot market price formation.

Flexible thermal power plants: Commissioned as low-flexibility base load incentivised to become the source of flexibility

The last commissioned coal-fired CHP plant in Denmark was commissioned in 1998 with the purpose of supplying base load electricity production, with heat being considered a by-product which during the summertime was rarely utilised.

At the time, Danish law restricted developing condensing power plants in order to take advantage of the high steam temperatures in the electricity generation process to produce heat for district

heating systems and achieve higher efficiency. In this way, CHP plants were also forced in as the main providers of heat in the district heating systems covering the major cities and urban areas.

Until 2000, there were two main contributors of flexibility in the Danish power system. One was the expansion in CHP plants and the other was increased energy efficiency in both heat and power sectors to shave of peaks in consumption, so in reality, the flexibility was relatively low. In connection with the CHP plants, district heating storage tanks had also been put in operation and optimised to take advantage of the flexibility they could provide over the course of a day.

The market opening, and thereby a market dispatch of the power system, led to the first operational flexibility measures in conventional power plants. Since almost all thermal power plants in Denmark at this point were CHP plants, a low electricity price was observed during periods with high demand for district heating. The high demand meant the CHP plants were required to produce large amounts of heat with the by-product being electricity. The CHP operators, therefore, had to ensure they were allowed by the market to produce electricity, so they chose to bid a low power production price in the market.

As a consequence, this had negative impacts on the revenue of the CHP plants, which launched efforts to improve the on-site flexibility through flexible decoupling of heat and power generation in the CHP plants when necessary. In brief, the decoupling meant that extraction plants gained a greater operational envelope and could therefore produce heat and power in a variety of ratios, allowing the plant to better follow the demand. The decoupling at this stage required no new hardware as it was implemented by altering the utilisation of existing plant components, therefore these first flexibility measures bore no investments costs (DEA, 2015).

Utilisation of interconnectors: Entire interconnector capacity becomes available for market dispatch

The strategy of connecting to neighbouring countries begun early on; already in 1915, the Danish and Swedish grids became connected. This was followed by several more interconnectors including some to Norway and Germany. In the early 2000s, the increasing share of wind power in a Danish power system dominated by thermal power plants resulted in periods with surplus or shortage of power generation. On the other side, the Swedish and Norwegian power systems had large amounts of hydro power, a cheap and dispatchable source of energy. Hence, the interconnection lines were built as a source of flexibility as Denmark gained access to cheap hydro power from Sweden and Norway while Sweden and Norway in cases of dry seasons could import energy from Danish thermal power plants. The hydro power capacity was used as a source of power when the Danish power system experienced shortage of power which could compete with the marginal cost of any available hydro as well as used as a source of storage by exporting

power during periods of excess power generation with low marginal cost (DEA, 2020). As a result, the interconnectors were valuable to all countries involved as their power systems had different characteristics and hence different needs.

To ensure optimal utilisation of the interconnectors, the increase in interconnector capacity had to be accompanied by suitable market mechanisms which became central in deciding the power flows. A prerequisite for achieving this was making the full interconnector capacity available to the market. Prior to the market opening, a large fraction of the cross-border interconnector capacity had been reserved for long-term contracts between the vertically integrated electricity companies. Figure 9 from IEA clearly illustrates how in 1995, contracts were directing the flow seemed more regular and predictable.

However, when joining the Nordpool exchange, the TSO freed up transmission capacity to make it available to the day-ahead trading. By connecting two areas, and therefore two price zones, the interconnectors would then work by having electricity flow towards the high-price areas acting on price signals rather than on a contract basis. As a result, the flows in 2000 as seen in Figure 9 change significantly from one hour to the next as interconnectors are put to more dynamic and flexible use. In addition, Figure 9 illustrates how interconnections were more extensively utilised in 2000 than in 1995 (Energinet and DEA, 2018; IEA, 2005).

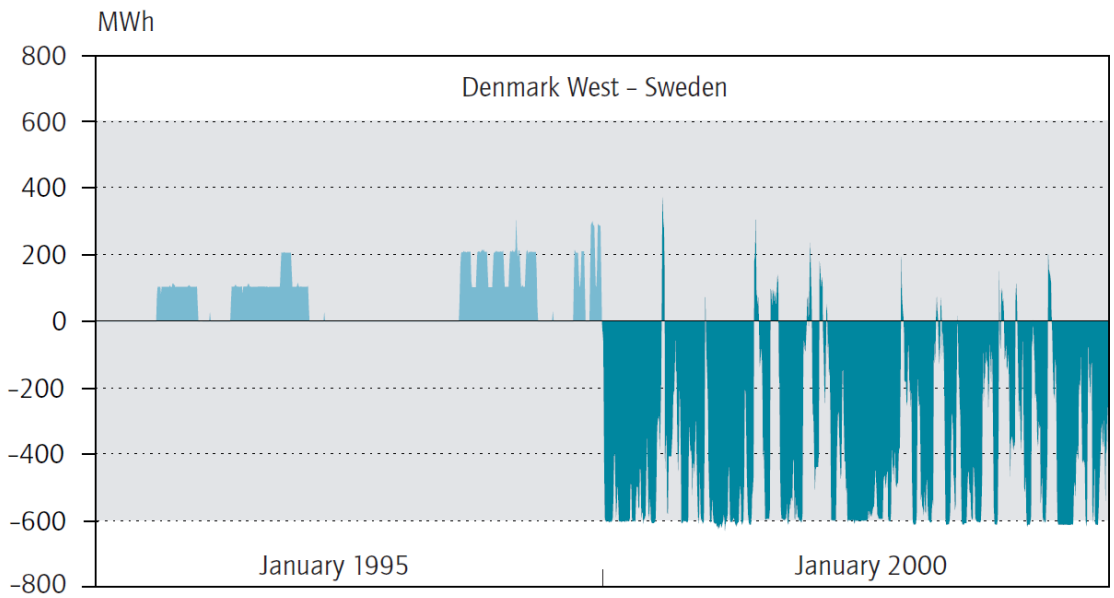

Figure 9 *Flow over the interconnector between Western Denmark and Sweden in January of 1995 and 2000. Positive numbers illustrate import and negative numbers illustrate export, and the shaded area marks the rated capacity of the interconnector. Illustration from (IEA, 2005) with Energinet as the source.*

Hence, only through the continuous improvement of trading mechanisms and the development of a common Nordic balancing market has Denmark been able to make full use of interconnectors as a source of flexibility. This has been both in terms of up-regulating and down-regulating power. In regard to up-regulation, Denmark accessed and still does today, Swedish and Norwegian reservoir hydropower as cheap short-term flexibility. In regard to down-regulation, when VRE production is peaking, a surplus of electricity production is exported. The importance of exporting wind power became more important later when VRE share became higher and is therefore included in the next section.

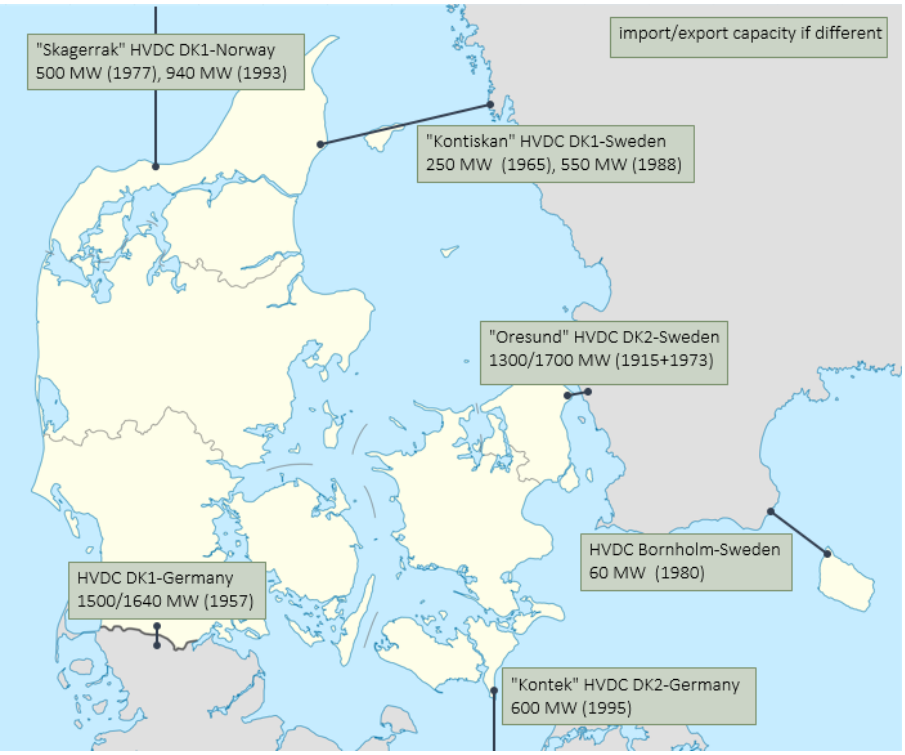

Figure 10 International interconnectors in Denmark as of 2004.

Balancing Responsible Parties and Nordic power markets

The Danish market model is a self-dispatch model with assigned Balancing Responsible Parties (BRPs) which act as an interface between producers, consumers and the TSO by buying and selling electricity on the markets (Energinet, 2020).

Larger power producers often act as BRPs themselves, while smaller market actors choose to be represented by a BRP which then trades on their behalf. The customers can freely choose among multiple BRPs and this is believed to create the right competition to

incentivise the BRP to provide the best service at the lowest cost to attract customers. Each BRP is responsible for providing the TSO, Energinet, with a plan of expected production and consumption on behalf of their wholesale electricity consumers and power generators on an hourly basis covering a 24-hour window. The BRP has concluded an agreement on balance responsibility with the TSO, and as a result, becomes financially liable for any imbalances. The choice of making the BRP financial liable for any imbalances was made to incentivise them to make the most accurate prediction, hence reducing the need for balancing by the TSO which reduces overall system balancing cost. Consequently, there is less need for flexibility in the system and less interference by the TSO as all BRPs are affected equally meaning VRE producers are given the same incentives as thermal power plants owners to not create imbalances (DEA, 2020).

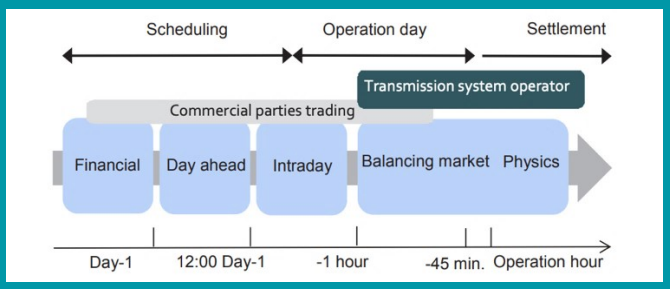

Figure 11 Main phases of the Nordic power market (Energinet, 2020).

Financial market

The financial market (also called forward market) allows for producers and consumers to hedge their price risk in the day-ahead market (DAM) by entering into financial contracts which create stability and increase investor security for both producers and consumers. This helps to unlock system flexibility as opposed to physical contracts which provide a more inflexible framework.

The basis for the financial market is the DAM price for each region. The price in the DAM is then the underlying commodity price for almost all hedging tools available and provided by power exchanges and the TSO. Since the DAM price is changing often and can be volatile the financial contracts allow for market participants to hedge their risk.

An important mechanism for the hedging to take place is a sufficient number of buyers and sellers participating in the financial market to ensure enough liquidity.

Day-ahead market

The DAM is a daily auction where the BRPs submit economically binding bids on production

and consumption to the TSO for the subsequent 24 hours on an hourly basis running midnight to midnight (DEA, 2020).

The cheapest production offers that meet expected demand for each hour are chosen resulting in a least-cost dispatch with the settlement price being the most expensive marginal cost of the accepted offers within a regulatory minimum and maximum.

All market actors receive/pay the same settlement price in the given hour (i.e. 'pay as cleared' pricing) to give the incentive to bid at their lowest marginal profitable price.

Intraday market

Intraday markets for electricity allow for BRPs to continue trading until an hour before delivery. Today, this market is handling increasingly larger volumes with increasing shares of VRE sources, as the production from these can be difficult to accurately predict in advance. This provides a flexibility option as market actors have the opportunity to compensate for imbalances themselves as well as offer their own unused flexibility.

Balancing market and ancillary services (reserves)

After closure of the intraday market, the TSO takes over the responsibility for the physical balancing by procuring balancing reserves covering the entire time scale.

As shown in Figure 12, the fastest reserves include the frequency stability of the transmission system which is secured by Frequency Containment Reserves and Frequency Restoration Reserves. The providers are paid to have a capacity ready that can be activated within 15 seconds to 2-5 minutes.

To minimise the use of expensive automatic reserves, slower replacement reserves (manual reserves) are activated through a request from the TSO. To ensure having sufficient manual reserves, the TSO is both purchasing capacity in advance and relying on participants' voluntary bids on the market. In this way, the TSO uses a combination of the reserves and the voluntary bids to balance the system.

General balancing categories	Activation time	Nordic market size	Payment
Frequency containment (primary reserves)	Automatic activation Full effect within 15-30 sec.	1200 MW	Reserve payment only
Frequency restoration (secondary reserves)	Automatic activation Full effect within 15-30 sec.	300 MW	Reserve + activation payment
Replacement (manual reserves)	Manual activation Full effect within 15 min. of activation	N-1 (load frequency control area)	Common Nordic market for regulating power reserve +

	activation (voluntary bids) payment

Figure 12 Types of balancing categories in the Nordics (DEA, 2015)

Takeaways from 2000-2004

With the share of VRE reaching 12-19%, the market opening spurred economic incentives for the implementation of the first major flexibility measures in thermal power plants. The market opening exposed inflexible CHP plants to price fluctuations in the electricity market and being the main providers of heat to district heating networks, their revenue was challenged. In periods of high district heating demand, it could be necessary for the CHP plants to incur an economic loss in the electricity market to fulfil the heat demand. This led to the first initiatives to decouple the heat and electricity generation in CHP plants beyond the already existing hot water storage tanks for district heating.

