Flexibility in the Power System

- Danish and European experiences

DANISH ENERGY AGENCY

Table of Contents

1 Executive Summary

This report is prepared by the Danish Energy Agency, the Danish TSO (Energinet.dk) and Added Values as part of the program 'Boosting RE as part of China's energy system revolution'. The aim of the report is to present international and Danish experiences on the power market challenges with dealing with more and more fluctuating and volatile RE power production over time.

The report also describes how Denmark already has and going forward will secure sufficient flexibility and capacity at lowest possible cost through several different solutions – of which several can be applied and used in a Chinese setting. Particular focus is in the last part of the report given to the possible flexibility available from the Chines existing coal-based power plant fleet and how the overall economic dynamics of flexibility from power plants looks like in the light of current wind power curtailment in China.

Flexibility describes 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. It is important that a proper balance is stroke between at the one hand security of supply and the cost of investing in capacity and flexibility on the one hand.

From the international experts current understanding of the Chinese power system some of characteristics which already challenge or will challenge the system balance in the near future are conditions like; fixed (6-12 months) power price and production regime given very limited incentive to supply flexibility from power plants, a history and tendency to use the power plant units rather inflexible, large geographical discrepancy between production and consumption areas and consequently still substantial curtailment of renewable energy (RE) production.

The power marked system design in Denmark/Europe with a least cost dispatch in a day-ahead market is one way of ensuring all RE production is dispatch first. Given this, ensuring enough flexibility in the system requires the use of a multitude of different technical solutions coupled with an appropriate market design and economic incentive structure. One of the key solutions is increasing the size and number of interconnections to surrounding areas coupled with continuous work on developing market and regulatory platforms, which integrates larger and larger areas in one common market for production and consumption. This smooth the challenges variability from RE production poses to the system balance. This topic is separately dealt with in the report "*Power markets and power sector planning in Europe*".

Other important flexibility means is the development of a more and more sophisticated and precise forecast and scheduling system for RE production. Likewise the increased flexibility at the power plants has been a very important tool in absorbing more and more RE energy production in the system. In addition to these measures a multitude of other means are used to cope with increase share of RE – for example through power for heating and improve ways of co-producing heat and power. Through these measures a very high degree of security of supply as well very low curtailment of wind power has been made possible in Denmark.

Looking forward until 2025 and ultimately 2035 and 2050 considerably more wind and photo voltaic power will be established in Denmark. The target for 2050 is to reduce CO_2-emissions to zero. In 2035 the power production is expected to consist of up to 80% (dependent on the given scenario i.e. biomass or wind etc. scenario) fluctuating production, which is expected to intensify the two interrelated challenges for the power system with very high level of fluctuating production: Firstly, much higher level of variation of the total power production and secondly, how the security of supply can be kept at satisfactorily level as capacity of thermal power plants decreases.

The first challenge will within the near future require development of new market models and new use of technologies in order to keep the cost of handling the renewable electricity production at reasonable level and maintaining security of supply. Improvement and build-out of interconnectors and power grid will continuously be a key solution to smoothing production and consumption peaks. In the future it is expected that power, heat, gas and manufacture of fuel are even more linked together and electricity will be used whenever it is possible to substitute fossil fuels. The expectation is a higher usage of electricity for transportation and use of electricity for heating through heat pumps as well as heat storage. In time of electricity deficits (when power production from renewable production is too little to cover demand) the solutions are expected to be a mixture of securing the consumption through import of electricity and demand flexibility.

The second challenge is whether the security of supply can be kept at the high level of today as capacity on thermal power plants decrease as more thermal capacity is expected to be required after 2035. Securing sufficient capacity is typically either secured through strategic reserves, capacity markets and/or capacity payments. In many countries, different models are either under consideration or have already been decided upon and so far advantages and disadvantages to all three models have been observed. The right model depends on the given country’s characteristics.

When coupling the experiences in Denmark and Europe to the current situation in China it is assess that one of the cheapest ways of providing more flexibility in China is likely through improving the flexibility of the existing and future fleet of power plants. Further increasing penetration levels of RE production will of course require more extensive use of other balancing measures too.

When comparing key technical flexibility parameters between Chinese and Danish power plants it can - at this early analysis stage - tentatively be concluded that many key flexibility design values are identical. It can also be concluded that the approach for obtaining higher flexibility in China and Denmark in broad terms are the same. It is proposed to conduct an analysis in form of flexibility enhancement pilot projects on several and different power plant sites, varying in size, configuration, location and penetration of the grid with renewable energy sources to develop a profound knowledge concerning the costs and capability of enhanced operational flexibility on power plants. The result of this will be an important input for determine the least-cost development of a power system which with increasing penetration of renewable energy will need more and more suppliers of flexibility. It is further tentatively suggested on the basis of the European experience that a phase by phase stepwise flexibility optimization approach could be applied. The overall assessment from a technical perspective is that it is deemed possible to increase flexibility in the existing power plant fleet at very low costs and this is probably the cheapest way of providing more power system flexibility (at low to medium RE production penetration).

