REPORT

NORDIC POWER MARKET DESIGN AND THERMAL POWER PLANT FLEXIBILITY

ENERGINET

Danish Energy Agency

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This report has been prepared by the Danish TSO, Energinet, for the Danish Energy Agency (DEA) and is a contribution to the Clean Energy Ministerial Advanced Power Plant Flexibility Campaign, May 2018. For questions and comments to this report please contact Peter Markussen, pmr@energinet.dk or Max Nitschke, mnc@energinet.dk

The purpose of this report is to give an overview of how the Nordic electricity markets and the flexibility from Danish thermal power plants have contributed to the efficient integration of more than 40 % variable renewable energy (VRE) in Denmark.

The liberalization of the Nordic power market started already in 1996 between Norway and Sweden and in 2000 Denmark and Finland had also joined. The Nordic electricity market has continuously developed to incentivize the flexibility from mainly hydro, and also coal and gas fired thermal power plants, as the share of renewables has increased. Today the electricity markets are getting more and more European, but the focus in this report, will be on the Nordic development. The Danish experiences can inspire and give overall recommendations for other countries with an objective to integrate an increasing share of renewables, but the specific Danish context has to be taken into account, when trying to transfer the Danish experience.

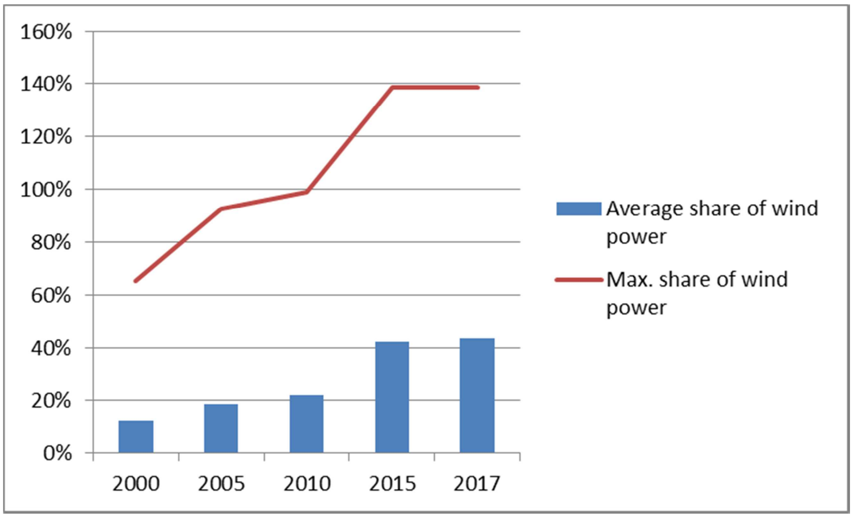
This document is organized in 5 chapters, beginning with an overall introduction to the Danish experiences with integration of high shares of VRE from mainly wind power. Then, the development of the Nordic power market is described followed by an introduction to thermal power plant flexibility. The more detailed description of the Nordic power market in chapter 4 is then combined with reflections on how the design of the electricity market influence and incentivize flexibility from thermal power plants. The final chapter offers conclusion and some forward looking perspectives.

1. The Danish experience on high VRE integration

1.1 Historic development of variable renewable energy

In Denmark the share of electricity produced from wind and solar has been continuously increasing over the past 15-20 years. In 2017 the share of the gross domestic electricity consumption covered by domestic variable renewable energy (VRE) sources was 46 %, of which 44 % was wind and 2 % solar power[1]. At the same time the share of hours with wind power production higher than consumption is increasing with up to 140 % wind power production above consumption in one hour in the last four years, see figure 1.

Figure 1: Wind power share of consumption in Denmark

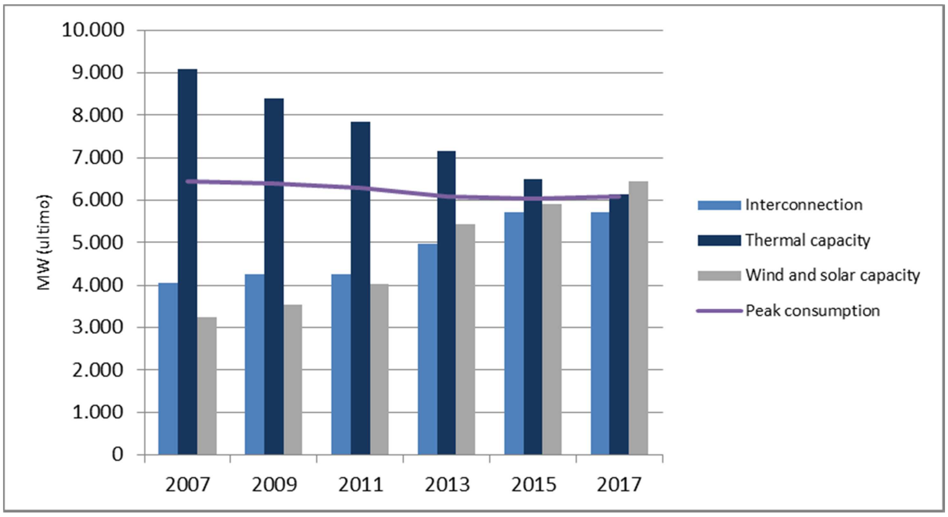


Source: Energinet (www.energidataservice.dk)

1 https://energinet.dk/Om-publikationer/Publikationer/Miljoerapport-2018

Despite the high share of wind power in Denmark, forced curtailment of wind and solar power have been negligible, while security of supply is among the best in the Europe. Two key reasons for this is: increase in interconnector capacity and enhanced thermal power plant flexibility. Figure 2 show that the Danish interconnector capacity with neighboring countries has increased significantly over the past 10 years. The high level of interconnection allows for a larger geographic balancing area, benefitting from both the different mix of production technologies and consumption profiles across the area. Figure 2 also shows that Danish thermal capacity has been constantly declining at the same time as VRE capacity has been increasing. The thermal power plant fleet in Denmark consists today almost exclusively of combined heat and power production (CHP). As the share of VRE increased, the role of CHP plants changed from being the main baseload of the power system to becoming a key source of system flexibility.

Figure 2: Development in Danish capacity and peak consumption over the past 10 years, MW



Source: Energinet

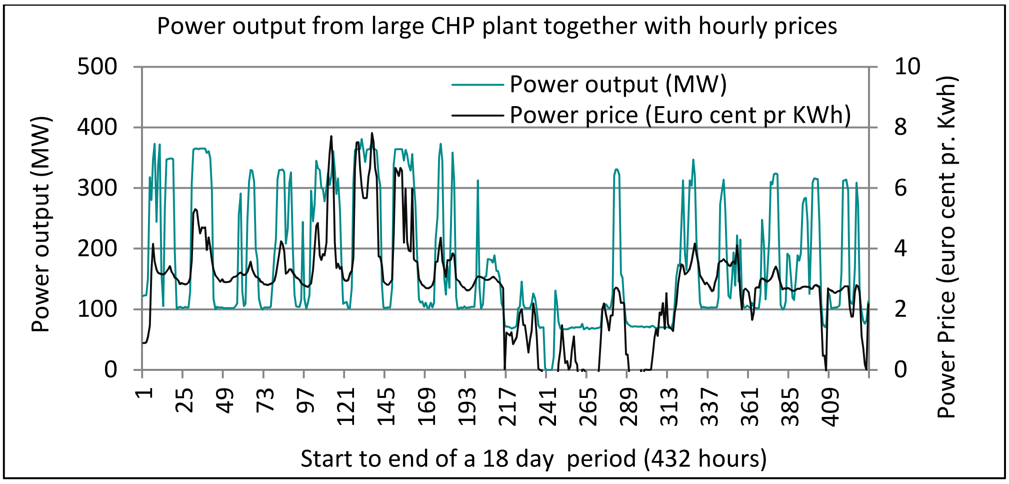
The successful VRE integration in Denmark relies on a market-based least-cost dispatch with clear and reliable price signals for market participants to react to. The integration is supported by high levels of interconnection and close market integration with neighboring countries, as well as a pro-active TSO planning and forecasting and a very flexible fleet of thermal power plants.

The establishment of a Nordic common power market and power exchange (Nord Pool[2]) about 20 years ago, has been a key enabler for a cost-efficient integration of VRE. The market-based least-cost dispatch in Nord Pool, ensures, a closely connected Nordic area with electricity always flowing towards high-price areas. Further, the development of a common Nordic balancing energy market allows Swedish and Norwegian reservoir hydropower to provide cheap short-term flexibility to the entire Nordic system, and reduce the costs of imbalances due to VRE. The coupling of the European Day-ahead markets and increasing interconnection to the Central Western European power system is fundamental for the continued market integration and cost efficient integration of Denmark's large share of renewable energy production. In recent years Denmark's TSO has agreed with respectively the Dutch and German TSO to invest in 700 MW (Denmark-Holland) and 400 MW (Denmark-Germany) interconnectors.

[2] https://www.nordpoolspot.com/the-power-market/

The price volatility in the day-ahead market driven by increasing shares of VRE production has incentivized the thermal plants in Denmark to become more flexible over time. By being able to produce power independently of the demand for heat production, but also through improving the plants ability to operate at low load and improve ramping abilities, Danish thermal power plants have been able to respond to the increasing demand for flexible generation in the market. Heat storage tanks can be found in basically all power plants and increasingly electrical boilers allow for better adjustment to power market prices without affecting heat delivery to the local district heating system. Today, Danish CHP power plants are among the most flexible in the world - a development that was undertaken by the sector itself through clear economic incentives in the market. In figure 3 the power output from a large coal fired CHP plant in Denmark illustrates the highly flexible production of the unit as well as it shows the close correlation between the output and the hourly power prices in the period.

Figure 3: Power output during 18 days in December 2017 from large CHP plant together with hourly prices in the market



Source: Energinet

The declining share of production from thermal power plants and reduced availability for delivery of ancillary services to the system and the ability to maintain system stability in the future, is a concern. Technological development, e.g. in system service provided by wind turbines, interconnectors and automation of the grid, as well as developing market models for ancillary services, are important solutions to these challenges. So far, Denmark has been able to cope with shorter periods, without operation of large power plants.