As interconnector capacity grew, Denmark reaped the benefits of a larger balancing area. Variations in generation from VRE sources could better be balanced with the help of other areas' different generation mixes. In periods with high VRE generation in Denmark, it could flow to areas with low VRE generation and vice versa due to uncorrelated timings in VRE generation and load demands.

A key market operational feature is the ability to handle the dynamics of a VRE based power system and reflect these in frequent price formation. Previously, Denmark had had a three-part tariff pricing scheme which meant the price paid to producers only was updated three times per day. However, with the market opening, this was increased in 2005 to 24 times per day to better capture the dynamics and variability of VRE and thereby provide the right incentives for flexibility.

3. 2005-2009: CHP plants changing from providing baseload to being a key source of flexibility and regulation changes to allow negative spot prices – 18-20% VRE share

Messages from this period

- To integrate increasing shares of fluctuating non-dispatchable production from wind, the role of CHP plants changed from being baseload to a key source of flexibility.
- The flexible operation was achieved through increased ramping rates and expansion of boundaries of operation.
- To incentivise the more flexible operation of CHP plants, new market structures were introduced such as allowing negative prices on the spot market.

During the period of 2005-2009, a large part of the power system was decentralised from power generation from central power plants to smaller natural gas CHP plants located across Denmark where they were coupled to the local heat production. This was part of the energy planning where expanding the local district heating systems was high on the agenda as they were considered the most effective way of delivering heat in urban areas. As a result, by 2015, the power generation landscape had undergone a significant decentralisation while also significantly increasing its numbers of windfarms as shown in Figure 13 (DEA). One way the decentralisation was promoted was through subsidies to local, dispatchable CHP plants to incentives integration of local district heating systems. This way new local district heating companies could earn income from the sale of power in addition to the sale of heating which improved their business case. This led to a high degree of sector coupling between heat and power and its flexibility potential was extensively explored throughout the coming years.

Before 2005, the small decentral CHP plants were paid in fixed three-part tariffs, which ensured them a stable income from electricity sales. This fixed tariff was benefitting technologies that were often not competitive in the market and ultimately incurred additional cost on the consumers. Small CHP plants were therefore added to the free electricity market, though with an added tariff. This tariff was named Public Service Obligations (PSO) and was meant to give these small CHP plants and the early wind turbines an extra income needed to be profitable. By gaining access to the market, the small CHP plants went from being passive power and heat producers to market players, switching production between CHP and heat-only dependent on the electricity price. To offer flexible services, these small plants further invested in heat storage so longer periods of zero electricity production could be achieved. The PSO was deemed problematic in EU laws and will

be phased out in 2022, making decentral power plants entirely market actors.

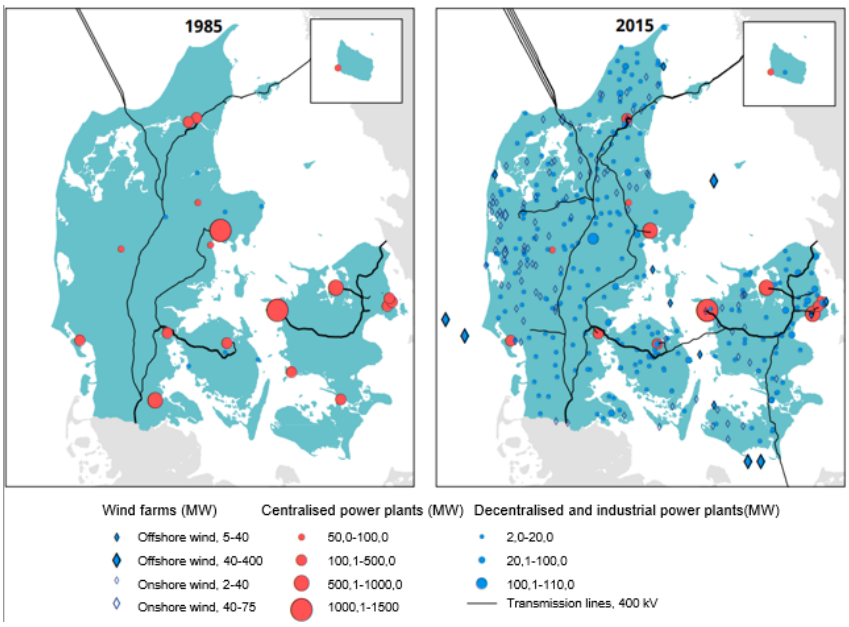

Figure 13 Shift from centralised CHP plant to decentralised CHP plants and wind farms. (DEA)

Flexible thermal power plants: The role of CHP plants changed from baseload to key source of flexibility

New market structure incentivised more flexible operation of CHP plants

Conventionally, within the Danish power system, CHP plants were considered must-run units as they had to meet a heat demand. In this period, the Danish power system faced the challenge of integrating larger amounts of fluctuating generation from VRE, which was addressed by deciding to change the operation of thermal plants to make them more flexible. As a result, in Denmark, CHP plants were (and still are) no longer considered real must-run units in the sense of being prioritised before the market dispatch. Instead, all CHP plants compete in the market with all other generating technologies. Some experience and strategies on this will be presented in the following section.

Operational flexibility solutions for thermal power plants: improving overload ability, increasing ramp rates and lower minimal load

More flexible operation through overload ability and lower minimum load

Operating in overload is the ability of a plant to deliver 5-10% additional power output relative to normal full-load operation, with a slightly reduced efficiency and temporarily higher stress on key components. This allows the operator of the power plant to further increase generation output when beneficial. These include situations both in day-ahead planning if prices are sufficiently high and in intra-day or ancillary markets where the plant can offer up-regulation closer to the hour of operation. This flexibility is also beneficial from a system perspective, as the overload capability reduces the risk of enforcing other plants or more expensive reserves to start up when supplementary output is required.

Reducing a power plant's minimum load is valuable as it allows the plant to stay online instead of being turning off. By not shutting down, its start-up cost and start-up time are significantly reduced. In addition, it can be valuable during periods of typically high non-dispatchable power generation when demand for electricity from thermal power plants is low as they can quickly provide a large volume of up-regulation in case of sudden lack of generation. A thermal power plant can typically operate around 40% of nominal output while retrofitting can reduce the minimum load to around 15-30%. This normally requires installation of a boiler water circulation system, adjustment of the firing system, allowing for a reduction in the number of mills in operation, combined with control system upgrades. These require a moderate investment; roughly only 15,000 EUR per MW, or approximately 4-5 million EUR for a 300 MW plant (European cost estimates) (CEM, 2018).

More flexible operation through higher ramping rate

Danish coal-fired power plants typically have a ramping rate of roughly 4% of nominal load per minute on their primary fuel. The ramping rate can be increased to up to 8% when supplementary fuels, such as oil or gas, are used.

The level of investment needed to refurbish the plant for a higher ramping rate highly depends on the power plant. Faster ramping leads to rapid changes in material temperatures and hence requires high-quality components as well as additional control of the processes. In some cases, investment can be limited to non-technical retrofitting such as retraining, new software and/or reprogramming of the control system, while in other cases technical retrofitting is required resulting in higher investment costs. An example of an operating procedure for fast ramping is keeping components at high temperatures which for example could allow for a power plant to connect with the grid within 60 minutes instead of an initial 90 minutes start-up time.

Expanding the operational area and increasing ramping speeds allow the plants to follow demand more closely. They do this by acting on price signals as illustrated by the simplified case provided in Figure 14.

As introduced in the previous chapter, the power market liberalisation resulted in the operation of CHP plants according to market conditions. The years after 2005 saw a reduction in average wholesale electricity prices particularly due to increased penetration of subsidised renewables with low marginal cost. This created longer periods with wholesale prices that were too low for operators of thermal power plants to generate profit. On the whole, the shorter periods before 2005 where electricity prices were low were now growing to longer periods in line with IEA's phases of system integration. As a result of these longer periods with low electricity price, providing baseload became a less attractive business case. These new market conditions, therefore, incentivised the CHP plants to change their business model; from providing baseload electricity production with heat as a secondary objective to producing mainly heat, filling the gaps in hours of low VRE generation, and providing flexibility services on the ancillary market.

Danish experiences from the 2005-2009 period showed that the early stages of enhanced thermal power plant flexibility could be achieved with limited investment costs in new hardware (CEM, 2018). Instead, flexibility was primarily achieved by designing flexible operational strategies such as improvement in minimum load capabilities and enhanced ramping speeds.

The key driving force behind flexibility improvements has been the plant owners' incentive to optimise their power plant's economic performance through their market operation. However, from a direct regulation perspective, network codes can be another measure used to mandate minimum flexibility criteria. In Denmark, codes mandated from 2008 specific minimum load capabilities and ramping rates for new power plants related to the plants fuel-firing type. These were important regulation at the time but were later taken out of force as to plant owners had learned the need for flexibility from the codes and the market. While direct regulation can clearly ensure a certain level of flexibility across the power plant fleet such as through stipulating minimum criteria, direct regulation does not necessarily ensure the most cost-efficient flexibility improvements. Consequently, motivating enhanced power plant flexibility through market-based incentives allows power plant owners to determine which flexibility enhancements are most profitable and viable given the plant's operation and role in the power system.

A simplified case of how the market provides incentives for flexibility services by dispatchable plants

As described in the previous text box, a retrofitted power plant with increased flexibility has a more flexible operation pattern compared to a standard power plant through a larger operational area.

In Figure 14, it is shown how the power plant takes advantages of this operational flexibility to

generate larger revenues for the operators as the plant can follow price signals more closely (Ea Energy Analyses, 2015).

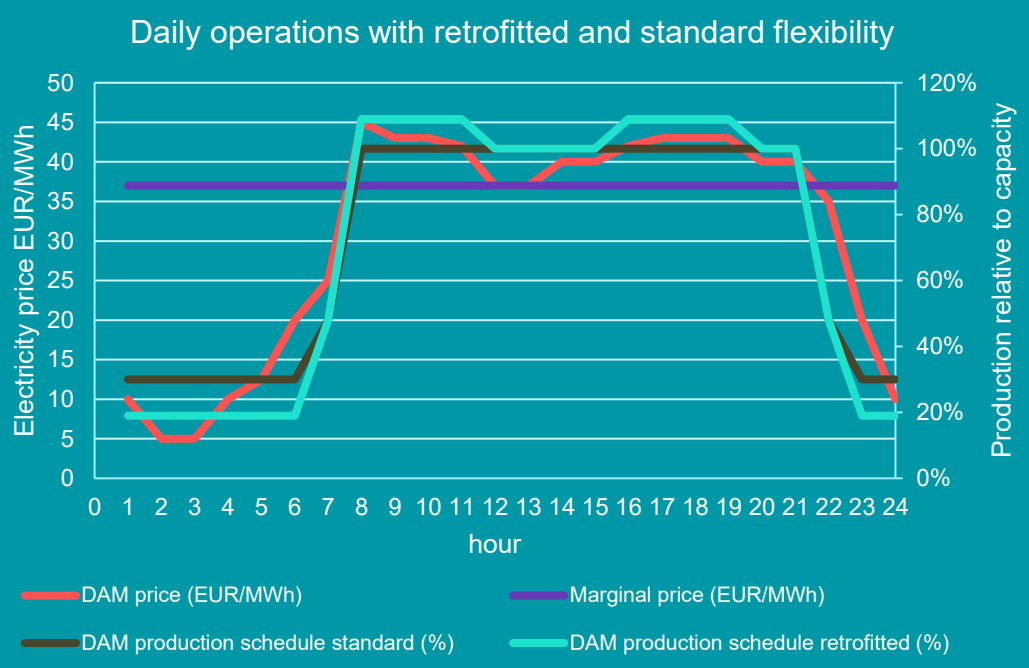

Figure 14 Example of daily operations in day-ahead market (CEM, 2018)

The day-ahead market price (red line on the figure) is below the marginal price (purple line) in the morning and in the evening while around 7:30 to 22:00 it is above the marginal price. The former period illustrates a period where it is not profitable for the plant to operate. In this case, the flexible power plant does not shut down due to start-up costs and potentially also due to heat demand, but it is able to reduce its minimum load to 10%. When market prices start increasing, the retrofitted, flexible power plant has the ability to ramp up more quickly as well as increase its output to up to 110% once the prices become sufficiently high.

As a result, the retrofitted plant generates more profit from the electricity market as it can change its output to minimise losses during unprofitable periods and maximise profit during periods of high prices.

Consequently, investing in retrofitted flexibility improves the financial performance of the plant on days where electricity prices are fluctuating above and below marginal costs of the plant which typically is the case during days with high VRE generation.

Negative prices lead to more dynamic operation of traditional generation through the use of electric boilers

Early subsidies for land-based VRE (wind turbines) in Denmark gave a fixed subsidy of up to ~0.34 €/kWh on top of the spot price for the first 20 years of the turbine's lifetime. This fixed subsidy meant that wind turbines still generated revenue, and thereby produced, even at some negative prices. This limited the flexibility of the wind turbine and as a result, these subsidies ended in 2018.