Danish power plant dispatches their production both to the general power market (Day ahead and intraday market) and to the ancillary service market thereby offering flexibility services. Secondary reserves are for example sold on a monthly basis to the TSO so they can use the reserve for ensuring sufficient flexibility. Other flexibility is offered by the power plants in the tertiary reserve capacity market through offering regulating power auction on an hourly basis. Offering of reserves are always fundamentally based on economic optimization – i.e. providing the product and services that gives the best return and profits to the power plant owner.

Assuming the technical capability of providing more flexibility from Chines power plants exist an economic incentive structure needs to be presented, which is sufficient to give the power plant operators incentive to change their operation capability and thus provide flexibility to the system when needed. Given the current market conditions in China where power plant operators are guaranteed a fixed yearly production and power price – then there is a total economic welfare loss when wind production is curtailed instead of power plants are providing the down regulation. A significant total welfare gain – equalling the saved variable production costs times the production - can thus be harvested if the proper incentives can be developed so the power plant owners are economic motivated to provide the down regulation. The lower the gross margin - or the higher the variable costs - the power plant owners have the smaller the needed incentive needs to be.

From both a technical and economical perspective there are thus very solid reasons for developing a political and regulatory framework, which supports both the technological development of flexibility on the power plants (perhaps through use of pilot cases to begin with) as well as create the right economic incentives for the power plant producers to provide the needed flexibility.

2 Introduction

This report is prepared by the Danish Energy Agency in cooperation with the Danish TSO (Energinet.dk) and Added Values as part of CNREC's program 'Boosting RE as part of China's energy system revolution' funded by the Children's Investment Fund Foundation. The aim of the program is to accelerate the deployment of renewable energy in China.

The report is one among others prepared for CNREC's reporting to the Chinese National Energy Administration (NEA) and covers European and Danish experiences with flexibility in the power system.

The report is closely linked to the report '*Power markets and power sector planning in Europe*', and the two reports should be read in the same context. Therefore you will find lots of references between the two reports on themes like the European power market, which is an essential subject for understanding both reports.

The structure of this report is firstly a definition of what is meant by flexibility in the power market followed by a presentation of our understanding of some of the main challenges China faces in terms of power market flexibility, which we hope our Chinese partner will comment on in order to deepening our understanding of the Chinese power market and its challenges.

Chapter 4 provides an overview of the measures taken by the Danish TSO with the aim of using the grid in a flexible manner in Denmark. Following this a comprehensive assessment of the technical potential of Chinese coal based power plants ability to provide more flexibility is given in Chapter 5.

Finally Chapter 6 describes how Danish power plant owners operate their plants in terms of dispatch in the power market and in the ancillary service market. This is followed by an illustration of the welfare loss that arises from RE curtailment in China.

3 What is flexibility in the power system

3.1 Definitions of flexibility

To analyze and discuss the requirement for flexibility in the power system, it is important to define what the term flexibility means. There is not a single standard definition, but several authors have proposed definitions which have more or less the same substance e.g.

The term flexibility describes 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.[1]

The definition contains several separate statements:

Variability and uncertainty

The term, *flexibility*, is often confused with the term reserves. Reserves are mainly used to compensate for the uncertainty in the power balance, as illustrated in Figure 1 . 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 during the year. This ability both covers the difference between min and max production and the ramping capability. If this kind of flexibility is not available, it will lead to very large price deviations in a power market based system (power exchange), and in some cases, a market clearance is not possible.

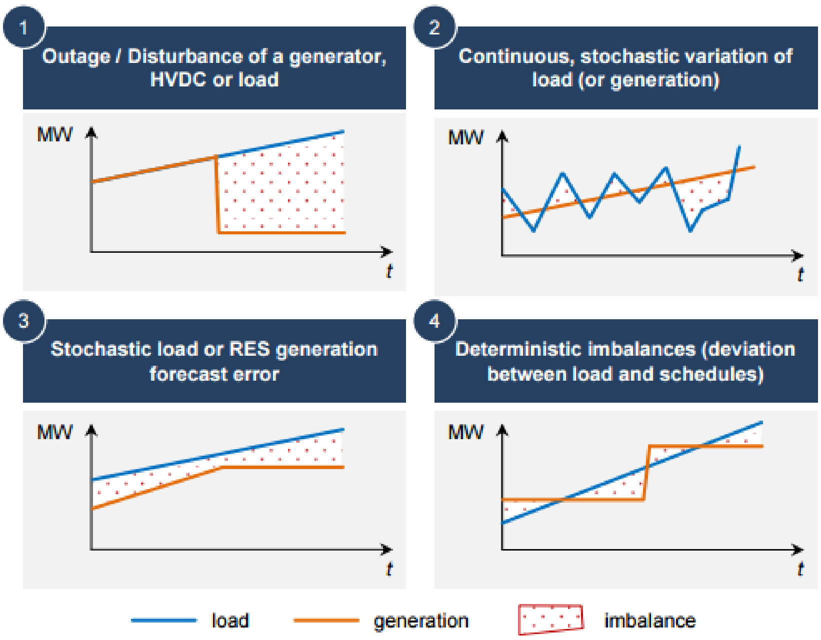


Figure 1: Uncertainty of imbalance[2]

---

[1] J. Ma, V. Silva, R. Belhomme, D. Kirschen, and L. Ochoa, Evaluating and planning flexibility in sustainable power systems IEEE Transactions on, Sustainable Energy, 2013.