1.2 Future VRE in Denmark

Denmark has set a goal of 50 % wind power of consumption in 2020 and independence of fossil fuels in 2050 of the total Danish energy consumption. Thus, the share of VRE in Denmark will continue to increase, and so will the need for cost-efficient integration of VRE into the system. Interconnector capacity to neighboring countries is foreseen to increase in the next decade with new interconnectors being built to Holland and Germany, and new interconnector planned to UK. Further development of the short term electricity markets is currently under discussion as part of implementation of European guidelines. These include a continuation of the day-ahead market coupling and intraday and European coupling of balancing market and harmonization, which will improve possibilities to balance VRE across Europe. Lastly, coupling of different energy sectors, i.e. heat, electricity, fuels, transport, are opening up for the possibility that variations in the single sectors are absorbed or to some degree mitigated through this sector coupling, given the right market structures. The Danish government has for instance recently decided to reduce the taxes on power to heat production.

2. Background for the Nordic Power Market

The electricity markets are seen as one of the most important tools for system operators, producers and consumers to ensure security of supply, operational control and planning of production and consumption. The electricity markets give the price signals, create competition and transparency in demand and production.

The electricity market development is the foundation for the integration of VRE in Denmark, through incentivizing the increase in thermal power plant flexibility, and the establishment of a dynamic and close market coupling, allowing for better balancing of VRE over a large market area. The electricity markets are getting more and more integrated in Europe, but the focus in this report will be on the Nordic development.

Other market designs are developed in USA, Australia, Brazil and other regions of the world. The distinct characteristic of the Nordic and European market setup is the common target model, to continuously harmonize and couple the national and regional electricity markets according to common European standards. The power markets in Europe have developed over the last 20 years, and will continue to adapt to the development of technology, regulation and electricity systems.

With increasing share of wind power and solar connected on the distribution grid, an increasing number of consumers with own production and batteries, and reduced capacity and operation of large thermal power plants, the electricity system and its complexity changes. It is recommended to continue the electricity market development, as it can handle this complexity with its transparency and decentralized decision making.

2.1 The development of the Nordic power market

The main background for successful integration of VRE in Denmark is the inclusion in the Nordic power market in 2000. The Nordic power market is a common market comprising the synchronous area of Norway, Sweden, Finland and Denmark. In the Nordic and rest of Europe the system operation and grid, ownership are by law unbundled from production to reflect monopoly and market functions of the electricity system, and this is an important pre-requisite for the European market setup.

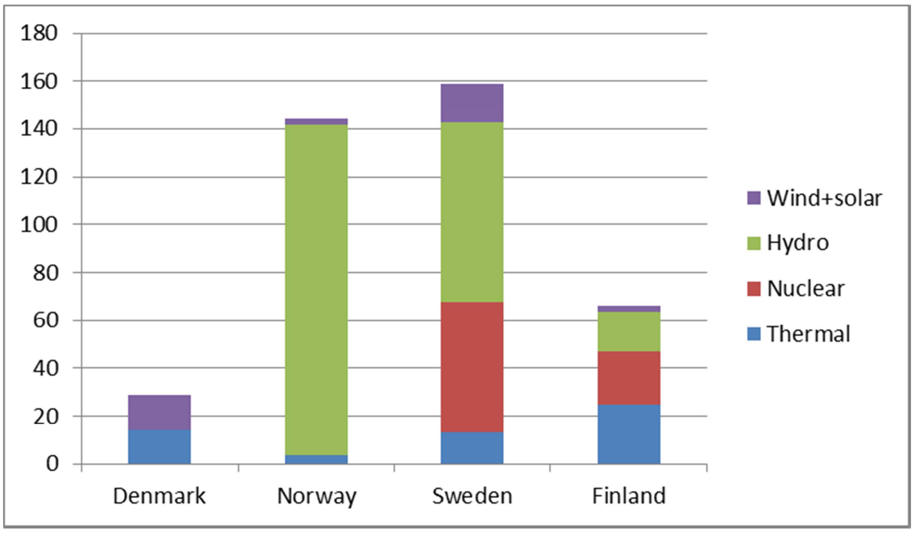
In the Nordic the market, development was driven by the system operators in Norway and Sweden, and the benefit of an efficient dispatch setup to manage the balancing of production and demand and support the development of the grid[3]. The large share of reservoir hydro and a dispersed ownership of the production assets, made it difficult and complex for the system operator to plan production and development of the grid. The price signal decentralized the optimization of production from the reservoir to the producer and differences in bidding area prices indicated benefit of development of the grid. Further, a large share of the heating in Norway and Sweden, is based on both electricity and individual heating, and is able to shift from electricity to other alternatives, if prices are very high. Contrary to the heating in Norway and Sweden the majority of heating in Denmark is supplied by district heating produced by large as well as small scale CHP plants.

Figure 4 shows the electricity production mix in the Nordic countries in 2016 and more than 60 % of the electricity production is from hydro. As will be described in chapter 3 the high flexibility of hydro, is in several ways reflected in the market design and incentivizing thermal power plants, to be more flexible to optimize the benefit from the power mar-

[3] The system operators in the four Nordic countries are: Norway: Statnett, Sweden: Svenska Kraftnät, Finland: Fingrid and Denmark: Energinet

kets. In 2000, Denmark was already connected to Norway and Sweden with more than 4000 MW of interconnectors and production on thermal power plants was already, to some degree, adapted to dry years with thermal power in Denmark, supporting the Nordic security of supply.

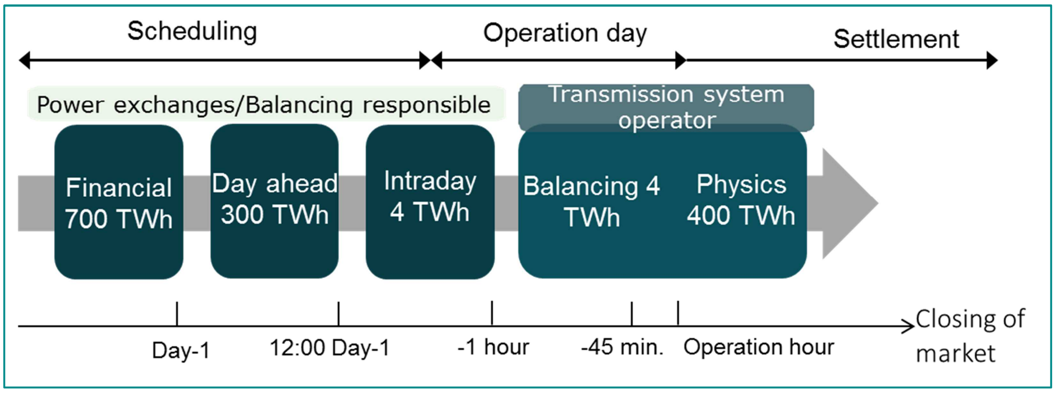
Figure 4: Nordic power production in 2016, TWh



Source: https://www.nordpoolspot.com/historical-market-data/

The Nordic short term electricity markets consist of three markets with different time scheduling. It is the day-ahead market, the intraday market and the balancing market, and they are described more in detail in the following sections. The day-ahead and intraday market is run by one single power exchange (Nord Pool), and the balancing market is the common responsibility of the transmission system operators[4], see figure 5. In addition the long term financial market is supporting the long term risk management with monthly, quarterly and annual forward price. This market is run by a separate financial exchange (NASDAQ[5]), and though an important part of the electricity market, the financial markets will not be dealt with in this report as focus is on the real time markets incentive for flexibility.

Figure 5: Overview of the Nordic electricity markets



Source: Energinet

[4] For more information on the Nordic market see: https://www.nordpoolspot.com/the-power-market/
[5] For more information see: http://www.nasdaqomx.com/commodities/markets/power/nordic-power

The day-ahead market in the Nordic is the primary price signal for the management of investments and efficient dispatching and balancing of the power system. Nord Pool handles approximately 75 % of the total market volume. The remaining share is traded over-the-counter (OTC) outside of the Nordic power exchange. This high penetration and market liquidity is a guarantee for power producers that price signals are reliable and flexibility is rewarded.

The overwhelming majority of the physical power trade in the Nordic power market takes place day-ahead. The volume in the day-ahead market amount to 97 % of the short term power markets, but prices are in general higher in the balancing market. In 2017 the prices in the balancing market was on average 12 Euro/MWh higher than day-ahead, see table 1. It is the single hourly price that is of interest to the thermal plant, with high production at high prices and reduced production at low prices. The annual average price does not show the volatility in power prices.

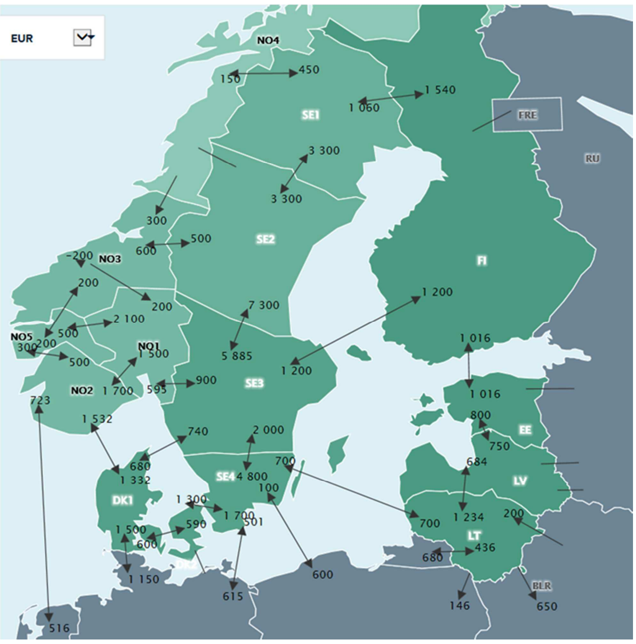
Table 1: Volume and annual average prices in the Nordic electricity market

2017	Volume TWh	Average price €/MWh
Day-Ahead	370	29
Intra-Day	5	28
Balancing	4	41

Source: https://www.nordpoolspot.com/historical-market-data/

The Nordic day-ahead market consists of 15 bidding zones (incl. Western Denmark and the Baltic countries). In the beginning Sweden was one price area, but in 2010 it was split in four price areas to reflect internal congestions after complaints from mainly Danish market participants on discrimination on access to Swedish bidding areas and extensive discussions with European Commission. Figure 6 shows the bidding areas in the Nordic power market. Western Denmark is part of the European continental synchronous area, but has from the beginning been integrated in the Nordic power market covering the Nordic synchronous area. From 2010-2013 the three Baltic countries (Latvia, Lithuania, Estonia) were integrated in the day-ahead and intraday market, see figure 6.