To better reflect the dynamics of the system, in 2009, Nord Pool changed the regulation to allow negative day-ahead prices, decreasing the price floor from 0 €/MWh to initially -200 €/MWh and later -500 €/MWh. This led to the market experiencing negative electricity prices in situations when subsidised non-dispatchable RE generation and must-run generation with marginal costs below zero exceeded demand. These periods would indicate periods of excess supply of power production from wind turbines and CHP units. In normal operation, any excess supply was exported to Norway, Sweden and/or Germany, but in some cases, limitations of usage of interconnector capacity or same time excess supply of wind power production in Germany led to situations with prices below zero. The negative prices on the market created incentives to terminate or at least reduce production when there was no value of electricity. This led to investments in flexibility measures on the demand side, especially driving the market for electric boilers in district heating systems. As shown in Figure 15, this even allowed power plants to become net consumers during periods with negative spot prices.

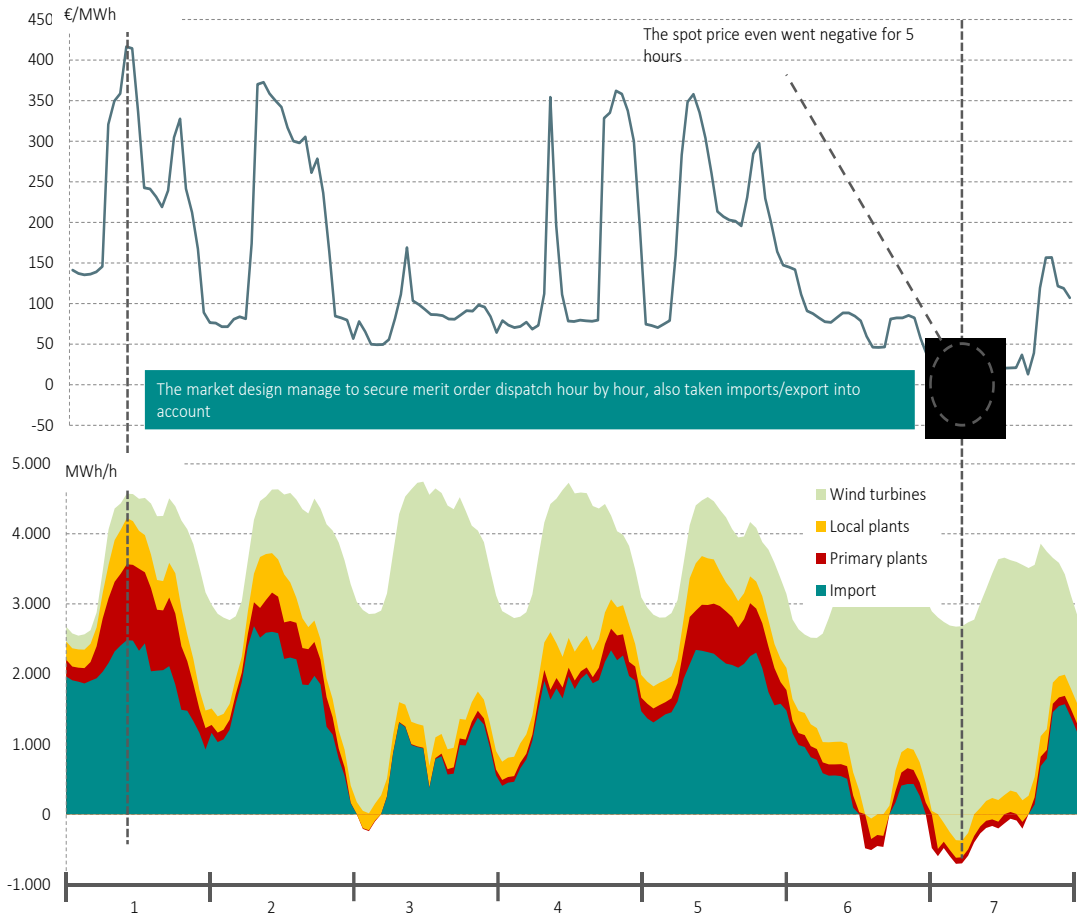

Figure 15 Example of how negative spot prices incentivise power plants to consume electricity

Additionally, in 2009, a new regulation for participation in the market for primary reserves was introduced which incentivised participation of electric boilers on the market. From 2009, the operators of the electric boilers were allowed to make block bids of 4 hours duration with asymmetric products. This meant that they were allowed to offer only down-regulation or up-regulation and not both at the same time. The operators could simply switch on the boilers and provide down-regulation when the system needed it.

As a result, the installed capacity of electric boilers doubled in three years during 2010-2012 after only increasing little between 2006 and 2009 as shown in Figure 16. However, the regulation proved too favourable for electric boilers and was therefore adjusted accordingly leading to very few new boilers being introduced after 2012. The experience with electric boilers illustrates how market mechanisms can be an effective tool in incentivising market actors to invest in flexibility measures and offer these when needed by the power system. It also illustrates how choosing the right level of incentives is a challenge and, in the Danish case, subject to constant evaluation. However, the investments in electric boilers were not in vain and are still key sources for down regulation.

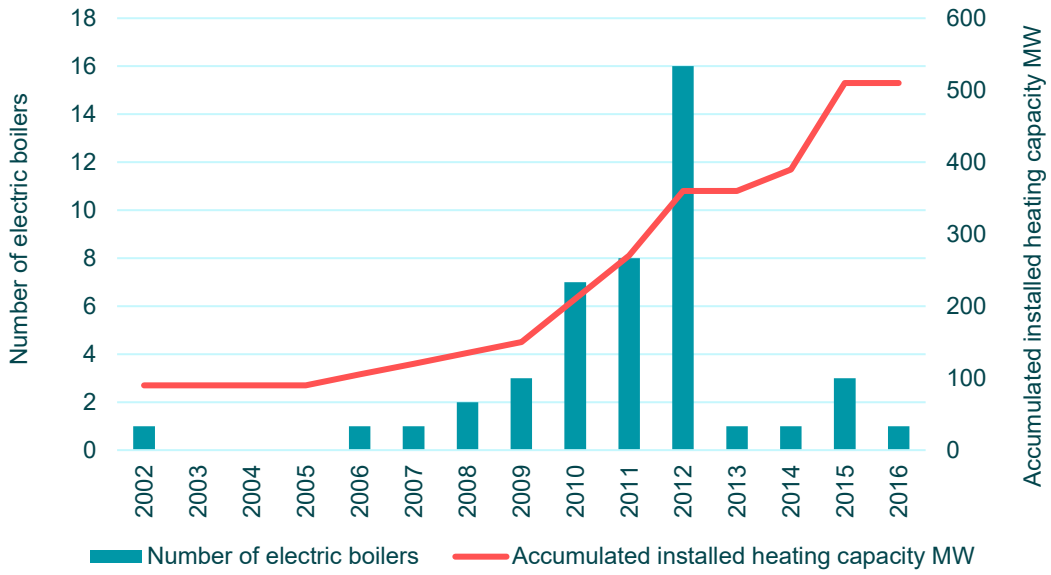

Figure 16 New electric boilers and accumulated installed capacity (DEA, 2016).

Takeaways from 2005-2009

In the period 2005-2009, the approximately 20% share of VRE required only relatively little investment in flexibility. Thermal power plants were made to provide the main source of flexibility by incentivising operational procedure which was in close response to the fluctuating production of VRE sources while filling the gaps in hours of low wind and providing flexibility services on the ancillary services market.

The improvement in flexible generation was found in increased ramping rates and expansion of operational boundaries. This change was encouraged through market and regulatory initiatives where flexibility was incentivised through increased profits for power plant operators. Most significantly, the low electricity prices changed the CHP plants from providing baseload electricity to being a key source of flexibility.

4. 2010-2015: Increased use of CHP plants as a flexibility source and large investments in interconnectors accompanied by an integrated day-ahead market across Europe – 22-44% VRE share

Messages from this period

- Integration of larger shares of VRE required thermal power plant to make further investment in flexibility measures.
- These solutions include electric boilers and complete turbine bypass.
- The cross-border trade via interconnectors, which had become large relative to peak consumption, came to play a central role in cost-effectively balancing intermittent wind production.
- The emergence of a harmonised day-ahead market spanning most of Europe promoted cross-border trade thereby giving access to a wider balancing area.

Flexible thermal power plants and sector coupling: Larger share of VRE incentivises thermal power plant to further flexibilise

From 2010, the continued expansion of renewable capacity required the dispatchable thermal power plants to operate even more flexibly in response to the fluctuating production profile of VRE. This therefore further reduced the runtime of conventional, dispatchable generation, including CHP plants. This posed challenges to secure an acceptable revenue for generators who as a result had to implement even more substantial flexibility measures. Hence, while the deployment of CHP plants initially was motivated by efficiency improvements, between 2005 and 2015 the sector coupling was further explored as a flexibility solution. This also included decoupling heat and power output by for example storing heat as shown in Figure 17.

During this period, power plant flexibility improvements started to require larger investments and hardware retrofitting. Reducing the start and stop time and the associated costs became increasingly important since it often became more economical to cycle a plant in intervals rather than running at minimum load for longer periods. With a lower share of VRE, the short duration and low frequency of electricity prices below the marginal cost of thermal power plants meant that it was still economically viable for thermal power plants to run, as periods with economical deficit would quickly be followed by periods with revenue that could recover the losses and create and overall profit. However, the increasing share of intermittent VRE generation resulted

in a higher frequency of periods with electricity prices below the marginal cost of a thermal power plant, thus the pattern of operation in intervals became less profitable as losses no longer could be recovered.

General operational flexibility improvements	CHP unit solutions
Expand the operational boundaries	Lower minimum load
	Overload ability
	Turbine bypass
Decoupling of heat and electricity or heat: variable heat-to-power ratio	Electric boilers and heat pumps
Decoupling of heat and electricity or heat: displacement of thermal load and production	Heat storage
More flexible operation within operational boundaries	Increasing ramping rates and fast output regulation
	Faster and/or cheaper start/stop

Figure 17 Implemented flexibility improvements in thermal power plants by owners (DEA, 2015).

The period after 2010 therefore saw large investments in flexibility measures as summarised in Figure 17 and described below:

- **Complete or partial turbine bypass.** In this system, the CHP plant can bypass either every power-generating turbines or just the high-pressure turbine, allowing for complete or highly reduced power generation while retaining the boiler pressure. The steam goes directly to a heat exchanger, providing district heating. The turbines can at any time be recoupled, saving most of the plant's ramping time (see text box: "Expanding operational area: Partial or full turbine bypass").
- **Heat production using electric boilers or heat pumps.** This solution converts electrical power into heat thus enabling operators to tap into balancing markets and take advantage of the increased number of hours with low electricity prices while still meeting heat demand (Figure 18).
- **Additional water-based heat storage used to shift power production.** Heat storage offers short term flexibility in a simple, relatively efficient and low-cost way. However, they cannot operate for longer durations as this would require larger investments making alternatives such as electric boilers a better solution. This had been already been partly implemented as a source of flexibility in previous years and was therefore considered merely a continuation of earlier practices.

During this period, and still today, in order to choose the right flexibility solution, the measures chosen were based on a long term (10-20 years) evaluation of expected load profiles of the power plant, market structures and the resulting economic incentives. The individual optimisation of the power plant is then an iterative, stepwise approach that involves determining bottlenecks for flexibility through data analyses and operator interviews and defining achievable flexibility levels. The right solution, therefore, has to be carefully made according to system requirements.

Decoupling heat and electricity: Heat pumps and electric boilers

Both electric boiler and heat pumps can provide fast down-regulation services in the intraday and balancing markets as they can turn electricity into heat by demand.

Heat pumps have high efficiency; in some cases, they can supply up to 4 times the kWh of heat compared to the kWh of electricity used. However, heat pump systems involve significant investments and have flexibility limitations due to the pressure needed to be built in the compressor. High-COP heat pumps also need an adequate heat source, which requires additional investments such as solar heaters and heat storages. An alternative is electric boilers. Compared to heat pumps they have lower efficiencies but also come with much lower investment costs and very high regulating capability.

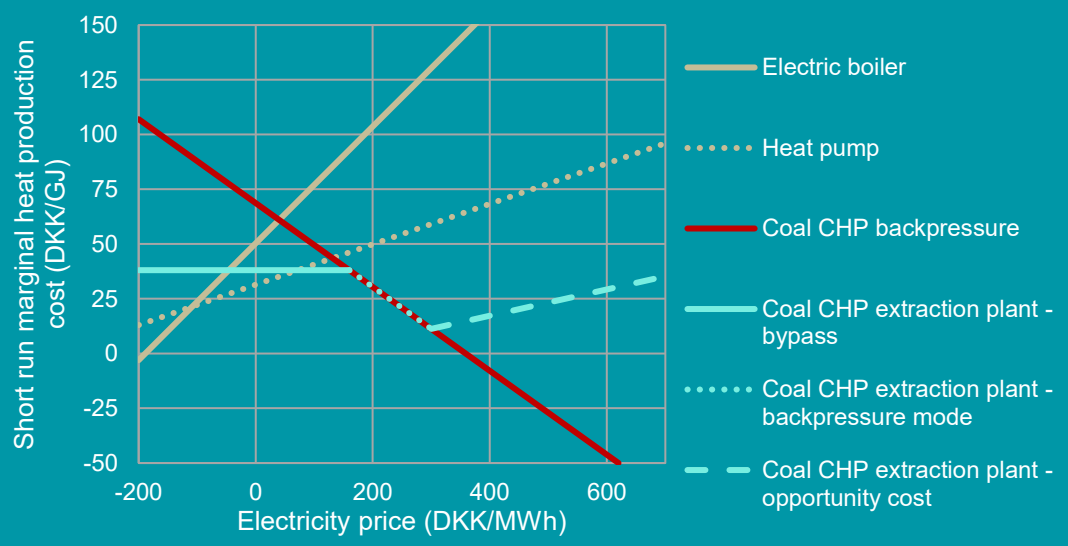

Figure 18 Illustrative example of short-run marginal heat production for different plants depending on electricity price.