In Figure 2 the left side axes show the power spot price (DKK/MWh), this is shown in a green line for each hour in the 24 hour span. On the right hand axes the power production and power demand is shown in MW (the red line shows power demand, while the blue and yellow area respectively shows the wind and solar power production). Discrepancies between power demand and RE production is filled by a combination of thermal production and export/import of power to neighboring price areas.

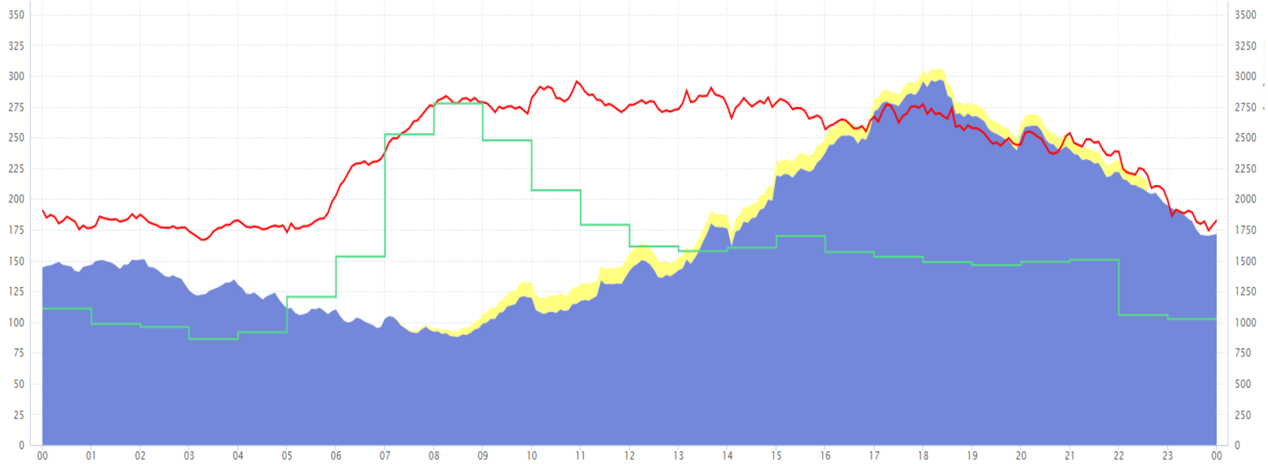


Figure 2: Data shown is from August the 25th 2015 in West Denmark (www.emd.dk/el).

<u>Both generation and demand</u>

Prior to the introduction of renewable energy, the main task of the generation units was to follow the variation of the load, and the tasks of reserves were to compensate for the loss of large production or transmission assets. With weather dependent renewable energy sources, like solar or wind based generation, the available production also exhibits variability. The objective is therefore to balance the net load, i.e. the difference between the non-dispatchable production and the non-dispatchable load. Flexibility can be achieved through production, load demand response or storage.

<u>Satisfactory level of reliability at a reasonable cost</u>

Due to the stochastic nature of load demand, production from renewable units and faults in the grid and larger production unit, there is a close link between the desired level of reliability and the requirement for power system flexibility and for reserves (this is further discussed in a later section). The level of reliability can be increased by a combination of investments in flexibility of the system, including the availability of reserves and investment in grid reinforcements. It is not an easy target to select the correct reliability level. In many European countries, the security of supply is generally higher than what a strict economic evaluation of the consumers' willingness to pay would yield (see Figure 3).

---

[2] ENTSO-E: Supporting Document for the Network Code on Load-Frequency Control and Reserves

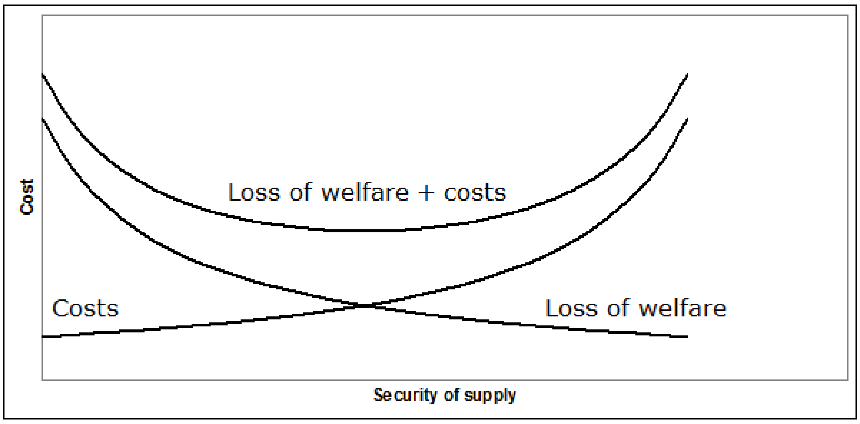


Figure 3: Tradeoff between security of supply and costs

Different time horizons

The time horizon is important to consider when planning flexibility. 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 hydro power.