Figure 6: The bidding areas in the Nordic Power Market



Source: http://driftsdata.statnett.no/Web/map/snpscustom (updated with prices and power exchange continuously)

In the Nordic balancing market, established in 2004, energy balancing bids are shared on an hourly basis between the four Nordic Countries, including the western part of Denmark belonging to another synchronous area than the rest of the Nordic power system. Despite the high share of very flexible hydro power, the Danish thermal power plants with their high share of CHP continuously increased their flexibility and where still competitive.

In the Nordic countries, the system operators do not own production facilities and all need for reserves and balancing energy are procured using market based instruments. The balancing management is the responsibility of the system operator and the balancing management model influences the use of intraday and balancing markets. In the Nordic countries a self-dispatch model is used for the scheduling process and the dispatching, and the unit commitment to the time of operation, is the responsibility of producers and consumers. This gives incentive to the producer and consumer to invest in flexibility. The alternative is a central dispatch model, where the system operators are responsible for the dispatching and unit commitment.

In the operational hour a proactive balancing philosophy is used in the Nordic countries compared to a reactive philosophy. The Nordic balancing market is crucial for this proactive balancing, where imbalances are foreseen by the system operators, who have the responsibility to procure and activate the necessary reserves. In the reactive philosophy, each market participant is able to balance its position close to real-time. The faster and automatic reserve plays a more important role in the reactive balancing. The intraday market is of less importance in the Nordic countries for balancing and optimization, due to the proactive balancing management with well-functioning balancing market and possibility for market participants to sell imbalances as up- or down- regulation on the balance market close to operation. Due to the high share of flexible hydro production in the Nordics, it results in a relative low imbalance prices and incentive for producers and consumers to use the intraday market is therefore low. The consequence for thermal power plant flexibility is described in more details in chapter 4.

The development of forecasting products for hydro, wind and solar is important to integrate VRE and reduce imbalance costs, e.g. the reservoir levels in the Nordics are published on daily basis on the Nordic power exchange. Meteorologists are employed in various energy related companies, and software and services have been developed to target energy businesses. As a consequence the proficiency in predicting hydro, wind and solar power production has improved significantly.

In the last 20 years the European Commission has pushed forward a European liberalization of the electricity production and consumption, and defined the common target model with one interconnected European power price based on the Nordic market model[6]. The market coupling between Nordic and Germany started in 2009. The day-ahead market has been harmonized with the European market coupling in 2016, and is today literally one integrated day-ahead market with a common price setting. The intraday markets will be harmonized and market coupled in 2018. Common European rules for harmonization of the balancing markets were agreed at the end of 2017 and will be implemented in the course of the next 4 years with final harmonization of the balancing markets in 2022.

[6] For more information on the European development see: https://ec.europa.eu/energy/en/topics/markets-and-consumers

3. How thermal plants can deliver flexibility

In this chapter the possibilities for thermal power plants to deliver flexibility is described.

In the Nordic power market, thermal power plants have the relative largest share of the production mix in Denmark and in Finland. In Norway, where hydro plants are dominating the generation capacity, the total amount of thermal capacity is less than 1 GW, also see figure 4. In Denmark thermal power plants have historically made up an important part of the necessary flexibility.

In Denmark a large share of the houses are heated by district heating derived from combined heat and power plants (CHPs). The large CHP plants can vary the heat to power ratio, while most of the smaller CHPs have fixed ratios. Consequently the heating season leads to an increased production of power.

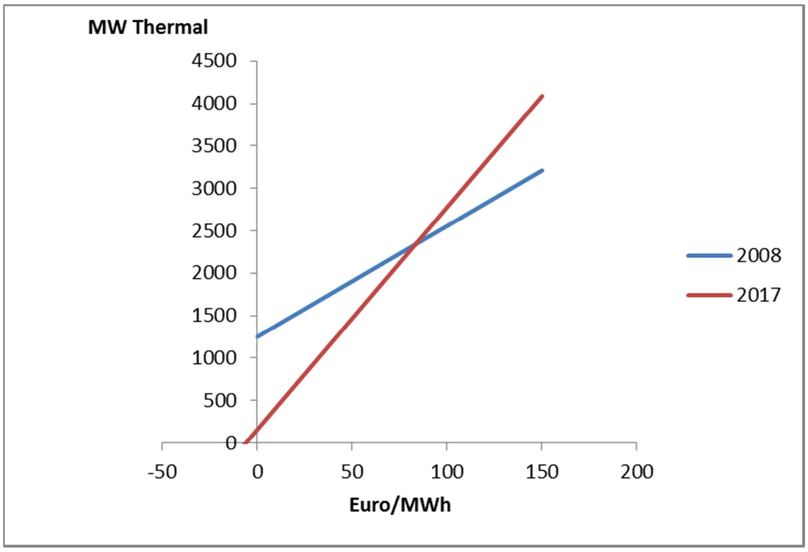
At the liberalization of the power market, the existing contracts between power suppliers and power producers to a large degree, allowed for the flexibility in production to variations in import and export possibilities, as they were already based on production costs and no fixed volume. Few years after the liberalization the long term contracts were cancelled and replaced by the use of the markets prices of the Nordic power market for risk management and long and short term planning.

During the expansion of district heating in Denmark from 1980-2000 it was through high tariffs and taxes on electricity incentivized to establish combined heat and power production and to reduce the direct use of electricity for heating. But as wind power shares increased after year 2000, the regulation of combined heat and power was changed to accommodate market incentivized flexibility. The regulation was changed from the feed-in tariff and priority access to the grid to a market based capacity payment securing the same absolute compensation, but with incentive to reduce combined heat and power production, when electricity prices are low. Further the power market increasingly saw low and even negative power prices in some periods, and allowing industrial electrical boilers to supply heat to the district heating system was an obvious useful regulatory adaption to a well-functioning power market[7].

Figure 7 below shows the thermal power plant increased ability to operate flexible in response to the day-ahead power price. It can be seen that electricity production from 2008 to 2017 gets more flexible to the day-ahead electricity price with increased production at high prices and especially reduced production at very low prices. In 2008, approximately 1,300 MW thermal capacity was operating at very low electricity prices, while this was not the case in 2017. In the same period the average full load hours on thermal power plants was reduced from approximately 4,000 hours to around 2,500 hours in 2017.

[7] For more information on the regulatory transformation and Danish district heating development see: https://dbdh.dk/download/DH%20Danish%20Experiences%20august%202015.pdf or https://www.iea.org/countries/membercountries/denmark/

Figure 7: Development of power plant flexibility in Denmark (illustrated by West Denmark statistical trend on hourly day-ahead prices and power production from thermal power plants)



Source: Energinet calculation

3.1 How thermal power plants serve flexibility demands

In the Danish electricity system with high share of VRE the difference between need for thermal power plant flexibility can be between 0-100 % share of consumption during the day and often a change between 30-50 % from hour to hour. Some of the measures available for increased flexibility from thermal power plants are:

1. Rapid response in thermal power production units (ramping)
2. Lower minimum outputs in the thermal power production units
3. Shorter start up times for thermal power production units
4. Overload capability

These are all parameters that can be improved to some degree on almost all existing thermal power plants. To make use of the flexible operation on the existing conventional generation fleet is one of the efficient ways to ensure power system flexibility at low to medium VRE production penetration levels. This is due to the fact that increasing operational flexibility of power plants utilizes the potential of an already existing infrastructure to its maximum[8].

Rapid response in thermal power production units, or load ramping, is the (improved) ability to increase or decrease the net power output in order to reduce the difference between production and demand. Default ramping ability in a thermal power plant build to deliver a continuous amount of power is typically 1 % of maximum power output per minute. Danish thermal power plants are built or retrofitted to ramp on average 4 % per minute, in a response to the demand for flexibility in the production fleet, expressed through power prices fluctuating through the day. Improved ramping properties allow the plant to increase or decrease participation in the market faster and follow the volatility in the power prices.

[8] For more information on thermal power flexibility see: https://www3.eurelectric.org/media/61388/flexibility_report_final-2011-102-0003-01-e.pdf , https://www.agora-energiewende.de/fileadmin/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf or https://webstore.iea.org/status-of-power-system-transformation-2017

Lower minimum output in thermal power producing units, or minimum load, is advantageous for thermal power plants to bridge two price peaks with a minimum of power production, when producing in this bridge is associated with loss. A lower minimum load also opens the possibility for large plants to place smaller bids on the market, which increases market liquidity and leads to more correct price signals. The minimum load is as low as 15 % in some Danish thermal power plants, whereas standard if this property is not sought optimized is 30 % to 40 %.

Shorter start up times for thermal power production units, lead to improved possibility for the units to react to sudden demands due to production fall-out. For bidders with a portfolio of assets, opportunities can emerge both in the day-ahead and in the intraday market, and for unit based bidders possibilities with e.g. 3 hours' notice can emerge in the intraday market. Warm starts can be reduced to less than 3 hours. Very often evaluation and re-organization of startup procedures shorten warm start up times considerably.

Overload capability is usually a characteristic that is built into a power plant from the beginning. But in some cases a minor improvement on overload capability can be achieved by a modest plant modification. The definition is mostly that the overall plant has its highest rate of efficiency at 100 % load, because all pieces of equipment that make up the plant are optimized for this load. If a plant has the overload possibility, the efficiency will decrease at loads over 100 %; and it will decrease faster per percent-point overload. As an example, a very flexible thermal power plant can run in the load range from 15 % to 115 %. At these two extremes, the electricity production efficiency in an average Danish thermal power plant is around 30 % while around 45 % at the optimal load. These factors influence the production costs and are important to take into account for the plant owner when placing bids in the market.

3.2 Flexibility "on power-heat coproduction"

Both large CHPs and small CHPs in district heating networks often have heat accumulators installed. The main motivation for having heat accumulators is flexible power production. If heat to power ratio is fixed, heat accumulators are used to store heat in time slots with high electricity prices and deliver it in time slots with high heat demand. If heat to power ratio is variable, accumulators can be used to prioritize power production in time slots with high power prices and produce the heat in time slots where power prices are normal or low.

Heat accumulators can store the heated water for district heating for a day or two. They will normally unload with an effect corresponding to the maximum heat effect of the CHP unit, and it will have a capacity of 3 to 8 hours maximum load.