The choice of technology depends on system requirements, for example the electricity price relative to heating price as illustrated in Figure 18. In the Danish power system, heating prices are regulated and stable while electricity prices change considerably.

If electricity prices are negative, then electric boilers are the overall best solution since the plant will generate revenue by consuming electricity. If electricity prices are slightly higher, but still negative, then heat pumps are a better choice due to their higher efficiency which then compensates for higher investment cost compared to electric boilers. Additionally, the high capital cost of heat pumps means heat pumps might be considered in systems which require many operating hours, while electric boilers are chosen in systems with fewer operating hours. In the Danish case, due to their lower capital cost, electric boilers have often been chosen over heat pumps. When electricity prices are around zero, there is no economic value in consuming electricity and CHP backpressure becomes the overall best solution. In the case of a CHP extraction plant, having the option to downregulate heat production even further to increase power output makes it the best choice at high electricity prices.

Hence, the choice of flexibility solution of a CHP plant highly depends on the expected electricity price. A power system with low electricity prices often indicates high generation from low marginal cost generators such as VRE, while high prices indicate a need for additional power generation. The exact crossing points are only for illustrative purposes while actual numbers will depend on prices of fuel and emissions, taxes and subsidies.

Expanding operational area: Partial or full turbine bypass

Turbine bypass expands the operational boundaries as shown in Figure 19 to for example up- or down-regulate power while meeting heat demand. This way, it serves as a flexibility measure by freely being able to shift the power-to-heat ratio at high overall efficiencies thereby fully benefitting from the coupling of heat and power.

If a high heat output is desired without power generation, for example, if electricity prices are low, the turbine can operate in full bypass mode. This is the yellow area. At the other end are periods where a high electricity output, or rather a high power-to-heat ratio, is desired which makes operating in the normal load optimal. If both heat demand and electricity prices are low, the low load area is the most economical.

This way, it is economically viable to install bypass or encourage new plants to be designed with partial or full bypass, as their output can be optimised to follow both heat and electricity demand closely to maximise profit. This is especially beneficial if the power market is characterised by long periods with low electricity prices or a high frequency of very low prices.

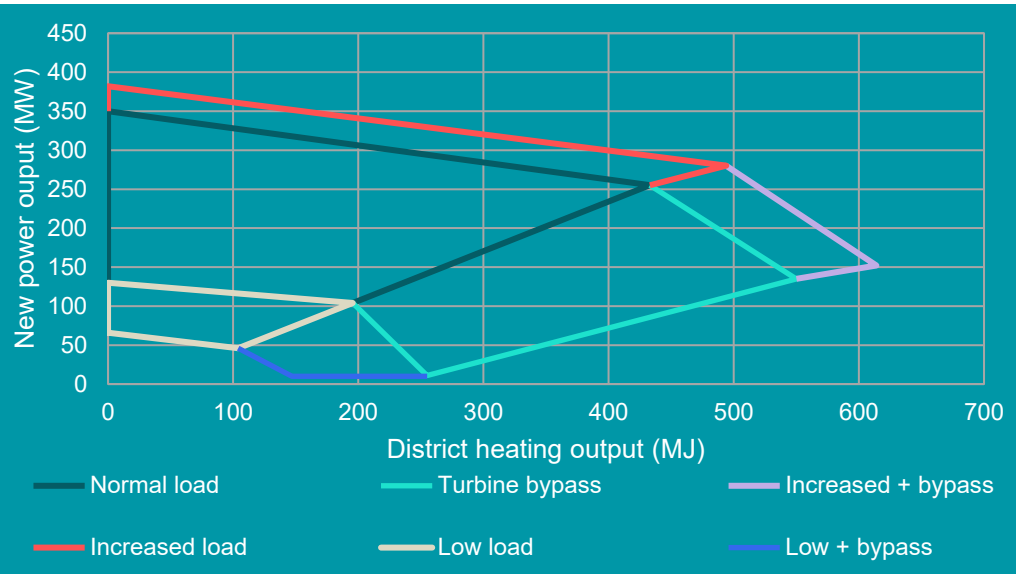

Figure 19 Operational boundaries for a CHP plant with various flexible measures

Utilisation of interconnectors: Increased use to balance wind power production

As the annual share of VRE and hours with high shares of VRE grew, it was necessary to increase flexibility in the power system and not only in the power plants, which as mentioned by this point focused more on heat generation. By this point in time, the major sources of flexibility were the thermal power plants and interconnectors and in general, the system was relatively conventional without any real flexibility from the demand side. Despite the measures already taken, the Danish power system transition had only just begun illustrated by the fact that the two asynchronous power grids in Denmark were not interconnected until the commissioning of the Great Belt Link in 2010.

As a consequence of the needed flexibility, the interconnector capacity grew rapidly throughout the 2000s. As shown in Figure 3 in Chapter 1, by this period, the interconnector capacity was almost equivalent to the VRE capacity as well as peak consumption. A large motivation for this expansion of capacity, was Denmark becoming a transmission link between neighbouring countries due to its geographical location between areas of hydropower in the Nordic and thermal power plants in Europe; the high interconnector capacity allowing for large amounts of energy to flow through the Danish grid without necessarily consuming it or benefitting from selling surplus VRE generation to neighbouring areas with lower shares of VRE penetration. This also made for a business case for the Danish government and power producers.

From a system perspective, part of the motivation for further increasing interconnector capacity to neighbouring countries was to enlarge the balancing area for especially wind power production. The investment required to reinforce and construct new interconnector capacity is expected to provide cost-competitive flexibility services in the long term. Even though other countries are starting to introduce larger shares of non-dispatchable power into their power mix, the cross-broader exchange continues to provide access to large balancing resources. This is due to a geographically dispersed fleet of wind turbines significantly reducing the likelihood of the entire fleet operating at high or low output relative to nominal. This effectively smoothens out the collective production curve as shown in Figure 20 as a large interconnected area, such as Europe, allows for the transfer of high wind output to areas with low wind output as long as the locations are located far enough to have uncorrelated wind pattern. This is very beneficial for a power system with high shares of VRE as it reduces the need for flexibility measures and reduces the cost of VRE integration.

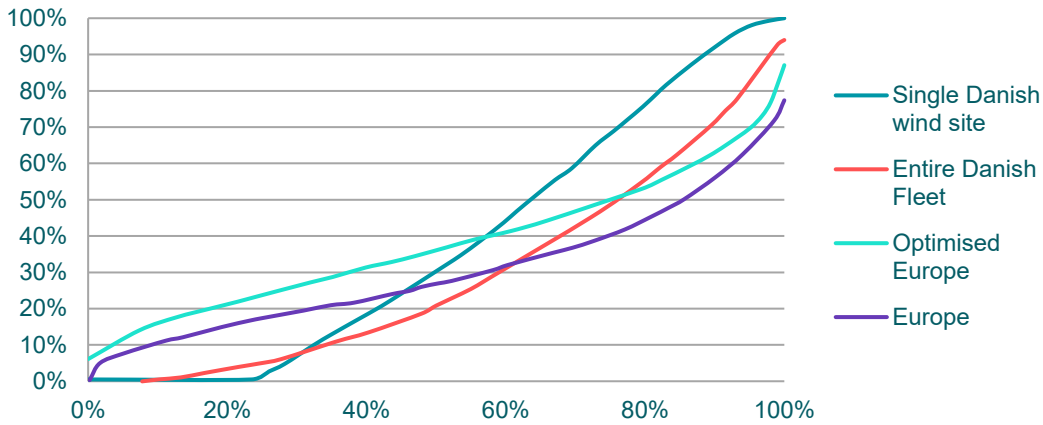

Figure 20 The smoothing effect of larger balancing areas (Energinet, 2015)

Interconnection with neighbouring countries is considered a key flexibility solution enabling the Danish power sector to successfully integrate 45% of RE share as achieved in 2014 at low cost.

A way to illustrate the importance of adequate interconnector capacity is the correlation between hourly change in power exchange and wind production in especially the Western part of Denmark.

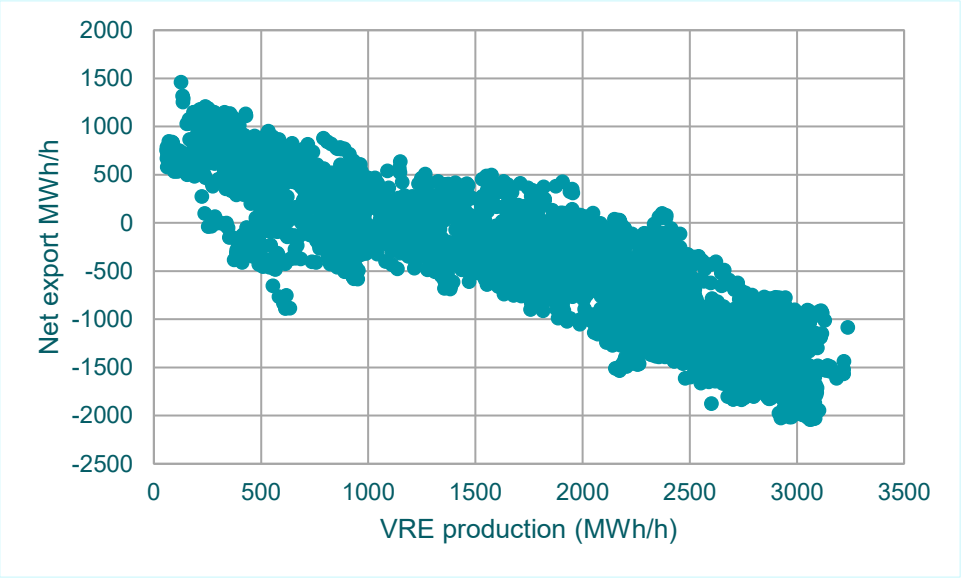

Figure 21 Correlation between export and wind power production in Denmark, December 2015. Data (Energy data service)

As shown in Figure 21, roughly 80% of the hourly variation in export can be attributed to variation in wind generation. This means that the market decides to export larger amounts of power during time with high wind production and import power when the wind production is low. It should be noted that this does not necessarily mean that the Danish power system would not have been able to do the balancing itself but rather that the market optimisation has found this to be the most cost-efficient balancing. Therefore, a combination of appropriate interconnector capacity and a well-functioning market has been shown to offer a cost-efficient flexibility solution.

This way interconnectors have been beneficial to the entire Nordic system by reducing the costs of imbalances induced by larger shares of VRE (CEM, 2018). Developing suitable trading mechanisms and increasing interconnector capacity continued to be focus areas and therefore continued to be improved in the following period as will be described in the next chapter.

Flexible operation of interconnectors

Interconnectors transmit power across large geographical areas, which typically have variable generation particularly those with high shares of weather dependent power generation. For example, weather fronts move slowly across land areas, meaning wind speeds are high in some areas and low in others.

Consequently, being able to move surplus VRE to other areas is important for the integration of VRE instead of curtailing it. These characteristics are illustrated in Figure 22, which is a week for power generation and demand in Western Denmark in 2014 that illustrates the variations

the system experiences.

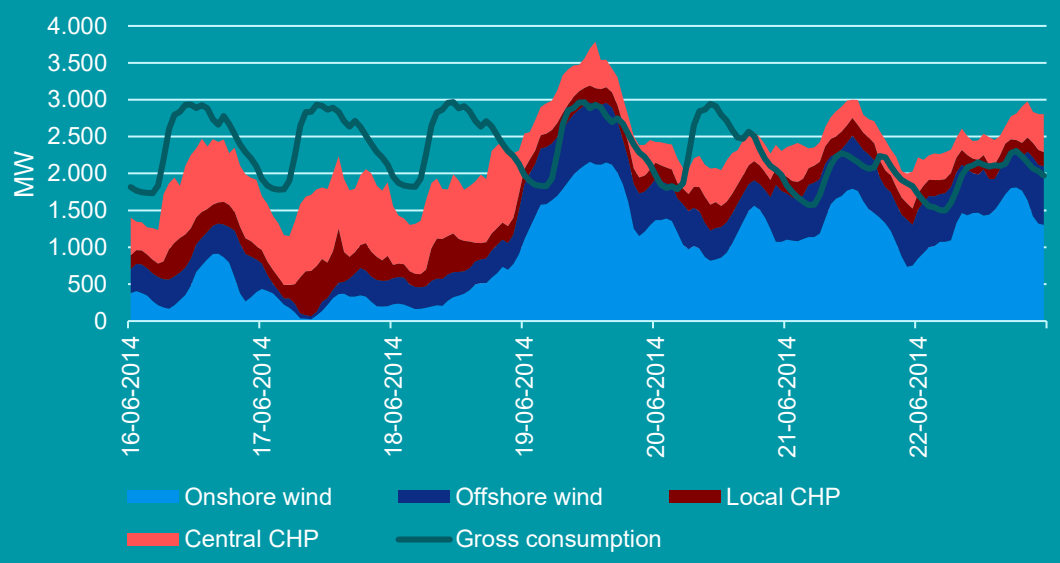

Figure 22 *Power generation in Western Denmark divided by types and demand. Export of power occurs when the total power generation is above the power demand, and in hours were total generation is lower than consumption imports cover the remaining power consumption.*

In Denmark, the flow of the interconnectors is determined by the markets before the operation hour. Within the operation hour, the TSO may have to purchase up or downregulation to balance out imbalances. The up or downregulation may be located on the other side of an interconnector, meaning that the flow can be varied during the operation hour. Naturally, this is only possible when the interconnector capacity is not fully utilised.