Figure 4 shows a few very rough examples of what generate imbalances and which measures that compensate the imbalances. In a long-term energy planning process, it is important to consider all aspects of the time scale.

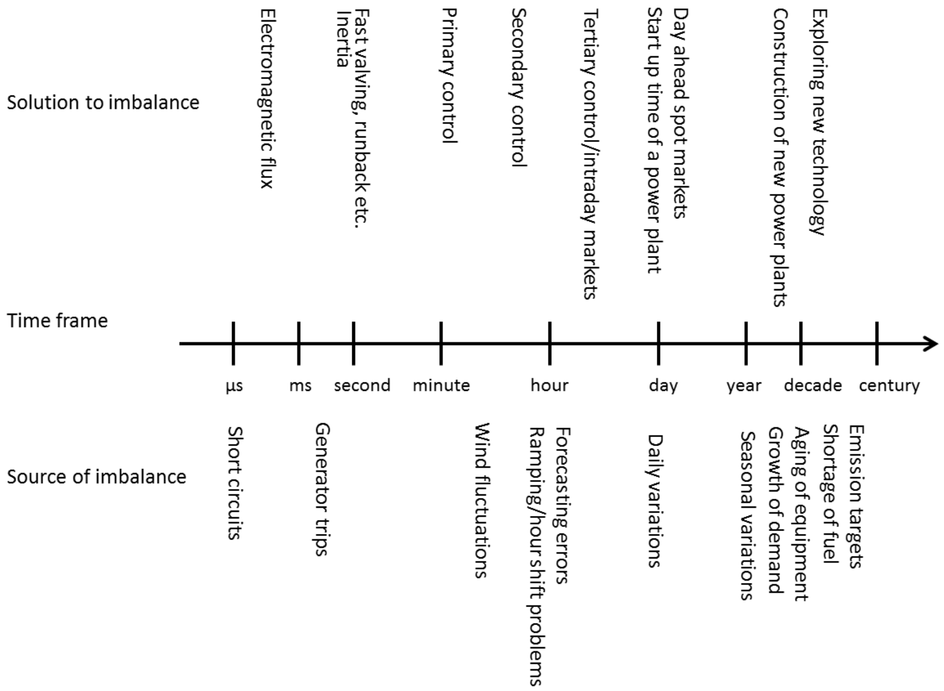


Figure 4: Examples of sinks and sources of flexibility with different time horizons

3.2 Flexibility challenges in the Chinese power system in 2014

As shown in Figure 5, the Chinese power system now comprises a production of 2 % wind power and 18 % hydro power (total production in 2012 was approximately 4,750 TWh). The curtailment of wind power corresponds to app. 8 % of the produced energy[3]. As a comparison, Denmark covered 39 % of its electricity consumption by wind power in 2014, and about 0.2% was curtailed. However, it should be noted that the Chinese wind production is concentrated in regions where the penetration is much higher than the country average 7%.

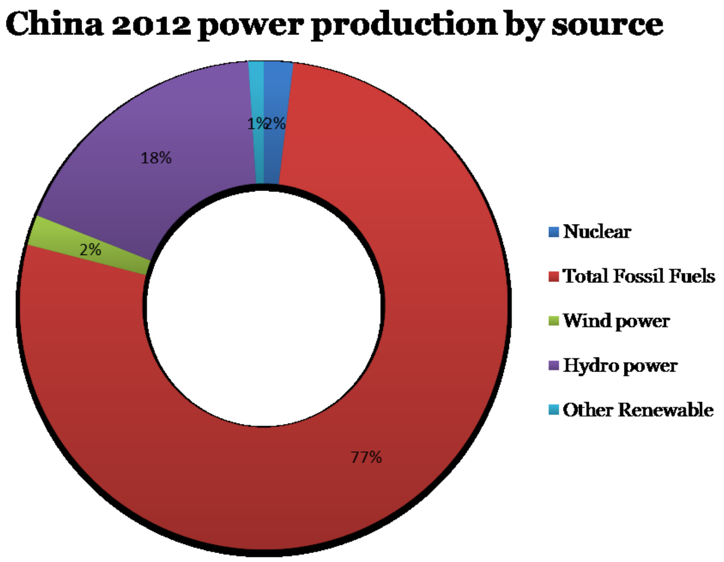


Figure 5: Chinese power production [TWh] in 2012[4]

The large amount of lost free and zero-emission wind energy is caused by both technical and non-technical issues.