Basically all heating technology in the district heating sector, as turbine bypass, heat pumps and electric boilers, ties into power production, and can be optimized to maximize profit or minimize heat production cost. Even the fuel expensive heat only boilers for peak load in the world's largest district heating system of Copenhagen, can serve as alternative at very high electricity prices and at negative electricity prices. In both cases it is not attractive to produce heat on a CHP plant.

So, when connected to the same district heating system, all these technologies together, CHP, turbine bypass, heat pumps, heat accumulators, electrical boilers and heat only boilers can result in a multitude of different production mixes that are optimized against the electricity market under the given local constraints e.g. heat demand.

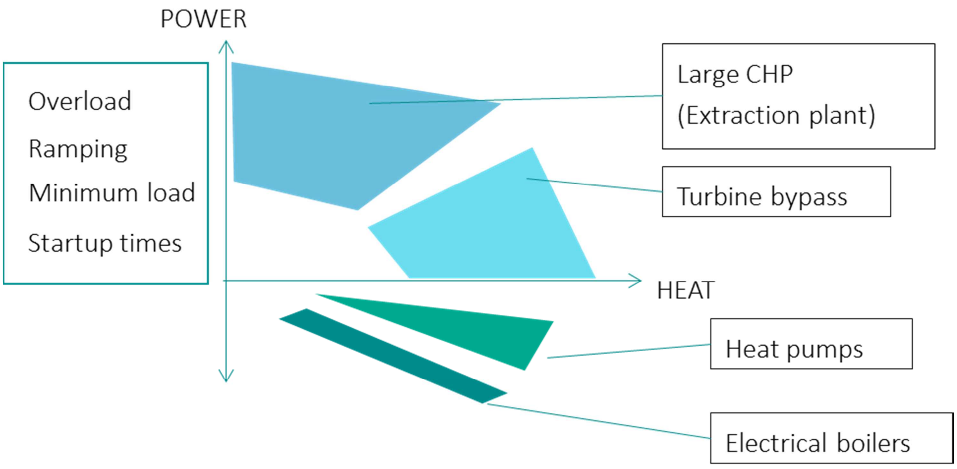
Two important preconditions for the optimization and planning are 1) contracts between heat producer and supplier that allow the flexibility, and 2) the spot market with hourly products allowing electricity prices to vary greatly during the 24 hour day.

3.3 Summary

The thermal power plants have more measures to increase flexibility, and in the Danish case both flexibility on power production and combined heat and power production, have been important. The different measures are summarized in figure 8.

In this report the focus will be on power production flexibility from overload, ramping, minimum load and start up times.

Figure 8: Illustration of power production potential on thermal combined heat and power plant



4. The Nordic market design and flexibility

In this chapter we focus on the Nordic market design to incentivize flexibility of thermal production. The market design may also have other more specific objectives as to create incentive for new investments in specific technologies, grid investments or increasing accessibility of electricity that need to be taken into consideration, when developing a market design. In the following it will be described how each short term market from the day-ahead market to the balancing market overall works and has developed, and how it incentivizes power plant flexibility.

Electricity markets and production and consumption are influenced by a number of regulatory frameworks as taxes, subsidies, legal approvals and restrictions, ownership and other political interests but are not dealt with in this report. At the same time fundamental factors for a market as competition, power exchanges and competition regulation must also in some way be in place and are also not described here [9].

[9] For more information see: Power markets and power sector planning in Europe, Danish Energy Agency, October 2015, or Flexibility in the Power System – Danish and European Experiences, Danish Energy Agency, October 2015.

A number of issues in the market design influence flexibility. Below some of the most important issues will be described, and table 2 gives an overview of the current Nordic market design, which will be described in the following sections, and the table can be used as guidance.

Table 2: Key characteristics of the market design for the Nordic Power market

	Day-ahead	Intraday	Balancing
Market type	Auction/Marginal pricing	Continuous bid matching	Prioritized bid activation/mix of marginal price and pay as bid
Minimum Product size	1 MW	1 MW	5 MW
Gate closure time	12-35 hours	60 minutes	45 minutes
Bid linking	Yes	No	No
Validity periods	60 minutes	60 minutes	60 minutes
Settlement of imbalances	1 hour (2-price model)		

4.1 The Nordic Day-ahead

The day-ahead market is executed as an auction the day before real time for 24 hours and handled by the Nordic power exchange Nord Pool[10]. For every hour in the coming calendar day, all bids are summed into demand and supply curves, and the intersection determines the price and volume for that hour. The price is settled as pay-as-cleared. “Marginal pricing” is another commonly used term for this pricing principle.

The maximum price is currently 3.000 Euro/MWh. But the Nordic day-ahead price has historically never reached the maximum price, but this might change in the future, with less thermal capacity. The maximum price has to balance both the risk for the consumers of very high prices and be high enough to incentivize earnings for peak load plants with only few hours of operation.

The minimum bid size in the day-ahead market is 1 MW and no maximum bidding size. For very small production units an aggregator might be necessary to establish a portfolio and for very small producers it can be the responsibility of the system operator to balance and settle the production. For large thermal power plants it is often an advantage to split up production in more bids as marginal production costs can vary from low to high production and in bidding areas with limited liquidity the bids might be split or not activated by the power exchange if it is not possible to balance demand and production.

In the Nordic spot market the timespan between bidding and delivering power is 12 to 35 hours. It is reasonable time for the thermal power plants to plan their production. In some power markets it is demanded that expected production or consumption are balanced in the day-ahead market. This is not the case in Denmark and this is mainly an advantage for VRE.

10 From 2017 it was possible for more power exchanges to establish in same market areas to create competition

In the Nordic market the consumers and producers are obliged to send expected production or consumptions plans to the system operators, following the same gate closure times on the day-ahead spot market. Considering variable renewable energy sources and the day-ahead market, this is close enough for the system operator to forecast based on weather prognoses fairly precise how much power can be produced and consumed to assess the system balance and potential need for balancing (see section on balancing market).

The change in activation between the hour shifts can be a challenge for thermal power stations. The ramping period for the power plants creates a difference between sold electricity and actual production, and the difference is treated as an imbalance (se section 4.4) and with a large difference in production from hour to hour there is a relatively high imbalance cost, which has to be taken into account in the bidding strategy of the power plant owner. The flexibility to ramp up and down fast is therefore important. In the Nordic market the imbalance settlement period is currently 60 minutes. This reduces the cost for the market participants as they can net out imbalances during the hour and leave the continuous imbalance (within the hour) to the system operator. There is a European development towards a harmonization of a quarter hour resolution in the markets to incentivize flexibility from consumption and better integration of VRE, and with expected higher time resolution in the intraday and balancing markets.

To allow for flexibility, a number of opportunities to link bids are made available. For thermal power plants it has high costs to start and stop from hour to hour and with the possibility to link hourly bids this can be avoided. The linking of bids is described in the example below in section 4.1.3.

Situations when VRE production is higher than demand can be a challenge. To avoid forced curtailment of wind power negative power prices was introduced in the Nordic day-ahead market from 2009. In the Danish bidding areas there have been negative prices in 10-100 hours per year, and wind power production is voluntarily reduced as a consequence. The negative prices have also incentivized thermal power plant flexibility, but also increased use of electricity for heat. This has further been incentivized by law as all power producers, incl. wind turbines, are responsible for balancing their respective production and have incentive to optimize production on the power market to reduce imbalance costs.

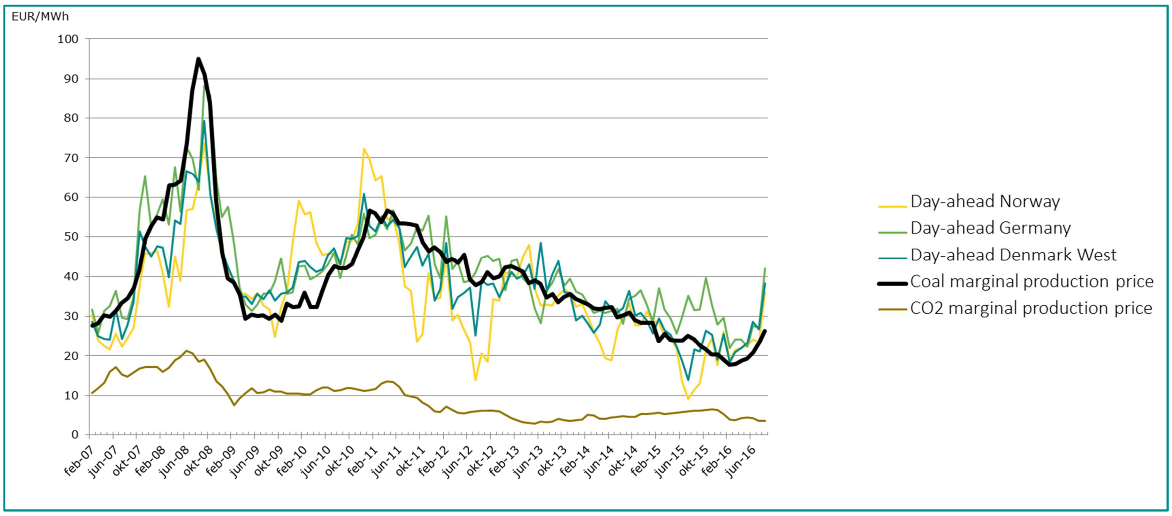
All important market data regarding day-ahead power exchange are published almost real time and in a fairly detailed fashion. This transparency enhances the function of the market, e.g. makes it easier for new entrants and existing market participants to assess the risks, and potentially profit in the market. In the power market all transparency measures add to the understanding also in services adjacent to the power market and services interacting with the power market without actually trading in the markets.

4.1.1 Power price development

The power prices in the Nordic synchronous area have a repetitive seasonal cycle mainly shaped by the large share of hydro. Hydro power plants have significant influence on power prices, and when there is a dry year in the Nordic, power prices go up, and vice versa. Thermal power plants have a natural role in the variations season to season and year to year.

In the Nordic production mix the most expensive bid often comes from a thermal power plant. Figure 9 shows the variation in power price in Norway, Denmark and Germany and compares with the marginal production costs from a coal fired power plant. There are dry seasons in winter 2010 and 2011 and wet seasons with prices lower than the marginal coal production price. In Germany the price is often set by thermal power and the power prices in Denmark varies between the Norwegian and German price. The Danish bidding areas have similar prices with one or more neighboring bidding areas in more than 90 % of the hours per year.