Since the market determines the flow on the interconnectors, the flow typically changes from hour to hour and often also direction, which is illustrated by the hourly flow on the oldest HVDC interconnector in the Danish system in 2020 in Figure 23. The figure shows the flow of the Konti-skan connection between Western Denmark and South Western Sweden of a week in 2014. The Konti-skan connection was commissioned in 1965 and later updated with another pole to double capacity to 740 MW. Over the years the link has had components updated and optimised, but the technology behind is the same as in 1965. Notice, that flow and direction change often and that there is only a price difference when the capacity is fully utilised.

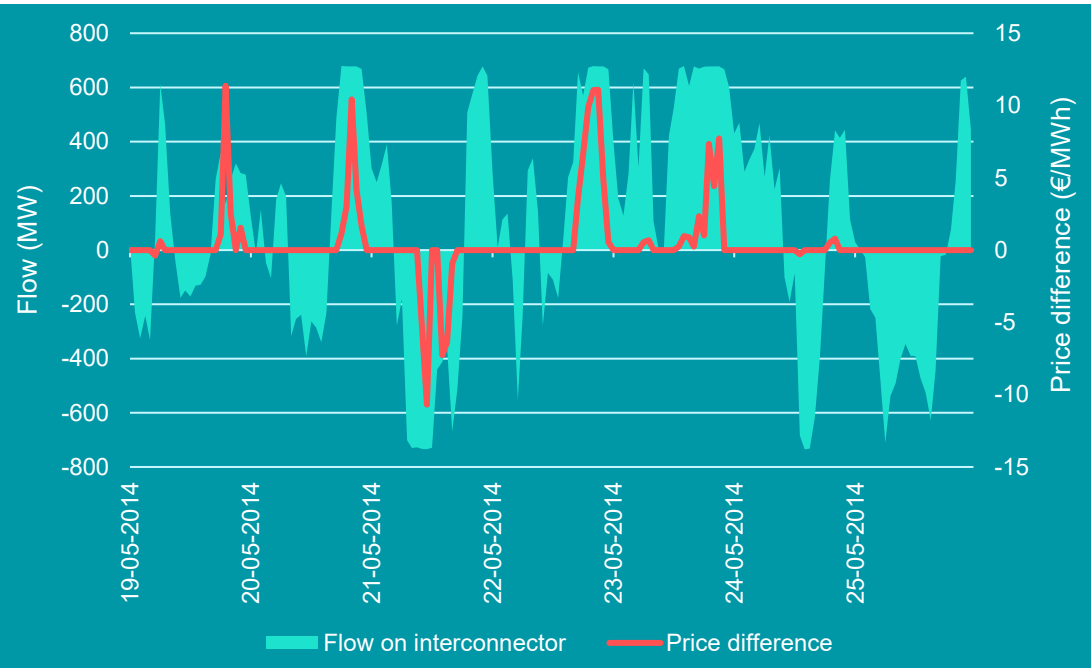

Figure 23 *Flow on the 740 MW Konti-skan connection between Western Denmark and South Western Sweden and price difference between the two price areas through a week in 2014.*

Emergence of a harmonised day-ahead market spanning most of Europe

While expanding the interconnector capacity provided a large balancing potential, this potential could only be realised if supported by well-functioning cross-border trade regulation aimed at reducing practical and technical exchange barriers. Through the 2000s, European countries coupled their electricity markets together and by 2015, the electricity market spanned across 10 European countries (Nord Pool, 2021) as shown in Figure 24. However, the first year of operation brought challenges as European member states had different ways of implementing the market.

In brief, the differences in regulatory frameworks between the countries meant that the market was hindered in performing efficiently and therefore the full potential of the interconnector capacity to provide flexibility was limited. Consequently, an important prerequisite for the market coupling was to have an increased level of harmonisation between European markets to allow for barrier-free exchange (DEA, 2020).

To address this, the European Commission began a process of harmonising the regulatory framework on the integration of markets across these European countries (DEA, 2020). A key piece of legislation in the harmonisation process was the “Capacity Allocation and Congestion

Management Guideline" established in 2015 by the European Commission (EU, 2021), which provided a common framework for a more effective cross-barrier exchange. The CACM Guideline was developed by the European Network of Transmission System Operators for Electricity (ENTSO-E), including Danish TSO Energinet, in a successful cross-border collaboration. Importantly, it defined the designation criteria and tasks of the Nominated Electricity Market Operators (NEMOs), which are the organisations mandated to operate the day-ahead and intraday markets. It also provided capacity calculation methodologies to determine the volumes of capacity simultaneously available in the day-ahead market between bidding zones, criteria to assess efficiency, and a review process for defining bidding zones.

In Europe, there are often large geographical distances between sites for VRE sources and the load centres, such as major cities. This is another benefit of harmonising the DAM as the best sites for VRE may be located in certain countries, while the major load centres can be located in other countries. Distances between sites of VRE is not a Danish or Nordic matter but should be seen in a European context.

By 2015, the intra-day market had yet to be harmonised and market coupled across all European countries and this was therefore the focus in the following years as will be presented in the next chapter.

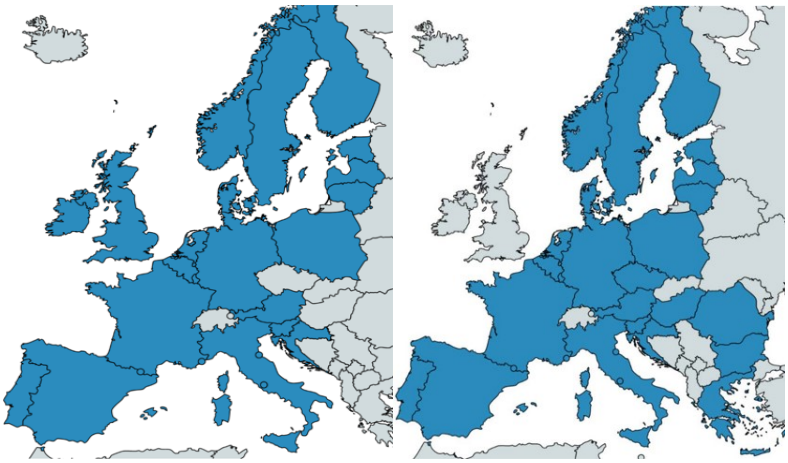

Figure 24 Coupling of day-ahead (left) and intra-day (right) markets across Europe (DEA, 2020)

Implicit auctions of interconnector capacity in the day ahead marked

Since 2010, implicit auction has been deployed in Europe and had until then only been applied in the Nordics. Implicit auction is the key thing that defines the single European DAM. By using implicit auctions, also known as market coupling, flows between bidding zones (or bidding areas) are calculated simultaneously with the calculation of equilibrium marginal prices and quantities in

the market. It implies that both the generation of power and the flow on the interconnectors are optimised at the same time. Market coupling is based on the idea that a bidding area with a lower price of electricity will continue to sell electricity into a higher priced bidding area across an interconnector until the prices between them equalize or the interconnector capacity is fully utilised. Figure 25 illustrates this function for a market with 2 areas.

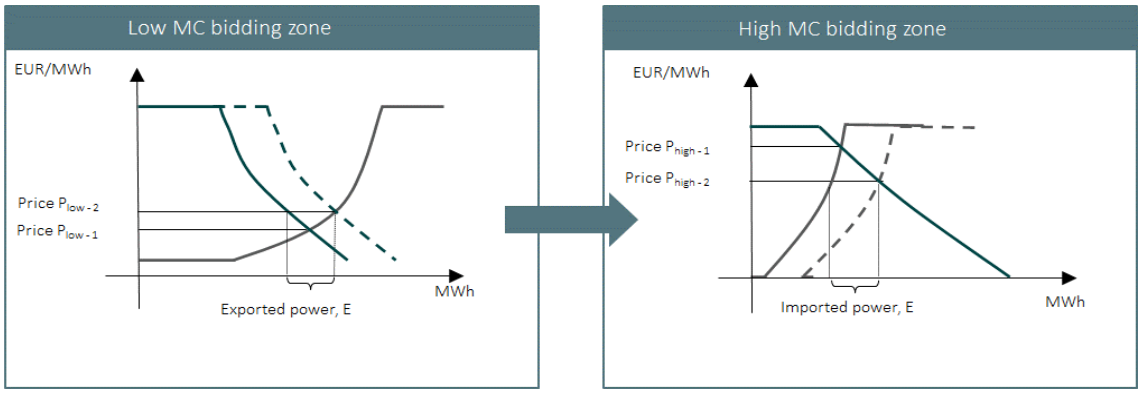

Figure 25 Illustration of market coupling between bidding areas with low and high marginal cost (MC), respectively. Source: Energinet.

The deployment of market coupling has occurred alongside the development of cross-border interconnection. When bidding areas are coupled via one or more interconnectors their respective purchase and sale bids are matched regardless of which area they originated from.

Reflecting supply and demand fundamentals, power flows to areas with higher prices, and, when there are no transmission constraints, the markets will converge entirely and the electricity prices will be identical. Trading in coupled areas is at the heart of the internal energy market and pan-European electricity project. Interconnector flows are based on bids from the coupled areas, so the auctioning of transmission capacity is included (implicitly) in the auctions of electricity in those areas. By comparison, in explicit auctions, the transmission capacity on an interconnector is auctioned to the market separately and independently from the marketplaces where electricity is auctioned.

Market coupling in Europe has secured that electricity is exchanged very efficiently from low to high-cost areas to achieve an efficient integration of VRE. As a result in areas during periods of high VRE, the electricity is moved from the area of high VRE/low price to areas of low VRE/high prices. A rule of thumb is that when the weather is windy, sunny or wet, electricity prices are low due to the low marginal cost of wind, solar or hydroelectricity and when it is calm, overcast and dry, prices are high. This has in Europe not always been the case, in fact until this period explicit auctions were applied on many bidding areas' borders. Using explicit auctions means that access to a particular interconnector between two bidding areas was auctioned before the electricity prices were known and therefore apart from the price calculation in those areas. The

consequence was that electricity was moved inefficiently, meaning in the wrong direction, that being from areas with a high price to areas with low prices in many hours as illustrated in Figure 26 for the bidding area border of Denmark and Germany in 2006. In an efficient market (with a radial grid) flows will always move towards high-cost area, however, for 25% of the hours in 2006, this was not the case on the Danish-Germany electricity border. This has been solved by moving to implicit auctions.

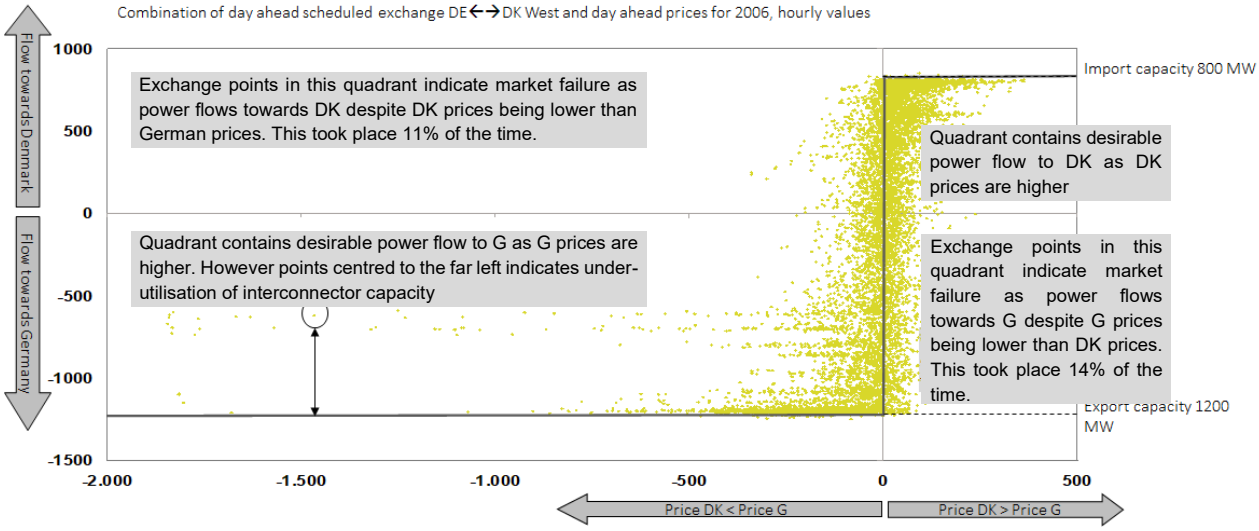

Figure 26 Illustration of combinations of day-ahead electricity prices in Denmark and Germany and directions of flows between the two countries under explicit auctions.

Takeaways from 2010-2015

The period of 2010-2015 saw increased penetration of VRE resulting in Denmark in 2014 being the first power system to reach a 45% VRE share. Since CHP plants participated in the power market and had to compete with the low marginal cost of especially wind, they were incentivised to make large investments in flexibility measures. Important technical solutions included electric boilers and turbine bypass which were used to offset heat and electricity production while still making use of sector coupling as a flexibility measure.

Another important trend was the continued investment in interconnectors to neighbouring countries and the extensive use of these for example by exporting electricity during periods with high wind output and accessing cheap hydropower to balance power when needed. This was also central for other European countries and hence the optimisation of cross-border trade was therefore a focus point these years. By 2015, the Nordic intraday market had been coupled with 10 other European markets. A prerequisite for this coupling was the harmonisation of market implementation across the European member states, in which a key piece of legislation was the "Capacity Allocation and Congestion Management Guideline" established in 2015.

5. 2016-2020: New flexibility measures focus on consumer participation in electricity markets, improved forecasting that allows for proactive balancing, and wind turbines as provider of balancing services – 50% of VRE reached.