3.2.1 The energy prices do not provide incentives to provide flexibility

There are generally two fundamental ways that a power system can be controlled and expanded effectively. The first option is that one central organization has the total control over all assets, both regarding investments and dispatching. In this situation, a global mathematical optimization can be made, and the system can be fully utilized provided that all information is available to the team doing the system optimization. The second option is that the price of energy is determined by one or more markets.

The problem is when the two paradigms are combined, which is to some degree the case in most of power systems in the world. Based on the information shared a workshop in Beijing this year on flexibility, the largest problem with integration of renewable energy in China at present time seems to be that the energy prices are to a high degree fixed and do not provide incentives for more flexible conventional production units to follow the net load and for the owners of power assets to run the units more flexible. For example, in some areas coal fired power plants run while wind

---

[3] Lu Zongxiang, Tsinghua University, presentation on April 27th 2015

[4] U.S. EIA - International Energy Statistics (http://www.eia.gov/beta/international/analysis.cfm?iso=CHN)

turbines in the same area are being curtailed due to shortage of export capacity of the area. Because the revenues of the coal fired plants are based upon a fixed feed in tariff which is higher than their marginal production cost, the owners of these assets have no incentive to take the plants out of operation. In a market based system wind generated electricity, which carries very low marginal costs (in principle zero), would have reduced the market price through the merit order effect and crowded out the coal based electricity with higher marginal cost.

Further, some of the plants are combined heat and power plants (CHP) which must run to serve the customers. If the price reflected the actual market value of the energy in the given minute, it would be more beneficial for the plant owner to install an electrical boiler and consume the electricity produced by the otherwise curtailed wind turbines at a marginal price close to zero and thereby save the fuel.

The same problem applies for the pumped hydro facilities. When the prices are fixed, there is no incentive to use such facilities, unless the owner of the facility also owns wind farms that would otherwise be curtailed. Also large HVDC links require proper price signals to be dispatched optimally. If the owner is paid a price per transferred MWh or the efficiency of the link is measured that way, there is a risk that the link will transfer power in situations where it does not support the optimal utilization of the whole system.

3.2.2 Inflexible production units

As will be described in detail later in the report, many of the coal fired power plants in China are quite new with modern technology (supercritical and ultra supercritical). However, they are only optimized to operate close to their nominal production capacity. There is a great potential for these power plants to become more flexible and follow the net load, as described in section 5. The size of the future production units could also be reconsidered. Today, the new plants that are being constructed are typically 1 GW. To cope with a future with fewer full load production hours, it would be a possibility to construct two 500 MW blocks per plant instead. Also the hydro power plants represent a large potential for flexibility and regulation. The best flexibility can be achieved with pumped storage, but also hydro plants with a reservoir have storage capacity. Even run of river plants can provide short term storage and can down regulate by bypassing water.

In Denmark (as part of the Nord Pool area) as well as most of the rest of Europe the market system is characterize by a least cost dispatch in a day ahead market place. This means that the market price is established through an auction-based supply/demand on typical an hourly basis for the coming 24 hours. The least cost dispatch simply means that the cheapest (marginal cost) production supplies the demand first (i.e. RE production) where-after the more expensive production types (fuel based technologies) are used to supply the residual demand using the cheapest production form first. A detailed description of the dispatch and scheduling is given in the report 'P*ower markets and power sector planning in Europe*'.

3.2.3 Distance between production and load centers

Most of the wind production capacity is located in the North of China – especially in Inner Mongolia, and the main load centers are in the South and East of the country. This means that there is a rather long transmission path between load and production.

By continuously reinforcing the transmission network and installing wind and solar capacity with a large geographic variation, flexibility can be achieved due to the diversity in production and load patterns in the different areas. The utilization of a large network which interconnects several provinces requires a control structure with the right incentives to produce on the most effective units at all times.

3.3 Overview of flexibility measures used in the Danish system

Since the late 80'es, Denmark has undergone and is still undergoing a transition from a system based on large central coal fired power plants to a system based on wind turbines, combined heat and power (CHP) units and solar panels.