Figure 9: historic development of electricity price and thermal power marginal production costs



Source: Nord Pool and Danish Energy Agency

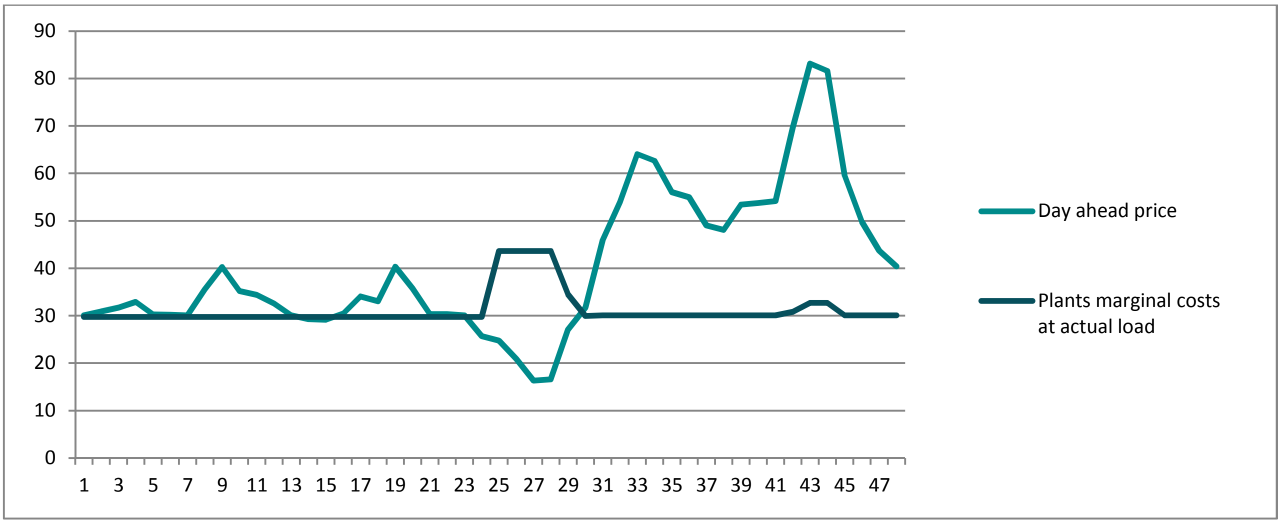
4.1.2 Example: value of thermal power plant flexibility

This simplified example shows how a thermal power plant could choose to bid and run according to the price variation over 48 hours in March 2018. The two days show four price peaks and a low off-peak in the night between the two days. The plant is assumed to have a load range between 35 % and 115 % of optimal load and production costs of 30 €/MWh with 45% efficiency and efficiency is reduced at minimum and overload.

The plant chose to go to minimum load for 6 hours where market price is lower than the plants marginal price (hour 23-29). Because efficiency decreases, when the plant operates outside optimum, the plants marginal cost gets higher. Still it is an advantage to go to minimum load to minimize economic loss. Since the gap with operating losses is only 6 hours, the plant chose to run at low load instead of shutting down as the start-up costs is assumed to be higher than the loss.

Figure 10 also shows a slight increase in the plants marginal price in the two hours with best market price. That is caused by extra production costs from overload production to produce more to the market with the favorable price.

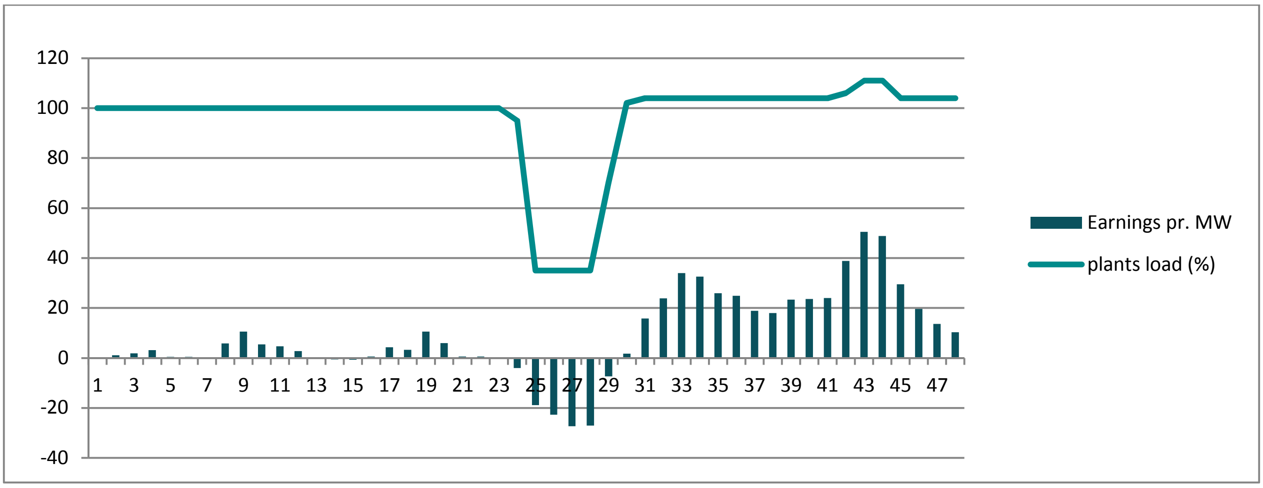
Figure 10: Western Denmark day-ahead price and marginal production costs for thermal power plant during 48 hours in March 2018 (€/MWh)



Source: Energinet calculations

Figure 11 shows the earnings achieved by the plant. It shows that the plant loses money during the six hours with low prices; it loses almost the same amount it has gained during the two preceding price peaks. It is also shown a considerable gain in the latter 18 hours of the period. It illustrates the importance of being able operate with flexibility as the market price goes up and down.

Figure 11: Load and earnings for thermal power plant, Euro/MWh



Source: Energinet calculations

4.1.3 Example: Block bidding

The high start-up costs can prevent thermal plants from bidding because the volatile power prices can lead to varying earnings/losses from hour to hour.

If a plant bids full production each of 24 hours at 30 €/MWh and the resulting price of the day-ahead auctions moves above and below 30 €/MWh, the plant will have to start and stop several times to avoid losses or try to sell excess production on intraday and in the balancing market but with the risk that the price is lower than marginal costs. If on the other hand the plant has a bidding strategy, where start-up costs are added to each hour, the bids will be so high that the plant will get much less production than the plants actual marginal price would indicate. The solution is that the power exchange allows block bidding. Power plants can offer blocks of several hours of production on basis of an average price in the hours in the block. The plant can then distribute start-up costs on all the hours in the block, and bid with a lower price. Thereby the plant has a much greater chance to be competitive and to produce for several consecutive hours. In table 3 below an example with a 400 MW thermal plant is illustrated. Without block bidding the marginal costs are 55 €/MWh and with the possibility of four hour block bids the costs are decreased to 36 Euro/MWh and is closer to the actual marginal costs when the assumed startup costs of 10.000 Euro are divided on four hours instead of only one hour.

Table 3: Illustration of bidding with hourly bids and block bids for thermal power plant

Hour	Hourly bids	Block bid 1	Block bid 2	Block bid 3
6-7	55	36		
7-8	55	36	36	
8-9	55	36	36	36
9-10	55	36	36	36
10-11	55		36	36
11-12	55			36
400 MW thermal coal fired power plant				
Start-up costs			10.000 Euro	
Marginal production costs			30 €/MWh	

Source: Energinet

Block bidding is important because it gives thermal power plants a possibility to participate in power markets with volatile prices and optimize production and availability to deliver flexibility. Without block bidding power plants would be operating in longer periods with high prices and close down in periods with average low prices. With block bidding the power plants have larger incentive to participate all year and all day which increases the availability in the intraday and balancing markets.

4.2 The intraday market

The intraday market is a possibility to adjust the power portfolio after day-ahead and to deliver flexibility. This is especially for thermal power plants a potential for extra earnings.

In the Nordic market the intraday market opens shortly after day-ahead prices are set, and closes 60 minutes before real time operation, but with the possibility to continue intraday trading OTC within each bidding area another 15 minutes, i.e. until 45 minutes before real time. Both producers and consumers can sell and buy electricity on the intraday market and optimize their portfolio or deliver flexibility. This is relevant if for example wind or solar units turn out to have a higher or lower production than foreseen in the day-ahead market, and this can often be the case. For all market participants the intraday market is an opportunity to use the markets to adjust according to much more precise forecasts.

The Intraday market is settled on a direct pay-as-bid price setting, and is often handled by aggregators for the smaller market participants. It can be costly to continuously adapt bids to forecasted production or consumption and the aggregators are given a mandate to optimize the portfolio. Minimum bid is 0.1 MW and no maximum bid. There is no maximum price. If production or consumption is not optimized to actual production during intraday, the market participants faces the risks of higher imbalances settled at the imbalance price.

In the Nordic the intraday market plays a smaller role than in other European countries. This is due to the well-functioning balancing market and relatively low prices for balancing see section 2 above. In Germany and Netherlands intraday is very important for the self-balancing of the market participants. Here the intraday market is open up until the operational time and it is possible for the market participants to trade their imbalances. This is opposite from the Nordic market, where the TSO takes over the responsibilities for imbalances 45 min before gate closure and this is explained in the next section.

As intraday is practically an adjustment to expected production, compared to day-ahead, the products are the same and imbalances are handled in the same settlement. Bids and offers are published and transparent for the markets, whereas settled prices are less transparent, because only an average price of the total number of trades in each hour is published. It is an open market, where a trade is conducted every time two opposite bids match, and then the average price is recalculated.

4.2.1 Example: Optimization of production on intraday

With the flexible production from thermal power plants the intraday market is an interesting opportunity to increase earnings. The intraday price is often in line with the day-ahead price, but can also differ quite a lot if unexpected things happen and the price for a given hour can vary from hour to hour up to actual operational hour. This gives opportunities for flexible power plants.

In these simple examples it is assumed that a thermal power plant has sold 100 MW at a certain hour in the day-ahead market at 33 Euro/MWh and with production costs at 30 Euro/MWh.