Messages from this period

- The Danish power system was running several hours, in some cases up to a week, without online central thermal power plants since under normal operation the system stability could be maintained without them.
- Demand side flexibility began to be promoted through several incentives to actively participate in the balancing of the system. However, progress was slow.
- Improved forecasting let wind participate in balancing markets for the first time
- A single integrated intraday-market promotes competition and increase liquidity at the benefit of VRE to self-balance deviations in production

During 2016-2020, the planning and implementation of additional flexibility addressed not only the level of VRE at that time but also aimed to prepare the system for higher shares of VRE in the future. The expected future need was guided by the legally binding target set in 2019 to reduce greenhouse gases by 70% by 2030 (relative to 1990 level) and to reach net-zero emissions by 2050 (Danish Ministry of Climate, Energy and Utilities, 2019).

Until this point, the thermal power plants had played a key role in delivering flexibility and critical system services to maintain stable system operation. However, while they continued to play an important role, their role in a future power system began to be questioned, and alternative sources of flexibility explored. As will be presented in the following, these included the flexibility potential of the demand side and improved forecasting to let wind power participate in the balancing market. Additionally, Denmark became further connected with other European markets as a cross border intraday market (XBID) was launched in June 2018.

Running the Danish power system without thermal power plants

In 2017, the Danish TSO Energinet performed a study on the needs for properties required to maintain power system stability, which found that the existing power system with all relevant grid components in operation was enough to counter most faults. In short, this means that in most cases it was not necessary to have spinning power plants running to provide properties required to maintain power system stability in the Danish power system.

According to the report, the important grid components for maintaining power system stability were, and still are today, the synchronous condensers, which historically have provided stability to the older HVDC interconnectors, the Voltage Source Converter (VSC) which are part of one of the newer HVDC interconnectors, and the AC grid connections to neighbouring countries' power grids. As a result, there was very little must-run power generation, meaning the market dispatch had few or no boundaries in determining the optimal generation mix, which could reduce curtailment.

Synchronous condensers

In the initial days of power systems, synchronous condensers helped maintain adequate voltage levels in collaboration with the power plant generators. Technical achievements in power electronics lead to the phase out of synchronous condensers during the 1960s as they had higher losses, but power electronics could not provide the necessary reactive regulation in case of short circuits.

A synchronous condenser is simply put a generator, much like one in a power station, and has therefore the same properties making it able to stabilise voltage and support the power grid in case of faults. Instead of being driven by a power plant, it is run by the power grid

Historically, the Danish HVDC interconnectors have been based on Line-Commutated Converters (LCC). LCC requires a high level of short circuit power to be in stable operation. As a consequence, in Denmark, these types of interconnectors have been supported by synchronous condensers to ensure stable operation and transfer of active power. Beyond supporting the LCC HVDC interconnectors with short-circuit power and regulation abilities, the entire grid also benefits, meaning that applied relay protection works as intended (Yang, 2016).

Energinet concluded in the report that only in case of grid deficiencies such as maintenance of certain components there may be a need for having thermal power plants in operation to provide properties required to maintain power system stability. In fact, since the publication of the report Energinet has operated the power system without ordering thermal power plants in operation. As a result, the market dispatch meant that the period 2017-2020 had quite a few periods without any Danish central thermal power plants in operation.

2015 was the first time neither of the two Danish power systems were operated without central power plants, but only for a day. In 2017, Western Denmark managed 985 hours in total without central power plants where the longest consecutive period was one week (Wittrup, 2018).

Similarly, Eastern Denmark had no power generation from central power plants for a total of 1181 hours in 2020 and for 2223 hours the power generation from central power plants were below 20 MW (Energinet, 2021). Due to this drop in demand for central power plants and generally decreasing operating hours, there was little to no new investments in thermal power generation in Denmark in this period (as illustrated in Figure 3). The only mentionable investment was the conversion from coal to biomass and from extraction to backpressure plants to supply more heat to district heating systems.

VSC HVDC

In later years, the traditional LCC HVDC interconnectors based on thyristor technology have seen competition from another technology in the HVDC market based on transistor technology. This technology is VSC and it has the same restrictive requirements to short-circuit power, which is why its operation is more stable in situations with grid faults in comparison to LCC's.

Besides being able to transfer active power from one area to another, the VSC is also able to deliver other services such as dynamic voltage regulation, frequency regulation and blackstart. As a consequence, HVDC's are no longer causing instability issues, but providing voltage regulation through thyristor-based voltage-source converters (Jensen, 2017).

Nevertheless, there were certain areas of the power grid which required additional support in case of a grid fault. These were particularly in areas with older wind farms or lower grid adequacy. Additionally, central power generation was needed during particular maintenance or expansion of the power grid where it was necessary to take components offline to connect new components. These constraints still apply to the current power system. Therefore, it should not be understood that central thermal power plants are already obsolete in the Danish power system. Firstly, they may be required to provide stability in situations where the grid is not fully available and secondly, they are still the main providers of heating. However, the shift to power-to-heat is underway meaning the business model is less and less attractive.

Demand-side flexibility: A consumer-friendly retail market

Transition from passive to active consumers

Previously, the perception of the power system had been, that supply should meet demand. As a result, regulation had primarily promoted large central power plants while awareness of consumer involvement and their role in providing flexibility remained low. This meant owners of new technologies were subject to high entry requirements and hence the system failed to include these

new actors in the electricity market. As a result, heat pump owners were private actors primarily focusing on their heating demand and electric vehicles owners only focused on mobility unaware of how their demand affected the state of the power system. Therefore, during this period new market structures were considered to avoid situations where regulation would impose barriers on new technologies and prevent them from contributing to system flexibility.

Datahub

Datahub is a central IT system that is owned by the Danish TSO. It gathers billions of data about consumers, consumption and prices and handles all communication between participants on the retail market. Participants acting on the retail market are TSO, DSOs, suppliers, and customers. The electricity market is divided into a wholesale market and a retail market. The wholesale market is where the bulk of electricity is exchanged at a European market between balance responsible parties. On the other hand, the retail market is where the supplier sells electricity to the customer. Datahub was first implemented in 2013 and with it came standardised processes for all participants. That reduced complexity and created better competition and improved terms and conditions for the customers. The introduction of Datahub also laid the necessary technical prerequisites to implement a brand new supplier-centric market design, where the supplier is responsible for providing the customer with a single bill with three components 1) energy and supply 2) transmission and distribution 3) taxes, levies, fees and charges.

While this regulation is still under revision and impacts remains to be seen, important steps were made in this period. These aimed to introduce proper market price formation to stimulate appropriate investments and performances. The aim was to expose the consumers to time-varying price signals and time-of-use to make demand-side flexibility an economic choice between the value of consumption and the value of non-consumption or postponement of consumption. The first focus was on investments in a digital communication infrastructure with vast amounts of real-time measurements and easy access to data for relevant actors. Two important turning points in this digitalisation of the power system has been the implementation of Datahub and the roll-out of smart meters which are described in this section's two textboxes.

Smart meters

In Denmark, the DSOs owns the meters and has responsibility for measurement of production and consumption in their respective area. This ensures real-time knowledge of their system and allows for an efficient distribution of electricity. Through Datahub they provide the suppliers

with consumption for each metering point that allows the supplier to settle with the customer through a single bill.

As of December 2020, the complete roll-out of smart meters has made the hourly settlement of every single customer possible. This has increased the amount of data even further and lets the suppliers provide their customers with detailed information and visualisation of their consumption, to bring awareness and thus better decision-making. The vast amount of data also tells a detailed story about the Danes' energy consumption which can be used to improve planning of infrastructure investments and activation or promotion of demand-side flexibility in certain areas.

The roll-out of smart meters has fostered new market products like hourly settlement and time of use tariffs. A contract for hourly settlement incentivises active consumers in balancing the system by increasing demand when the prices are low. While the time-of-use tariffs penalises inactive consumers by increasing transmission tariffs in hours with peak demand. This helps balance the system by reducing peak demand and postponing consumption to hours with less loading on the system.

Aggregation

In January 2020 a new actor called an aggregator was introduced in the Danish regulation. The purpose of the aggregator was, and still is, to sell system services from a portfolio of smaller units by regulating the consumption remotely. The aggregator reduces transaction cost for each individual unit and enables them to participate in markets with high entry requirements. Just as the aggregators for small RE production plants, these use price signals to individually control individual units. Using the "many small streams make a big river" principle, these aggregators can come to control large capacities. This provides small plants like heat pumps and electric vehicles easy access to the markets and enables them to sell flexibility services to the DSO or ancillary services to the TSO through an aggregator. As this is a new initiative, the effect has been limited so far. However, it is expected that it will contribute to a more economic transition to renewable energy sources and efficient operation of the transmission and distribution systems.

These initiatives are only considered the first steps in tapping into the vast flexibility potential of demand-side flexibility.

Forecasting and scheduling system: Proactive balancing and accurate forecasts ensure wind turbines can balance the power grid.

Energinet has been doing forecasting of wind since 2000, however as the forecast methods have continuously been updated, a clear overview of the developments for each period is difficult to provide. Nevertheless, on the whole, the development of forecasts has accelerated over the last 10 years and the key was gaining experience within developing forecasts and applying them in power system operation.

To that end, Energinet initially performed its own forecasts of wind generation to gain experience with producing forecasts and operating the system with the uncertainties between forecasts and reality, but in later years Energinet shifted towards using commercial forecasts and today Energinet mostly relies on commercial forecasts and does quality assurance with its own previously developed tools of the commercial forecasts. Energinet is continuing to enhance its forecasting capabilities based on its balancing strategy. A key learning point from Energinet is that the forecasting system should be dependent on how the system operator wishes to balance the system and that there is not a one-fits-all solution.

Denmark had great success with proactive balancing based on continuously updated forecasts.

Having flexible thermal power plants and interconnectors is a necessity to react to fluctuations in VRE generation, however, they alone cannot react quickly enough to variations in VRE generation, which is why forecasting of VRE generation is hugely important.

Power production prognosis from renewable resources, in particular wind and solar, is a challenging task, since good forecasts need to be based on a large number of meteorological forecasts such as wind speed, temperature, precipitation, humidity and cloud cover. As a consequence, Energinet has continuously updated its wind forecasting tools in order to ensure the optimal dispatch of thermal power plants and reserve requirements.

Due to the uncertainties associated with the stochastic nature of the weather, the margin of error in forecasting often increases with a longer forecasting horizon, limited data availability and poor data quality, which can distort the optimal dispatch, balancing and reserve requirements.

As a consequence, the Danish TSO uses multiple internal and external wind forecasting tools. In all, they cover both the short term horizon used for operating the grid in real-time as well as the day(s) ahead horizon used for planning purposes. A combination of different meteorological forecasts is paramount as different forecasts imply different expected wind speed, which can lead

to consistent challenges in terms of power production.

In addition, Energinet has integrated online measurements from wind farms in system operation procedures to compare the forecasts for the coming few minutes with the actual generation. In this way, it is possible to see whether the generation will likely be as expected and react in advance by ordering up- or down-regulation where relevant.

In reality, this so-called *proactive balancing approach* is a philosophy that Denmark has had great results applying. The thought behind this is that the TSO uses the forecast to predict the imbalance in the system before it appears, allowing the TSO to handle any imbalance with slower/cheaper reserves compared for instance with reactive balancing, where the TSO reacts to the actual imbalance (DEA, 2020).

The strength of the Danish forecasting approach relies on (DEA, 2020):

- Collection of historical data on VRE generation based on geographical location used for validation and calibration of new forecasts.
- Collection of weather forecast parameters (e.g. global radiation, wind speed, wind direction) to improve the weather forecasting tools
- Development of weather forecasts based on geographical location in order to cover the geographical distribution of the (future) VRE generation
- Trained and experienced staff, able to understand and deal with the challenges of running a power system with variable renewable generation and using the relevant information (forecasts, schedules, measurements, etc.)
- Development of state-of-art forecast models and operational planning tools which enable a high forecast accuracy of VRE generation, demand and interconnectors.

Wind delivers ancillary services for the first time

Some of the concerns about a power system built on VRE sources relate to the ancillary services and whether VRE sources can provide ancillary services. An issue is, whether VRE sources can provide any type of reserves to the power system balancing. In a bid to understand this further, Energinet and Energi Danmark (an energy trading company) investigated in 2020 whether wind turbines can provide up-regulation.

The conclusion was that due to the forecasting precision in wind turbines generation, wind

turbines may from now on participate in the market for balancing services alongside conventional thermal power plants for slower balancing services, called mFFR. Naturally, conventional power plants will still be required for some time to deliver balancing services in times when the wind generation is fully utilised. As a result of the study, not only may wind turbines participate in the mFFR market, but Energinet will continue to investigate which ancillary services wind turbines can provide in the future (Energinet, 2020).

A major component behind wind turbines being able to provide ancillary services is that technical requirements for wind turbines have been strengthened over the past decades. In general, the earliest wind turbines imposed challenges on the power system, which were evident during faults in the system, where wind turbines were allowed to disconnect from the system to protect their wind farm and not the power system.

Today, the network codes that span all of Europe help ensure that power generating plants do not impose greater challenges on the system. Specifically, the RfG network code has responded with technical improvements of wind turbines including so-called *fault ride-through* capabilities and requirements for reactive power. In brief, this means that the most advanced wind farms are able to actively take part in voltage control instead of causing further issues (DEA, 2016; Energinet, 2018).

Utilisation of interconnectors:

XBID: Improved ability for VRE to self-balance intraday deviations across Europe

As presented in previous sections, the intraday market lets participants trade bilaterally, up until an hour before operation to give renewables a chance to trade with active consumers and other power producers close to real-time. In this period, the trading on the intra-day market continued to be a cornerstone in the operation of the power system; the traded volume increasing for each year.