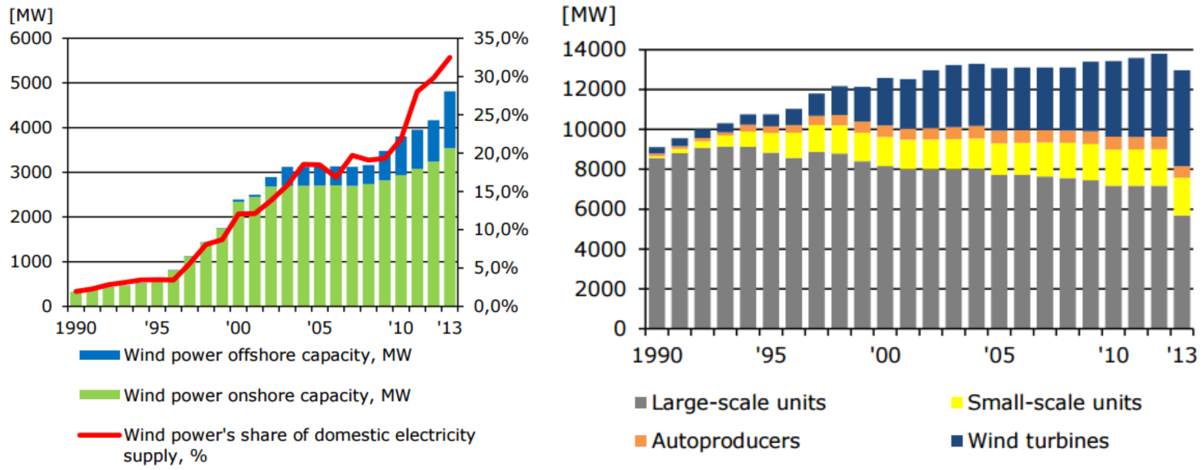


Figure 6: Power capacity and wind power's share of domestic electricity supply in Denmark[5]

The significant increases of RE production – in Denmark primarily wind production – naturally poses great challenges to the power system in terms of flexibility. While CHP plants provide great total energy efficiency (up to around 90%) they do however in their inherent form also poses some inflexibility in the system due to forced power operation when there is a demand for heat.

3.3.1 Use of 'Must Run Unit' in the Danish system

A must run unit is as power plant unit which are required to run for technical reasons. Must run units in the Danish system can be categorized according to two conditions:

- Units which are necessary in order to secure voltage control and grid stability
- CHP Units which are required to run due to heat production or industrial usage of steam

The first condition imposes a technical requirement on the number of power plant units or synchronous condensers online[6].

---

[5] http://www.ens.dk/sites/ens.dk/files/info/tal-kort/statistik-noegletal/aarlig-energistatistik/energystatistics2013.pdf

[6] The requirements for online units with voltage regulation abilities are different for DK East and DK West (Denmark is separated into two different power prize zones (DK East and DK West). This is due to the systems are not synchronously connected. In DK East the requirement is mainly

CHP units ‘must run’ characteristics

CHP units in their inherent form pose some inflexibility to the system due to forced power operation when there is a demand for heat. However, in Denmark CHP units are not considered real must run units today as most have the ability to either shift production using heat storage, produce heat on alternative units such as boilers or in some cases bypass turbines altogether and operate in heat only mode. Despite of this CHP units are seen to produce power even when there is zero or negative prices in the market (see section 4.2 for an explanation of zero or negative power prices). There are several reasons why this happens:

- For short durations with low power prices it may be too costly to stop a CHP unit and produce heat with alternative units compared to paying to get rid of power
- In some cases the alternative heat production is a peak boilers using oil. Compared to coal fired CHP this is in many cases much more expensive even with power prices below zero. This effect is strengthened by the tax and fees imposed on different kinds of heat production
- Industrial CHP and waste fired CHP units may have other technical or economical restrictions preventing them for stopping production of power

In most cases it is possible to overcome the technical or economical restrictions to remove power production when it is not needed by retrofitting of the power plants:

- Additional heat storage in order to shift power production
- Heat production on electric boilers and or heat pumps
- Full or partial bypass possibility of turbines

The above technical solutions for providing flexibility are elaborated in section 3.3.4.

During the transition from the 1980’ies to now, spilling and curtailment of renewable energy has been kept below 0.2% of the produced electricity. The required flexibility 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.

3.3.2 Interconnectors

Compared to the installed production capacity, Denmark has a high amount of interconnectors to the neighboring countries. The first HVDC line between Jutland and Sweden was constructed in 1965. The idea was to import cheap hydro power from Sweden to Denmark and in cases of dry seasons to export energy from Danish thermal power plants to Sweden. Today, the interconnectors to Norway, Sweden and Germany serve to balance out especially the wind production in Western part of Denmark. A new interconnector to Holland is decided, and an interconnector to Great Britain is being considered. Figure 7 shows that roughly 80 % of the variation in wind power during 2014 was compensated by the exchange connections. This does not mean that the Danish power plants would not have been able to do the balancing, but the market optimization has found this to be the most cost efficient balancing.

---

dependent on demand and the amount of power imported from Sweden. In case of low demand, low import and intact grid only two units are required to be online. The units can be in the form of synchronous condensers. With high demand or import the requirement is for 3 units to be online where two can be replaced by synchronous condensers. In DK West the requirements for online units with voltage regulation abilities are defined from wind power forecast and the availability of a VSC-HVDC interconnector. If onshore wind power forecast is below 75% of installed capacity only one power plant unit needs to be online. If wind power forecast is above 75% two to three units needs to be online. Source: From internal Energinet.dk system operation instructions