In this first example, an excess production on the thermal power plant of 10 MW compared to volume contracted on day ahead is expected as the operational hour approaches. The power plant owner can try to sell the 10 MW as up regulation or buy down regulation to balance itself. The intraday market is direct settlement with a counterpart and to get the optimal price the power plant can choose to offer more bids for the 10 MW above and below the marginal production costs at i.e. 36 Euro/MWh, 33 Euro/MWh and 30 Euro/MWh and down to the expected down regulation imbalance price often lower than the day-ahead price. The plant owner might be lucky that the price in intraday is higher than day-ahead if there is a demand for up regulation, i.e. a wind forecast is lower than expected, and there is a higher demand for production. Alternatively the power plant must accept the lower down regulation price in the intraday market below day- ahead price or try to sell the excess production on the balancing market or ultimately accept to be in imbalance and thus pay the imbalance price for down regulation.

In the second example the plants expected production equals the volume contracted on day ahead. Here excess capacity or capability to reduce production can be sold on intraday for extra earnings. For up regulation the same strategy is used as above, but with no bids lower than 30 Euro/MWh (marginal production costs). If excess production from wind is expected compared to forecast, the intraday price will very likely be lower than the day-ahead. The power plant then has an incentive to buy production at lower price than own production costs, sell settled volume from day ahead as down regulation and reduce own production. The example for this case is that, the plant has sold 10 MW in the day ahead at 33 Euro/MWh and with profit of 3 Euro/MWh. Now the plant buys 10 MW production on intraday at 25 Euro/MWh, sells down regulation at 20 Euro/MWh and reduce own production with 10 MW. The plant saves 30 Euro/MWh in production costs, and still earns 5 Euro/MWh from the difference between bought up regulation and sold down regulation, which is higher than the profit of 3 Euro/MWh in the day-ahead market if the power plant had not tried to optimize its production on the intraday market.

The power plant can place new bids to test the market further, all up to 60 minutes before real time. The higher the flexibility of the power plant, the better it can use the potential benefits of the intraday market to deliver flexibility.

4.3 The Nordic balancing market

After intraday gate closure the Nordic TSOs takes over the responsibility for the physical balancing of the electricity system. To secure the balancing the TSOs both relies on buying reserve capacity and on market participants to give their voluntary bids for flexibility in the balancing market, i.e. excess capacity for up regulation or reduce production for down regulation, including wind and solar.

As described earlier the Nordic countries employ a proactive operation philosophy. Proactive operation implies that the TSO collects production and consumption plans several hours ahead, and at the same time the TSO use meteorological forecasts to validate the plans. All these data allows the TSO to predict imbalances half an hour ahead. The TSO then uses the reserves and the voluntary bids on the balancing power market to balance the system.

The common Nordic balancing market is a merit order list of separate bids of down and up regulating power bids to increase or reduce production/consumption. The asymmetric bidding makes it easier for wind power to participate and for thermal power plants to optimize pricing of down and up regulation depending on production costs. Gate closure time for bids is 45 min. before hour shift, but TSOs can activate bids at any time in the operational hour and the merit order is used dynamically by the TSO to balance the gap between production and consumption in real time. If production is too low, bids for upwards regulation is activated. If production is too low, bids for downwards regulation is activated. The marginal pricing is used for settlement of the price to give transparency and incentive to participate in the voluntary balancing market.

Market participants place upward or downward regulating bids, which are then activated when necessary in merit order, i.e. the cheapest bids first. Power producing units running at maximum production can offer downward regulation, as can industrial consumers by increasing consumption. Currently the minimum bid size on the balancing power market is 5 MW, which means that only larger industrial consumers or producers can place bids or alternatively in a portfolio of bids.

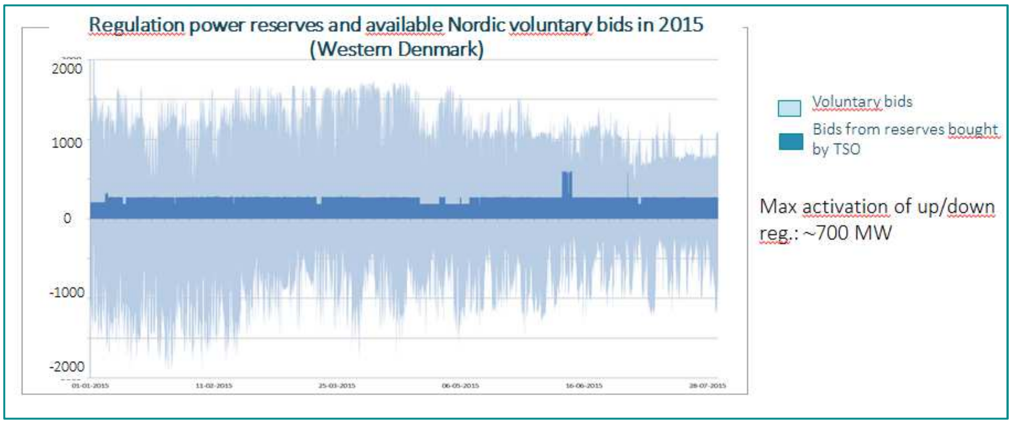
The required time from activation to full power delivery is 15 minutes, and this is enough time for thermal power plants to be able to participate.

Upward regulation is the most critical balancing and Energinet buys upward regulation reserve capacity. This is an attractive market for thermal power plants as they can increase production on demand. Downward regulation can always be achieved by reducing production from wind or power plants. Upward reserve capacity is obliged to place hourly upward regulating bids on the balancing market in the periods they are contracted and paid. They can bid with any price they want up to the maximum price of 5000 Euro/MWh, but they must place bids according to the volume that is reserved. Energinet buys reserve capacity roughly corresponding to the largest power supplying unit in the price area. Also interconnectors are considered in this context, and often they are the dimensioning factor. The reserve capacity is purchased in different ways in the two price areas in Denmark. In the western price area reserves are purchased in daily auctions the day before real time. In the eastern price area reserves are bought on five year contracts as the amount of reserves are more limited. Currently wind and solar are not allowed to participate in the capacity market without back up capacity to be sure the load is available if needed, and this is an advantage to the thermal power plants.

The bids placed on the balancing market without reservation time ahead, are called voluntary bids. Voluntary bids for upward or downward regulation can be placed until 45 minutes before real time. Contracted bids must be placed 5 p.m. the day before. Since 2012 wind turbines has been allowed to take part in the balancing market. They do this in an aggregated portfolio. Typically wind turbine farms under same balancing service provider take part in the balancing market and usually only offering downward regulation.

In average over a year the Nordic balancing power market has more than 1.000 MW available for upward and downward regulation in the Danish bidding areas and this is much higher than the needed reserve capacity. Figure 12 shows the available bids for activation and the reserve capacity bought by Energinet on a daily market in Western Denmark in 2015.

Figure 12: Available Nordic capacity in the balancing market for the bidding area of Western Denmark



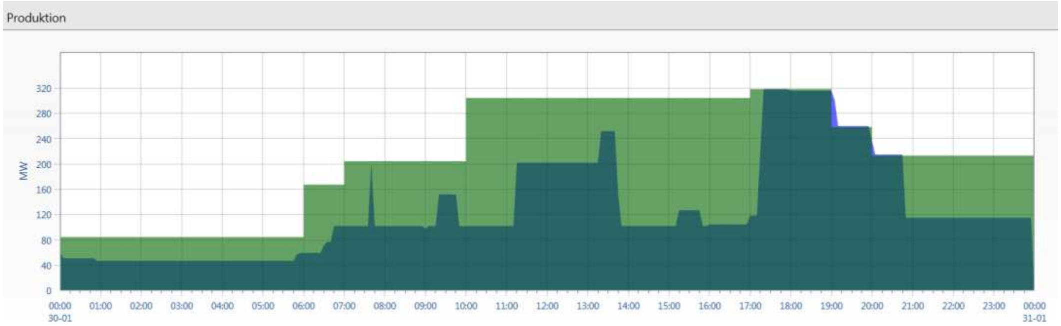
Source: Energinet

When day-ahead prices are negative the system is sometimes confronted with a problem, that wind turbines have already stopped production and down regulation potential from voluntary bids can be critically low. A solution could be to buy down regulation capacity, which could be an attractive product for thermal power plants to offer.

4.3.1 Example: Advantages of a lower minimum load and ramping

An advantage of very low minimum load on thermal power plants is that they can participate in the day-ahead market with minimum load, say 20 %, and then participate in the intraday and balancing markets with the remainder of the plant capacity. If there is a great demand for flexibility, the prices are likely to be higher in intraday and balancing markets. Therefore, plants with higher levels of flexibility will be able to minimize the production sold at low prices, and maximize the production at high prices, yielding higher profits.

Figure 13: Production from thermal power plant sold on day-ahead power exchange (light green) and actual production (dark green) from 30 January 2018



Source: Energinet

Figure 13 shows power production on 30th January 2018 from a Danish coal fired unit. The light green area is the production sold in day-ahead, while the dark area is the actual delivery. The plant is able to adjust its production very fast. In certain periods it can adjust production by 16 MW per minute and on this particular day, there was a great amount of wind production, meaning that the plant's flexibility to lower production was wanted, in order to keep balance in the system.

The difference between the light green area and the dark green area is equal to the amount of power that the plant has bought from a wind power producer and down regulated own production saving production costs. Hence, the plant lowers its production in order to let wind power producers maximize their production based on the intraday price signal. From the power plant's perspective it simply substitutes its own more expensive production with cheaper wind production it can buy in the intraday market in those hours. The market actors utilize the intraday market to optimize their own profit by either increase or reduce production, which at the same time ensures that the overall social welfare is maximized. In this isolated example the market ensures that the lower marginal cost wind production is fully utilized and balanced by substituting more marginal cost expensive fossil fuel production avoiding last minute expensive balancing by TSOs or in the worst case forced curtailment. How the overall net benefit is shared between the two actors in the given example depends on the particular prices during the relevant hours in the market.

As there is a requirement to upward regulation reserves to reach full activation within 15 minutes from the activation signal is given, the plant must be running at some load because start up time by far exceeds 15 minutes. Normally the power plant will choose to sell as much as possible on day-ahead. If a thermal power plant is not able to sell up regulation reserve capacity to cover costs at minimum load, the power plant owner can choose a bidding strategy to offer at a lower price in the day-ahead than marginal production costs to be able to increase earnings in intraday and balancing market. In an example of the practical application of such bidding strategy, the plant would offer 20 % (minimum load) at a very low price in day-ahead, which at normal price level would lead to engagement in the market with minimum load, and free capacity to act on other markets if day-ahead is below marginal production costs. In intraday the offering of excess capacity should be at high prices above marginal production costs as the settlement is pay-as-bid. In the Nordic balancing market the price is settled with marginal pricing and offer of up regulation of excess capacity should be at marginal production costs to optimize earnings and production.