In order to promote trading across borders closer to real-time, the European cross border intraday market (XBID) was launched in June 2018. Initially, it covered 15 countries and in November 2019 seven more countries joined. A large number of buyers and sellers promotes competition and increases the liquidity of the market, which also means that a single integrated intraday market makes intraday trading more efficient across Europe. Making it easier to share energy across borders benefits the participants, as unexpected changes in consumption or outages can be remedied by others.

XBID allowed Danish wind power producers to trade imbalances with power producers in Spain up until an hour before delivery which drastically improved renewables ability to balance their

production with other market participants.

A similar development is expected to be seen in the balancing market. Where two new market platforms are on the horizon. One platform for the international coordination of automated frequency restoration and stable system operation (PICASSO) and one platform called the manual activated reserves initiative (MARI). Both markets are expected to promote competition and increase liquidity and thus improved utilisation of interconnectors and power system flexibility as has been the case with the single integrated intraday market.

Rising issues with limitations in neighbouring countries' domestic power grids lead to an increase in Danish wind curtailment through market downregulation

A prerequisite for cross-border trade was to have adequate physical capacity available on the interconnectors. Historically, Denmark has benefitted hugely from its many interconnectors to neighbouring countries as a source of flexibility from trading power with power systems with different characteristics.

However, in this period Denmark started to see the effects of grid infrastructure not keeping up with the expansion in interconnector capacity. The curtailment of wind generation rose from roughly 1% in 2019 to roughly 4% in 2020 mainly due to grid bottlenecks in the neighbouring countries' power grids. The reason wind generation was curtailed was due to the low down-regulation price bid into the market. In fact, the curtailment was a ramping down of these plant's generation determined through the market down-regulation bids to uphold a cost-efficient.

The bottlenecks meant that in hours with high VRE generation in Denmark, particularly Western Denmark, interconnector capacity was restricted due to limitations in the North German internal power grid. The limitations meant that in these few hours, power from Denmark could not flow as otherwise determined by the market auction, mainly due to local transmission grid limitations, but also due to the fact that most renewable power generation in Germany is seen as must-run (due to legislation) and may not be curtailed. Instead, German system operators compensated Danish consumers to increase demand or Danish power producers to lower generation. This included increased consumption from electrical boilers in district heating systems or curtailment of Danish power producers, typically wind turbines. Moreover, the German and Danish expansion of internal power grids and interconnector capacities also caused some of the increased curtailment as during the construction phases it has been necessary to limit flow on existing connections to work in proximity to these (Energinet, 2021).

Meanwhile, this spurred the development of sector coupling between different technologies. In fact, the expansion of electric boilers in district heating systems was nearly overwhelming in the last few years owing particularly to the requirement in these few hours for added demand as these

few hours meant that the break-even cost of most electrical boilers, was seen to be as low as 5-6 years.

The bottlenecks in the grid infrastructure remains a challenge and therefore needs to be further addressed in the future.

Takeaways from 2016-2020

As the amount of flexible demand increases and flexible production decreases, it is paramount that the consumers transition from passive to active. Otherwise, the system operator will fail to uphold a satisfactory level of security of supply. A means to improve customer participation is a highly digitalised power system that provides close to real-time data about all connected plants. The ongoing digitalisation of the power system has yet to show its full potential, but there are high hopes for the newly introduced market products like hourly settlement and time of use tariffs and that they will promote the consumers' active participation in balancing the system according to price signals.

Another important initiative is the introduction of an aggregator. The aggregator can trade flexibility on behalf of the customer, and thus provides access for small units to electricity markets that would otherwise be inaccessible. Such a market is the Intraday-market, which received an upgrade in 2018, where 15 countries joined a single cross-border market platform allowing participants to trade imbalances up to an hour before delivery, significantly improving VRE sources' ability to self-balance.

Forecasting has become increasingly more important with higher shares of VRE and today Energinet include online measurements lowering mean absolute forecasting error in order to lower the need for balancing.

A study warranted that normal operation of the Danish power system does not require online thermal power plants to maintain system security due to accurate forecasts, proactive balancing and that current grid components and AC interconnectors supply the need for properties required to maintain power system stability. However, the continuous transformation of the power systems in these and coming years may lead to different needs in the long term.

6. After 2020: The second half of the green transition of the power sector requires flexibility from new technologies and consumer participation – towards 100% VRE in 2030

Messages from this period

- The market will still remain the main driver of flexibility and its design will keep being developed to promote increased levels of flexibility.
- The "low hanging fruits" of flexibility have already been implemented and sources of flexibility that have enabled the integration of the first 50% of VRE in Denmark will not suffice in the next phases where Denmark envisions a 100% renewable power system by 2030.
- Increased sector coupling and demand-side flexibility are seen as the key providers of new flexibility measures in the future through new technologies, innovative use of existing technologies, digitalisation and data-driven business models, where important prerequisites are digital frameworks, promotion of free exchange of data, removing obstacles for the new technologies and digitisation of market processes.

On December 6th 2019, the Government reached an agreement on a new Climate Act in the Danish Parliament. The act includes a legally binding target to reduce greenhouse gases by 70% by 2030 (relative to 1990 level) and to reach net-zero emissions by 2050 (Danish Ministry of Climate, Energy and Utilities, 2019). It was followed up by a Climate Action Plan in 2020 which also presented strategies and initiatives on energy islands, PtX and many more. Meanwhile, Denmark still aims at having a 100% renewable electricity sector by 2030.

Despite the ambitious targets, the security of supply is expected to remain high following a politically set target for outage minutes, which Energinet is responsible for planning for and upholding. As a result, the average consumer is expected to be without power 35 minutes annually in 2030, in comparison the average consumer was without power for 22 minutes annually for the last ten years (Energinet, 2018).

As of today, the Danish cross-border interconnection capacity is slightly higher than peak demand and technological advancements in HVDC is assisting with critical system services. Thermal power plants are transitioning to biomass while also improving their ability to respond to market signals with heat pumps, electric boilers and heat storage. But the power plants continue to struggle, as their ability to compete in the electricity market diminishes when the penetration of VRE increases.

This is important as the Danish Energy Agency is forecasting a 65% increase in the Danish annual gross electricity consumption and a 30% decrease in thermal power plant capacity towards 2030 as illustrated in Figure 27. A large part of the increase in consumption is expected to be adjustable like power-to-heating, charging of electric vehicles, smart buildings as well as production of biofuels through electrolysis and certain industrial processes. These new technologies must be given the right incentives to contribute to the system with flexibility otherwise a significant phase-out of dispatchable power production will not be feasible. Especially since this development is prominent across most of Europe and thus Denmark cannot expect to rely on neighbouring countries to provide flexibility in all hours particularly those with high power demand and low production from VRE resources.

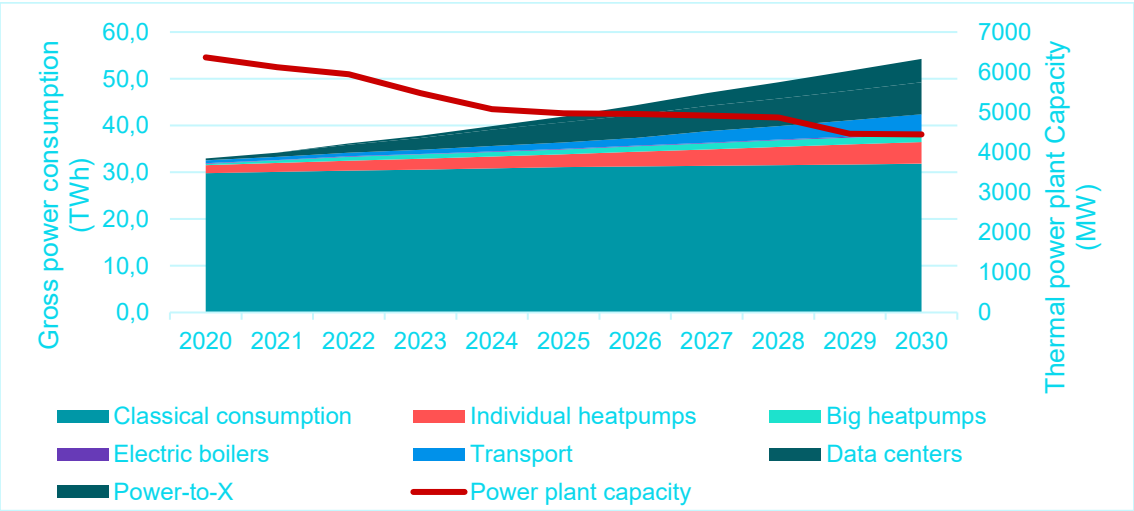

Figure 27 Expected trend in electricity demand and power plant capacities 2020-2040 (DEA, 2020).

Looking back, the first 50% of VRE integration in Denmark were not easy, but they were likely easier than the next 50% VRE will be. The aforementioned measures in the previous chapters are not expected to suffice in the next phases where Denmark envisions a 100% renewable power system by 2030. In short, the low hanging fruits have already been picked in the first half of the green transition, and now the fruits at the top of the tree must be reached.

Consequently, sources of flexibility that have enabled the integration of the first 50% of VRE, and for Denmark to be in the IEA's Phase 4 of system integration (see Figure 5), will soon be exhausted and the role of the traditional system operator is expected to change as the characteristics of Phase 5 and 6 become more evident. With challenges such as longer periods of energy surplus or deficit and a need for seasonal storage, new types of markets and consumers are expected to help drive the green transition and provide flexibility through market incentives. This shift is illustrated in Figure 28 and elaborated on in the following sections.

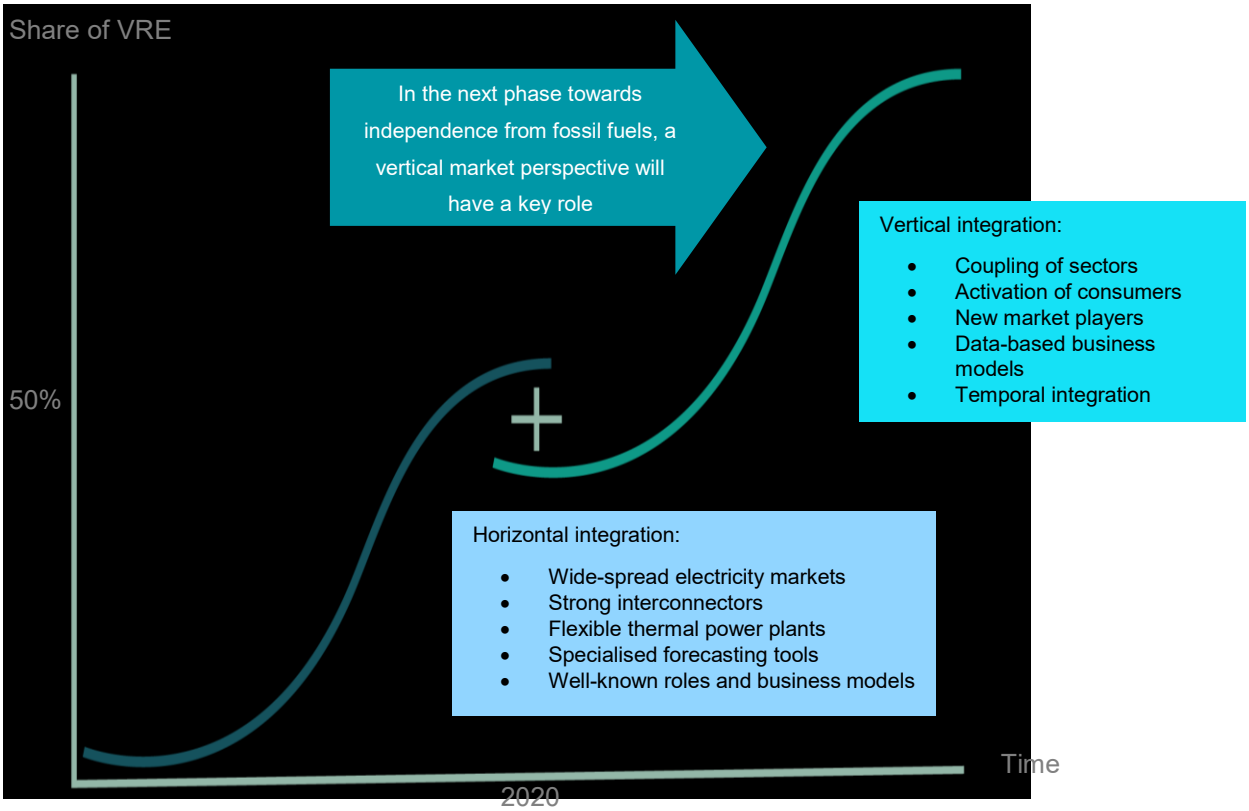

Figure 28 *Illustration of growth in VRE penetration over time and the timing of relevant and expected measures for integration of VRE. Source: Energinet.*

Sector coupling: Electrifying all possible sectors should in theory provide great potentials for flexibility

Sector coupling between the power and heating sectors through flexible operation of conventional thermal CHP's has been major source of flexibility for many years, but in the coming years, the capacity of these plants is expected to drop. As conventional thermal CHP plants are phased out, it will be necessary to have other sources of flexibility, possibly through electrification. Again, the coupling between the power and heating sector will be key, but it is alone not expected to be able to provide sufficient flexibility. Moreover, further steps in sector couplings between power, heating, transportation and the gas systems are needed for efficient energy storage and system balancing (D. Lew, 2019). Nevertheless, there is still some uncertainty as to which degree these sector couplings can provide flexibility and to which extend the users of these sectors will act flexibly.