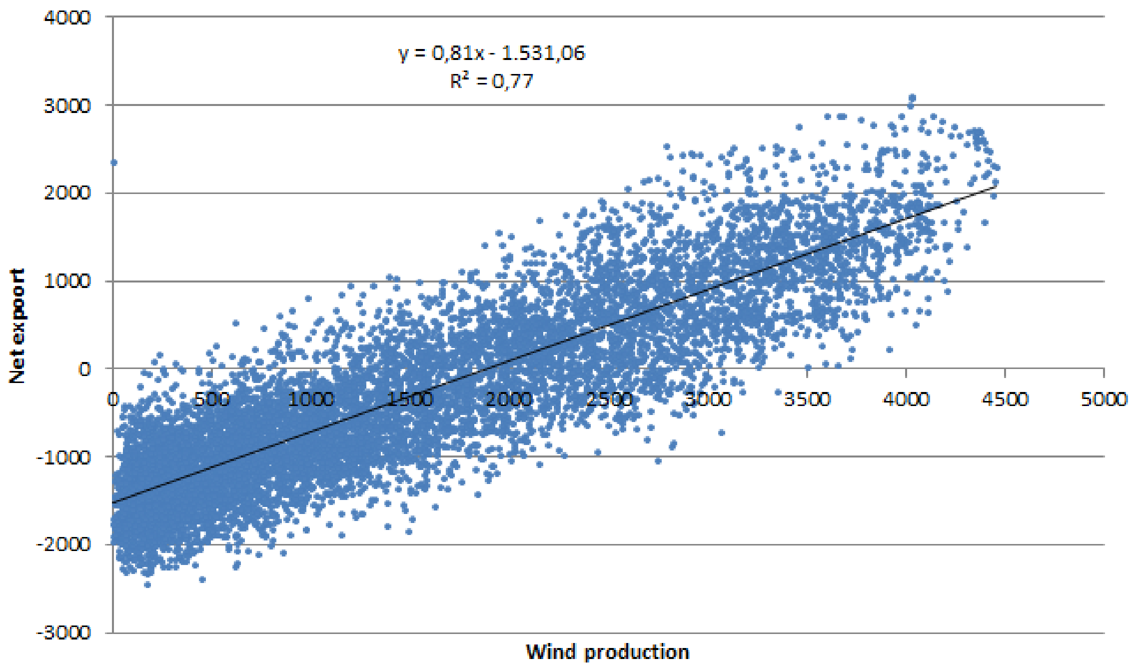


Figure 7: The correlation between export and wind production in Denmark during 2014[7]

Since e.g. Northern Germany is also pursuing a strategy of an increasing share of wind power, the balancing through transmission requires an increasing amount of grid reinforcements to transfer the wind power to areas with an uncorrelated wind pattern. The bigger the balancing area is the better. It is a way to smoothen out impact of peaks in output from wind and solar. If e.g. wind penetration in one system is 30% of demand and it connects to another system with twice as high demand and no wind, the overall wind penetration as a whole will be 10% which is much easier to manage. Balancing a system with little share of wind is easier than balancing a system with high share of wind. An illustration is given in Figure 8 where a duration curve is shown for the power production from respectively a single wind park (blue line), wind power in Denmark in total (green line), and two hypothetical scenarios of wind power spread evenly across Europe (red line) and optimized wind park location across Europe in order to maximize production at minimum wind (purple line). As is shown the production is smoothed out as the production area increases.

---

[7] Data extracted from http://www.energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