4.4 Power imbalance settlement

To incentivize power producers to deliver exact production plans to the TSO, in turn allowing the TSO to perform high quality proactive system operation, The Nordic TSOs impose a payment for producer's imbalance between planned production and actual production. This is called the power imbalance settlement. The total amount of power imbalance settlements per year is approximately 1.5 mio. Euro and less than 0.1 Euro/MWh and is a relative small amount compared to the overall revenue in the power markets, but as long as the imbalance price on average is higher than the day ahead price it has an important effect on the quality of production and consumption plans to be delivered to the TSOs.

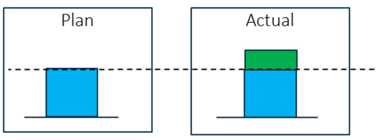
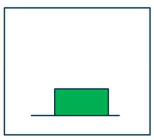
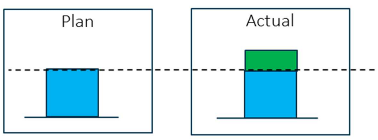
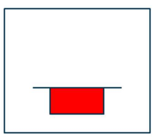
In Denmark production plans can be changed until 5 minutes before real time. Both thermal power and VRE must deliver production plans and are part of the imbalance settlement regime. Power imbalance settlement is yet another incentive to ensure Energinets ability to have a pro-active balancing. Energinet also forecast variable renewable energy production by the help of own meteorological forecasts as plans from the wind power production and solar might be delivered late and changed in the last minute.

4.4.1 Example: Nordic two-pricing model for imbalance settlement

In the Nordic market a two-price model for imbalance settlement is used. The imbalance settlement price for producers and consumers are different to reflect capability of the production to be flexible as opposition to consumption and give incentive to deliver voluntary bids in the balancing market. Therefore production pays a higher price for imbalances. In figure 14 the imbalance settlement is described for a situation where the producers generate more than its production plan. If production is higher than planned and the imbalance helps balancing the system the producer receives day-ahead price for the excess production. If the production is increasing system imbalance, the producer receives the down regulation price, which is often lower than the day-ahead. If the production is lower than planned the producer only pays the day-ahead price if it improves the system balance, and must pay the up-regulation, if it increases the system imbalance.

If the consumer has an imbalance, they always pay the day-ahead price if they increase the system imbalance, and receive the balancing market prices if they improve the system balance.

Figure 14: Illustration of imbalance settlement with producer generating more electricity than production plan

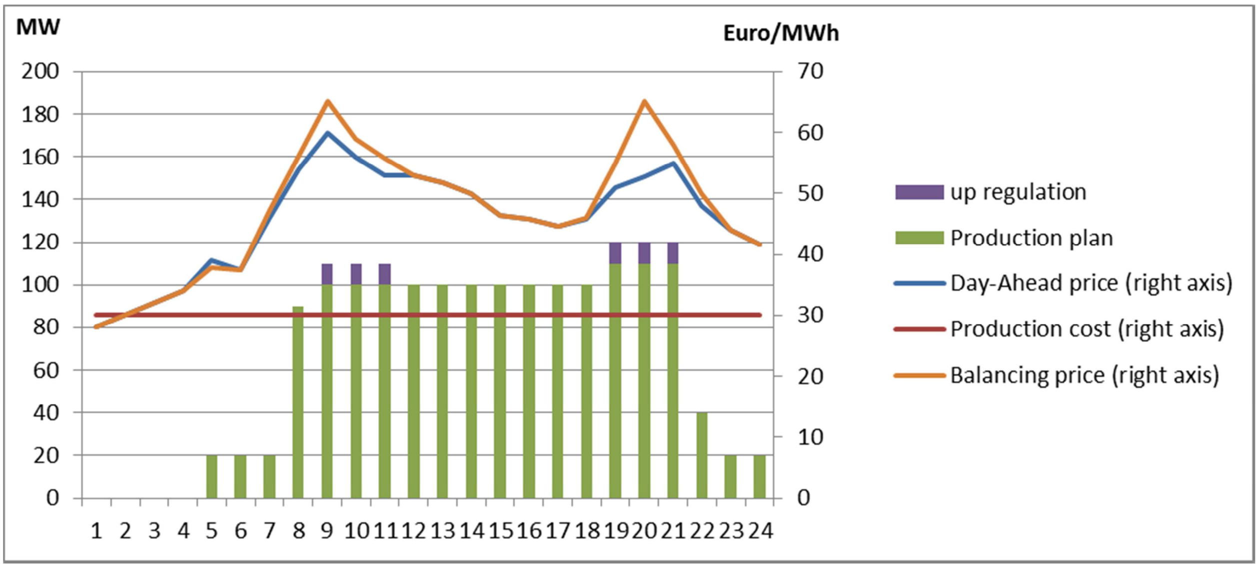
Producer with positive imbalance	Regulating power	Imbalance price
		• Actual production improves system imbalance • Excess production imbalance recieves Day Ahead price
		• Actual production is increasing system imbalance • Excess production imbalance recives imbalance price (lower than day ahead price)

4.4.2 Example: benefits of flexibility in balancing markets

First of all, the intraday and balancing markets give the opportunity to optimize the production both in case of unexpected changes in production and for increasing earnings.

Figure 15 below illustrates how the day-ahead price sets the reference production plan (red columns) and in the balance and intraday market the power plant can offer up and down regulation (blue and green columns), as the intraday and balancing prices are settled. With low minimum load in hours 5-7 the power plant start up to deliver on production plan from day ahead. The minimum load production is sold with a loss on the day ahead and in this case the balancing price is not higher and there is no incentive for selling up regulation. In hour 7-8 fast ramping from minimum load to 100 MW imbalance is reduced and during the day, capacity is offered for flexibility, where in this example up regulation for balancing is attractive in most of the time from hours 9 to 11 and hours 21 and 22.

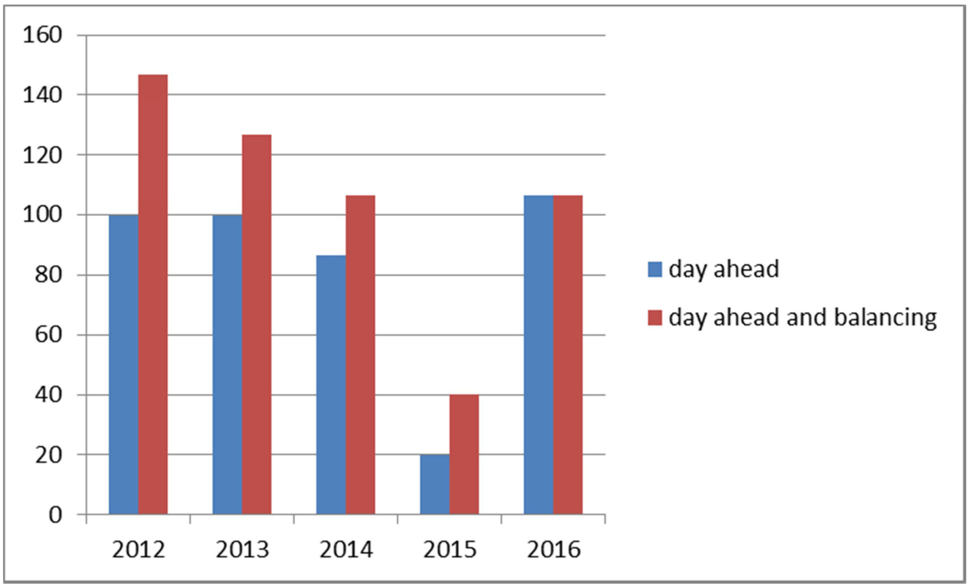
Figure 15: Illustration of optimization and offering of flexibility on intraday and balancing markets for thermal power plant



Source: Energinet

Assessment of the historic potential for increasing earnings for thermal power plants by participating in the balancing market shows there are good opportunities to increase earnings. Based on the historic day-ahead and balancing prices in Western Denmark the percentage difference in earnings for a thermal power plant participating in day-ahead only, and in both the day-ahead and balancing market is shown in figure 16. In 2012 earnings could be increased with more than 40 %, whereas in 2016 it made no difference. At the same time it can be seen, that earnings are very volatile from year to year. The day-ahead market has the by far largest volume but the balancing markets play an increasing larger role for thermal power plants, as their number of operational hours have decreased.

Figure 16: Assessment of potential earnings from participating in balancing market in Western Denmark (index)



Source: Grøn Energi and Energinet

To be able to take active part in the market optimization it takes a solid forecast to back a bidding strategy to foresee high up-regulation prices or need for down regulation. Further good availability of all market data and good tools for data analysis are important. Data access is crucial and a corner stone in the transparency that makes markets function, and predictive analyses is a parameter of competition.

4.5 Other balancing markets

Energinet and the other Nordic TSOs have further reserves at hand that are used for fast frequency stability of the transmission system.

These are two different automatic reserves: Frequency Containment Reserves (FCR) and Frequency Restoration Reserves with automatic activation (aFRR). The full capacity on these markets is purchased as reserves i.e. they are paid to be ready to potentially become activated between 15 seconds to 2-5 minutes. They are then activated automatically, when the system needs regulation from these sources, and for the energy activated the suppliers of aFRR are also paid but not for FCR as the running time is limited. These reserves and activation are today mainly delivered by thermal power plants in Denmark and from hydro in Norway and Sweden.

Wind and solar could in principle participate in the aFRR and FCR market but costs for installing the necessary communication and regulation equipment is relatively expensive and it is a challenge to deliver capacity. With increasing battery and storage capacity this technology can also be attractive. With harmonized and future integrated and larger markets the costs for equipment and attractiveness of participating for new technologies is expected to increase. This will increase competition and potentially result in lower prices and reduce the market share of thermal power.

4.6 Non-frequency ancillary services

A robust transmission system needs inertia, short circuit power and voltage regulation. These products are called non-frequency ancillary services collectively. Broadly speaking non-frequency ancillary services protect the transmission system from black-out in the inevitable event of fall-out of a large unit in the system. These services are also mainly delivered by thermal power plants today.