In the heating sector, electrification is underway with a large focus on heat pumps and electric boilers as the main components of flexibility. Particularly, electrical boilers have already been

implemented in some district heating systems, while large heat pumps in district heating systems have only recently replaced existing conventional thermal CHP's, both as surplus heat boosters and regular district heating heat pumps. In fact, electrical boilers already provide a great amount of flexibility by consuming power with a start-up time of minutes and producing heat for large district heating systems in hours where it, due to limitations in neighbouring power grids, was not possible to transmit power beyond Danish border.

The expectation is that with the green transition, heat pumps will be the main source of heat in Denmark in general, both in large district heating systems and for individual heating purposes. As a consequence, the power and heating sectors will be closely entwined, meaning that flexibility in the heating sector will be necessary to operate the system. In reality, most of the measures of flexibility will be the same, for example utilising storage tanks and producing power when economically beneficial meaning when the power price is low, which is typically when renewable power generation is high.

Other sectors of electrification include transportation, where Energinet is currently planning to strengthen the grid for coming consumers with high demands such as PtX facilities and EV charging stations. The first might even be in combination with ongoing projects like energy islands, where DEA and Energinet are looking at two projects, one in the Baltic Sea in relation to the island of Bornholm, and one with other partners to create the first wind power hub in the North Sea (Krarup, 2021).

And green hydrogen from PtX has the potential for decarbonising many other sectors, such as heavy industries, farming and shipping further making the case potential for expansion of PtX facilities.

However, the generation of hydrogen through PtX is expected to have higher costs than common methods, meaning that these plants will try to optimise their generation according to the electricity price, which is deemed a critical cost component. Aligning their consumption with hours of low electricity prices would presumably in the future coincide with high shares of renewable generation in the power system, meaning PtX facilities could provide much-needed flexibility.

On the whole, electrification of other sectors are expected to bring additional flexibility and help balance the system due to the economic benefits they are exposed to in the power market, however, the realised potential is yet to be seen. Market incentives have driven flexibility thus far, but operational parameters of new technologies may cause them to act inflexibly in certain periods, for instance in very cold periods and low VRE share, heat is still necessary and with heat pumps being the main source there might not always exist flexibility, and likewise for EV owners that need to charge their vehicles at certain times.

Utilisation of interconnectors: Sailing closer to energy islands, but rising issues at home.

Another topic that has gained a lot of attention in recent years is the concept of energy islands whereby large offshore wind farms are connected to a single point offshore that is in turn connected to several countries. From a flexibility point of view, the concept allows for increased balancing opportunities by enabling access to large geographical areas and in general higher power generating capacities, albeit variable ones.

Energy islands and PtX

If a large part of the Danish energy system is to be decarbonised through the means of PtX, it will require many facilities and high annual power demand. Moreover, large scale wind power generation and PtX in combination will set high demands to the energy infrastructure, where arbitrary locations would require additional power grid infrastructure to cope with the added demands and peaks.

Consequently, it is natural to consider whether the electricity from offshore wind should be transported further as electricity or as hydrogen in pipes. Of course, there are various benefits and drawbacks of each option, but hydrogen or gas pipes are expected to have a low unit price and little to no impact on the landscape onshore.

Additionally, it can be possible to couple Danish hydrogen infrastructure to other European countries hydrogen infrastructure, as has been the case with natural gas lines, or store the hydrogen in storage facilities (Energinet, 2020).

Energinet is also getting invaluable experience in the technical aspects of creating energy islands from the *Kriegers Flak - Combined Grid Solution* project, where two winds farms became an integral part of an interconnector. This was the first time that an interconnector connected two asynchronous areas through offshore wind farms. Besides the technical parts of constructing and commissioning the link through the wind farms, the operational experiences from operating this new type of interconnector are invaluable when considering the long term implications from ideas such as energy islands, which will utilise some of the same technologies.

Kriegers Flak - Combined Grid Solution (Obbekær, 2021)

In December 2020, Energinet and the German TSO 50 Hertz launched the world's first offshore interconnector by using the national grid connections to offshore wind farms in the

Baltic Sea.

The two wind farms, Kriegers Flak (Denmark) and Baltic 2 (Germany) are less than 30 kilometres apart and both wind farms are linked by two sea cables giving the interconnector 400 MW of transmission capacity as illustrated in Figure 29.

The transmission capacity of the interconnector will be allocated to the grid depending on generation from the wind farms on the interconnector, where power flow depends on market prices in the connected regions. As a result, the interconnector capacity will first be allocated to power from the wind farms and secondly be allocated to the markets in Denmark and Germany.

The Danish island of Zealand and the North German state of Mecklenburg-Western Pomerania are out of phase, but the Kriegers Flak - Combined Grid Solution connects the two regions via the two offshore wind farms through AC sea cables and having a so-called back-to-back converter in the North German region.

The installation, implementation and operation of Kriegers Flak are providing Energinet with experience and knowledge within challenges of energy islands.

Figure 29 Illustration of the grid in the Kriegers Flak – Combined Grid Solution (Obbekær, 2021).

Demand-side flexibility: Further inclusion of consumers, new business models and barriers

Denmark is implementing demand-side flexibility measures both for electricity and district heating demand. These measures can adjust demand to feasibly cover minor and medium changes in supply and demand in a cheaper, rather than applying flexibility or curtailment on production units.

Many types of consumers could in theory provide demand-side flexibility, but trials and studies have found that the price incentives and their nexus with consumer behaviour change make sense for only a few types of market actors. For this chapter's purposes, three distinct types of consumers are considered:

- Large and mid-level companies
- Aggregators
- Private household consumers

Large production facilities with high electricity consumption are already investing in technologies that allow certain processes to participate in the market. This could be large electric boilers, just-in-time processes and similar, where the usage of the equipment need not be fixed, but where queuing can be allowed. For large scale burners and heaters, for instance, the marginal cost for capacity can be low enough that investing in overcapacity can make sense on a lifetime-basis when allowed to take advantage of electricity price fluctuations.

Some equipment may become able to act in both directions, ramping up its operations when the price falls and likewise be able to suspend some capacity when prices increase. Internationally, likely equipment types are electric arc furnaces for steel production, boilers and chillers (where the heated/cooled water can cheaply be stored) and electric furnaces. Newer technologies that are planned with this in mind are some data centres, where backup rates are determined by electricity price and hydrogen production plants using PEM electrolysers. Industrial equipment (incl. district heating boilers) can enhance flexibility on GW scale, making them very attractive for demand-side flexibility investments.

Already in use are aggregator companies for public and private electric vehicle charging, where the current to the individual vehicle is electricity price adjusted dependent on the vehicle's charge state, charge current ability and user profile. This segment for parked slow and mid-charging is useful, as a vehicle owner is unlikely to care whether her car has charged mostly right when she parked it or in the early morning hours, as long as it is charged when needed in the morning. These aggregators already control a majority of EV charging and are expected to be the leading

service provider in the future, making their capacity much larger than now. Other examples of this are computational models in data centres, where CPU, GPU (and thereby power) intensive uses can be loaded and queued for when electricity prices are projected to be low. These are for now unexplored, but technically ready for implementation.

Even in the early stages, some compromises have been made that were unforeseen before rollout. For electric vehicle charging, a user may want to override the smart charging if they need to drive earlier than normally scheduled. Similar aggregators of EV charging non-flexibly "dumb"-charges vehicles to a minimum level, before applying smart charging. For other sectors, users might determine price optimisation is lesser important than immediate processing, making the aggregator's capacity in the market variable. In many ways, this again mirrors the aggregators of privately owned onshore wind turbines, but for consumption. As EVs, data centres and other flexible demand proliferates, the role of aggregators will become increasingly larger and more important in the energy market.

Many analyses and even companies have been founded own demand flexibility for private house owners, but with very little success until now. Most of the limitations relate to very limited profit potential for the individual house owner, combined with the "just-in-time" unplanned aspects of household energy consumption. For many of the highest consuming home products (e.g. washing machines, ovens, washing machines), the internet-connected equipment is more expensive than the benefit over the lifetime for electricity savings. Even for products where price variation may make sense, such as water heaters and room heating through heat pumps, the cost savings for the consumer is not worth the inconvenience of having to comply with price variation in their consumption. For the potential (very minor) savings, having to run the washing machine or dishwasher at night may be noisy during sleep, be inconvenient or similar. Room heating has been suggested, using the housing shell itself as storage. However, to do this effectively, the building has to be very well insulated and the user has to accept some variation in temperature. With the high efficiency of consumer heat pumps, there is little benefit for the user.

The lesson so far for demand-side flexibility is that investments in consumption flexibility are best served in large consumers – especially in key industries. This fits well with general electrification in these sectors. For aggregated consumption types, demand-side flexibility only works under the conditions that the user experience is not meaningfully impacted and that end consumers easily can temporarily opt-out where needed. For most aggregated sectors, this share will be very small but serves to establish user trust. Small non-aggregated consumption types in individual households are unlikely to see user benefits and are therefore likewise unlikely to see wide-scale adoption. For these, energy storage of different types would be necessary, which is unprofitable due to low electricity prices and cheaper flexibility options.

Takeaways for after 2020

The Danish Government aims to have a power system consisting of entirely renewable power by 2030 and while thermal power plants are being phased out an increasing share of the power generation will come from VRE sources, which in 2019 and 2020 accounted for half of the Danish power consumption.

Nevertheless, the flexibility measures that supported the integration of the first 50% VRE will not alone suffice towards 2030. This first 50% VRE share was mostly integrated using known flexibility measures, so the low hanging fruits have already been picked. Consequently, a 100% renewable system will require new and innovative solutions for providing the necessary flexibility.

In general, the focus on flexibility measures is shifting towards having consumers be an active part of the power market and to further couple other energy sectors together with the power sector to unleash a huge potential for flexibility. To that end, the sector couplings already implemented, such as power-to-heat and EV charging, are expected to assume even greater roles and provide additional flexibility to the power sector through economic incentives.

In fact, the market is still expected to be the driver of flexibility measures in the future leading to new sources of flexibility. These new sources of flexibility are expected to be unlocked by new technologies (or well-known technologies used innovatively like electrolyses for PtX), digitalisation and data-driven business models, where the TSO has an important role in creating digital frameworks, promote free exchange of data, remove obstacles for the new technologies and digitise market processes. The thought behind this is that the market provides the needs for flexibility to the market players which in turn provides the most cost-effective flexibility providing solutions. In this way, there is not an explicit goal of how much flexibility needs to be available in the power system, instead, the price signals in the market expose the value of flexibility.

Demand-side flexibility is most beneficial in large industrial and aggregated consumption sectors. With already planned investment for electrification and automation of energy-intensive industrial processes, market participation can be a great benefit both for the grid and the individual company. Some individual consumption sectors that can delay electricity use for processing and charging can benefit from market participation, but mainly in aggregation, controlled as a lump capacity. Individual heating and household electricity use is the most difficult to make “smart”, as these are just-in-time uses and will inconvenience the consumer without them seeing any meaningful financial benefit.

7. Suggestions based on the Danish experiences

This chapter summarises general suggestions on VRE integration based on the experiences from the Danish power system over the last 20 years.

Flexibility is a tool, not a goal

The main driver behind the power system development in Denmark and Europe over the last 20 years has been the desire to secure fair and equal access to the electricity market for all. This desire resulted in the opening of the power market, with the purpose of ensuring no conflicts of interest, and enhanced access for all interested actors. This has allowed for the most cost-efficient power production and flexibility measures. From this perspective, it can be said that flexibility has not been forcefully developed by political ambitions or command and control regulation, but as a natural consequence of the measures produced to promote fair and equal access to the market. This leads to the Danish view that flexibility should not be a goal in itself, but a tool, and therefore, a well-designed market should reflect the need and provide incentives for flexibility.

Design pricing scheme that reflects system requirements

In order for a well-designed market to provide incentives for flexibility, these have to be aligned with the needs of the power system. Ensuring that the pricing scheme provides a transparent price signal that is reflective of such needs will ensure that participants of the market are presented with incentives for meeting these needs. Such has been the case in Denmark, and most of Europe, where flexibility measures in thermal power plants have mostly been developed not by specific regulations enforcing flexibility, but by the desire of producers and consumers to develop a more attractive business model and take advantage of these price signals.

Enlarge balancing areas to gain access to more diverse generation mixes and increased flexibility

The utilisation of the differences in the timing of VRE generation across large land areas to balance the system through flexible dispatch of interconnectors has proven a great source of flexibility. Not only one can see that VRE generation patterns become smoother when the geographical balancing area is increased, but it is additionally possible to take advantage of differences in generation mixes stemming from difference in natural resources. In the case of Denmark, hydropower plants in other Nordic countries have been huge sources of flexibility for the Danish system. However, this flexibility can only be fully exploited when regulations allow for a barrier-free exchange of power between areas.

Improve scheduling and forecasting to reduce flexibility needs

When looking at flexibility as a tool, and not an end goal, it can be seen that limiting the need for flexibility is as effective as increasing the flexibility of the system. The continuous development of forecasting and scheduling systems has been a central tool for reducing the system's need for flexibility in Denmark. By having accurate forecasts and coupling these with real-time measurements, the need for sudden increased amounts of flexibility through balancing has been limited. Coupling the forecasting scheme as an integral part of the balancing strategy of the system operator will contribute to an optimal balancing strategy, such as the proactive balancing based on forecasting done in Denmark.

Explore future innovative flexibility solutions

Once the low-hanging fruits have been fully exploited in the search for enhancing flexibility, it is necessary to look for innovative solutions. These new solutions will be tasked with addressing the needs of tomorrow, as the power system develops towards being carbon neutral. In Denmark, this has led to solutions such as wind turbines providing ancillary services, as well as being able to operate the power system without central thermal power plants under normal operation. These novel approaches were previously thought to make the system unstable and vulnerable to faults. Today, by taking advantage of technological and operational improvements they further increase flexibility in the system as it reaches new record-high shares of VRE.

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