The first generation of variable renewable energy production units is incapable of delivering non-frequency ancillary services in qualities corresponding to thermal power plants. This is yet another potential source of income to thermal power plants, and part of it is purchased on market-like condition or at a regulated price. There is an ongoing work to increase the use of market mechanisms in the purchase of non-frequency of ancillary services.

With very high penetration of VRE an important question is where non-frequency ancillary services shall come from. Thermal power plants delivers non-frequency ancillary services as a by-product when they produce power, and the falling share of conventional thermal power production in Denmark has led to scarcity in some of these properties. The properties then have some value above zero because of the scarcity, which can be measured and documented in the grid.

In economic theory, by-products with monetary value should have a price formation mechanism in the market for the product and by-product to find equilibrium at the right quantity. For alternative producers of the by-product the price signal gives a monetary measure to evaluate a possible entrance into the market. In Denmark an attempt is on the way to pay for the delivery of non-frequency ancillary services from thermal power plants to the high voltage transmission system. The level of payment does not warrant market participation only to deliver non-frequency ancillary services, but in a marginal production calculation of a thermal power plant, the payment can tip the outcome towards market production in more hours. Maybe the future will show that the by-product has a much higher value than the power production. Then the main purpose of thermal power plants could be to deliver non-frequency ancillary services.

4.7 Lowering barriers for new entrants

The Nordic power exchange currently has ca. 360 members, i.e. entities placing bids on the different markets, mainly the day-ahead market. The power exchange, Nord Pool, and the Nordic TSOs are alert to have as many players on the market as possible, because of the obvious benefits to the market to have as much competition and liquidity as possible. Mitigating the inevitable complexity in power markets is done for example by having the highest possible degree of transparency. Transparency means detailed information about prices and volumes the soonest possible, as well as information on all other circumstances in the market e.g. revisions, failures and change in procedures. Aiming for a high level of service in the administration of markets is also a measure of transparency.

To have markets work well, many participants is an advantage. Places where barriers can be lowered to encourage new entrants are:

- Product definition. Product definition is tied to the physical properties of the product, but sometimes definition of smaller units can let more participants into the market. There is a trade-off limit because smaller units increase the amount of data to be handled, and other administration matters. This limit moves constantly.

- Auxiliary technical requirements. Technical requirements surrounding the product, is sometimes controlled and measured in a prequalification process. Often parts of these are more nice to have than need to have. For instance a very high frequency of online measurements.

Due to the complexity of power markets, checks and balances along every process is necessary for operational security. This causes some amount of administration on market participants. Whenever market rules are changed, e.g. product definitions, these processes are disturbed and it takes some time to reestablish routines. Also changes are often followed by some IT-investments. These are good reasons to reduce the numbers of changes, for example by planning them to come in batches.

Pilot projects, where different requirements to market participants are alleviated on an experimental basis, has been used in the Nordic markets to test new methods and help new types of participants to enter the market. This is a good way to make sure that markets are continually developing and a litmus test whether the usual way is still the best way. An example of such a pilot project is aggregated demand side capacity supplying frequency containment reserves (FCR), albeit technical requirements to the product were not completely fulfilled.

5. Conclusions and market development reflections

For CHP plants many measures exist that enables the plants to continuing serving the local heat demand while increase the flexibility of the power output. The most obvious possibilities for thermal power plant to improve their power output flexibility are however:

1. Faster ramping
2. Lower minimum stable power production
3. Shorter start up times
4. Overload capability

The key to flexibility in the Nordic power market is the continuous public disclosure of the price signals reflecting the power balance and need for flexibility. With the voluntary bids and participation in the intraday and balancing markets the thermal power plants can react and benefit on it almost up to operational hour. In the day-ahead first indication for the need for flexibility is established, and as forecasts for wind and solar might change or handling of unexpected events the intraday market, and finally the balancing markets can in almost all situations deliver the flexibility needed to handle the imbalances that arises after the day ahead market is closed.

Further the product design is important with low minimum bids, linking of bids and high caps on prices. Finally the imbalance settlement must reflect the real costs of balancing the electricity system and incentivize market participants to either make flexibility available to the market and the TSOs or to reduce their imbalances up to the operation hour. The voluntary bids in the balancing market play a very important role in that matter in the balancing of the Nordic power system.

Table 4 summarizes the flexibility and benefit from thermal power plants and how the Nordic market incentivizes the use of the flexibility.

Table 4: Incentives for thermal power plant to deliver flexibility

	Reduce start up times	Reduce minimum load	Overload capability	Ramping
Situation	Low power prices during off peak	Volatile power prices below production costs	High day ahead, intraday or balancing prices	Volatile power prices and changes in production volume
Benefit	Shorter period with imbalance and loss on power production during start up	Reduce costs in hours between high and low prices. Increase possibility to optimize earnings in intraday and balancing market.	Supply extra capacity and earnings	Reduce costs for imbalance
Market incentive	Linking bids	Price reflect market situation and trading close to operation	Prices reflect scarcity situations and trading close to operation	Imbalance settlement reflect system costs

But it is not all parts of the Nordic market design that are optimal for incentivizing flexibility from thermal power plants. The incentivizing force for flexibility is transparent and reliable power prices reflecting the demand for flexibility in all time schedules. The Nordic market design calls for certain products and reward:

- Invariability in 1 hours resolution
- Availability
- Ability to react fast
- Sustain production in time

Overall the Nordic market works well for thermal power plants, though it was originally established to dispatch hydro-power. The hour shift and ability to react fast is still and advantage for hydro compared to thermal power. But the thermal power plants have over time adapted and most importantly the price signal has from the beginning been very transparent. Table 5 gives and overview of the benefits and disadvantages of the Nordic market design for thermal power plant flexibility.

Table 5: Benefits and disadvantages for thermal power plants in the Nordic market design

	Forward markets	Day ahead	Intraday	Balancing	Other flexibility
Thermal power plant incentive	Long term risk management (incl. seasonality)	Main platform for offering capacity	Production optimization	Deliver flexibilty	Technical capabilitees
Nordic market advantage	High liquidity Reduced need for long term contracts	Linking of bids Transparent price setting	Cross border market	Sell Reserve capacity Voluntary bids	Part of grid codes. Cost+/regulated prize
Nordic market disadvantage	Limited volume in some price areas	Ramping in hour shifts	Limited liquidity	Product definition (hydro advantage)	Reduced transparency on system demand

Improving flexibility on startup time, minimum load, ramping and overload can increase earnings for thermal power plants. It is difficult to say what the exact economic benefit of change in startup time, ramping, minimum load and overload capacity is. It is very dependent on market and imbalance prices, volatility and the very concrete power plant and operations management.

Until now the Nordic market development has been a success and supported the integration of high shares of wind power in Denmark, but change and adaption is needed to continue the success and the integration of even higher shares of VRE. The market design should secure reliable, adequate and cost efficient production and not least system flexibility.

To support this, a stable regulatory framework for the market actors is needed together with a competitive market that facilitates the flexibility needed for balancing and other critical system services. Markets should as far as possible be designed as non-discriminatory with regard to which technologies that can deliver the flexibility and services. Product definitions shall minimize overall system and balancing costs by reducing barriers for all producers and consumers in the market. A crucial market design element is to secure that reliable and transparent price signals are established in the market, which the market participants can react to. This should both support operational flexibility in the short term, but also support the market participants' ability to foresee what services and technologies that will be of high value in the future.

The three real time markets in the Nordics facilitate market participants to balance and optimize their operation and supports overall system balance. This gives a transparent price setting reflecting the demand for flexibility from day-ahead to operational hour and ensures security of supply. From the very start of the market marginal price setting has been used and created transparency, which has been particularly valuable for the many small producers and has ensured a high degree of competition. At the same time large price volatility and short periods with very high or low prices has not created demand for intervention in the market. It also reflects that both the political and market participant have confidence in the market. For thermal power plants the continuous price signals gives good information to invest and plan to optimize and benefit from the delivery of flexibility. Product sizes, bidding products on the power exchange, and imbalance settlement are all examples of design elements that have been changed to incentivize to deliver flexibility.

The Nordic electricity market is in many ways successful, but it also has its challenges. Subsidy schemes, taxes and tariffs are barriers for further market flexibility, and it takes time to change regulation and changes can only be done in small steps. For the market participants the primary challenge is generally not the expected volatility in prices, but rather the uncertainties on changes in regulation and how those potentially can influence prices and their risk management strategies. The existing market design and regulation together with technical obligations are to some degree a barrier for new solutions. The most challenging design feature in the current Nordic market design is the 1 hour product. It is not expected to be changed in the day-ahead, but with 15 minutes imbalance settlement as the agreed future harmonized period in Europe it will also change intraday and balancing products to 15 minutes in 2-3 years. For thermal power plants the block bids are very important tool for optimizing the production and it is expected to stay.

Besides the more specific market design considerations mentioned above, well interconnected and coupled markets are a key in the ability to integrate high share of VRE as variations level out. The ongoing and continued integration of markets in Europe further supports this and will also generally facilitate increased supply of flexibility. However, integration of markets also means harmonization and thus changes in design. This represents a trade-off between larger market area and the adaption of local market design. This is a challenging and long process and the European market integration shows it is time consuming but also necessary to be able to adapt contracts, strategies and assets to the new market conditions. A special feature of the Nordic market is also the large number of bidding areas and their limited size. The market was established by the TSOs for balancing and system operation and the bidding areas reflected grid congestions internally as well as between national borders. The small bidding areas give incentive to integrate bidding areas in the same market to increase liquidity and competition. Sweden started with one bidding area but after challenges with internal congestion and complaints from other Nordic market participants, Sweden was split in four prices areas in 2010. If consolidation continues in the Nordic power sector the Nordic model with more small bidding areas can be challenged if one company can influence prices. In Denmark high share of interconnector capacity has however limited this risk and this will also be the case in more of the other Nordic price areas.

To support the continued increase of VRE in Denmark in the future the existing sources of flexibility must be supplemented by integration of new technologies, further sector coupling and increased consumer flexibility. Further, non-frequency ancillary services from thermal power plants may become scarce at high VRE penetration levels and new ways of securing system stability and security of supply must be found. Some sort of payment for these services can be an additional means for thermal power plants to participate and creating an extra earning in this market or for other cheaper technologies to provide those services in the future. One thing is certain, the market design and regulatory framework needs to be continuously developed and refined to secure reliable, adequate and cost efficient production and not least system flexibility in the future for integration of VRE.

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