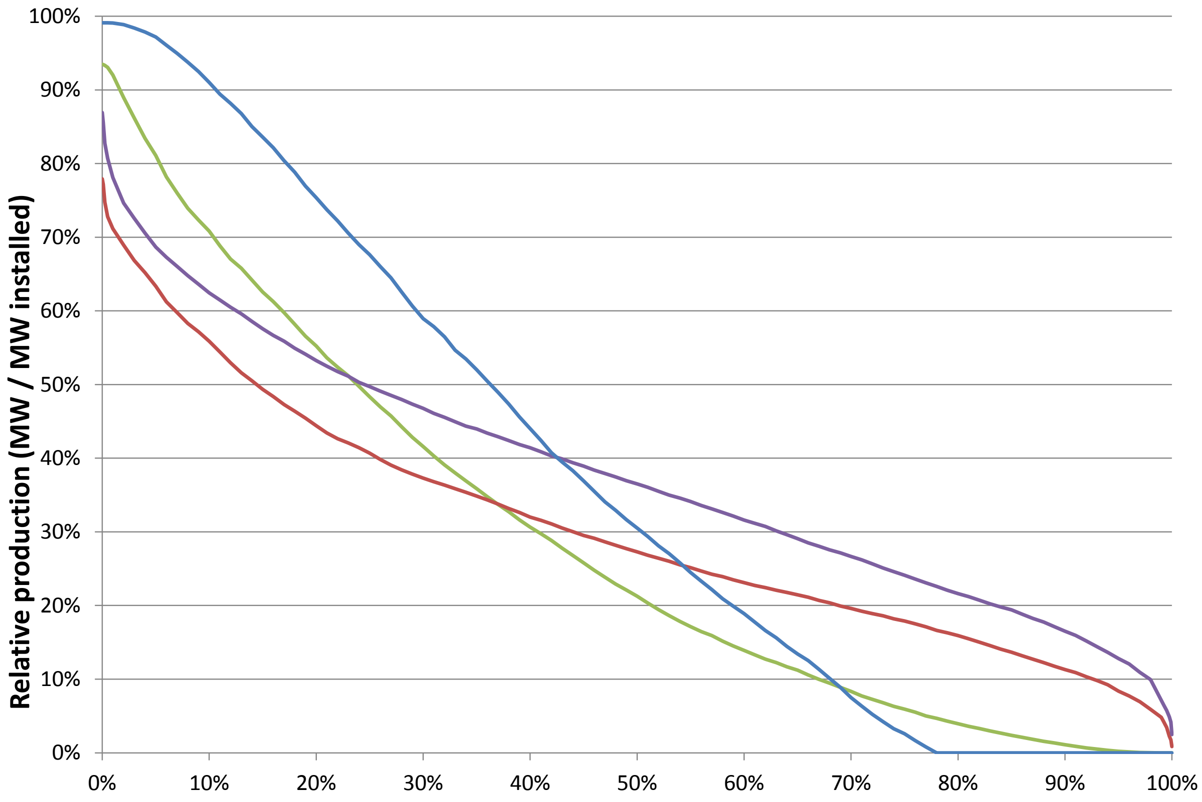


Figure 8: The smoothing effect of larger balancing area[8]

3.3.3 *Forecasting and scheduling systems*

The success of balancing renewable energy production is highly dependent on the availability of accurate forecasting and scheduling systems. A good day-ahead forecast can help the owners of the production units to make the right bids on the spot market, and a good short term forecasting model can help the TSO to proactively order slower reserves, rather than depending on fast and expensive reserves, once the imbalance is there.

Energinet.dk has forecasting models for wind production, solar production and load. The models are autoregressive and they use input from different meteorological services.

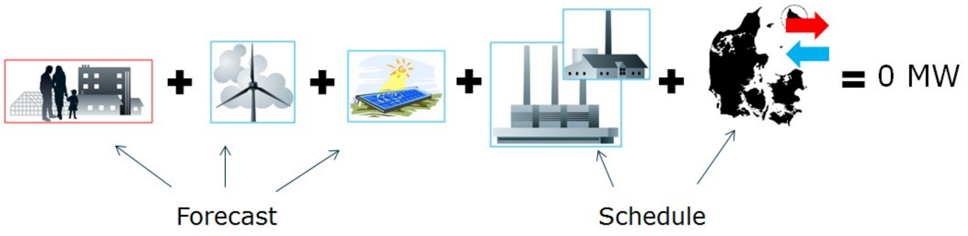


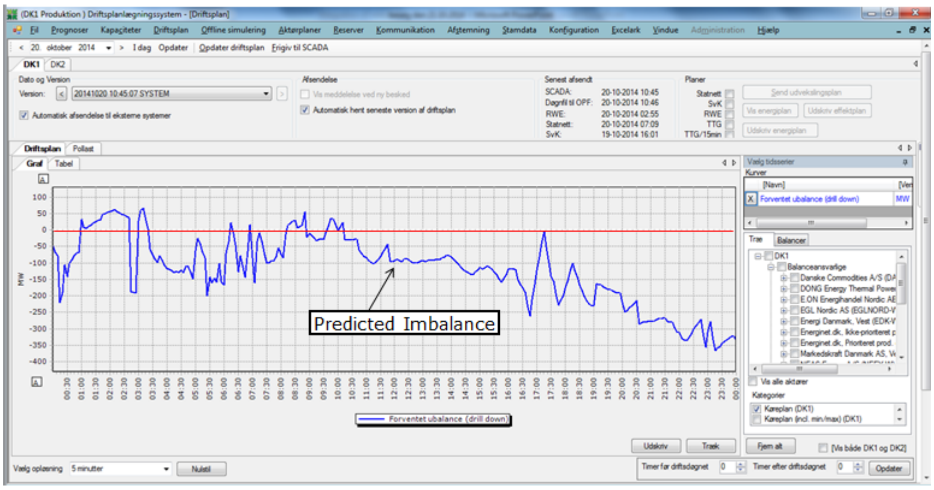
Figure 9: The forecasting process of Energinet.dk[9]

---

[8] www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Klimaogmiljo/Energikoncept%202030%20-%20Baggrundsrapport.pdf

[9] Figure by Lasse Diness Borup

The results from the forecasting models go into a scheduling handling system where they together with schedules from all production units and schedules for interconnectors are used to calculate the total power balance for the next 24 hours. The tool also gives the dispatcher access to a bidding list for up and down regulation during the day.



Version: 20141020 10:45:07 SYSTEM

☑ Automatisk afsendelse til eksterne systemer

☐ Vis meddelelse ved ny besked

☑ Automatisk hent seneste version af driftsplan

SCADA: 20-10-2014 10:45
Dagnfil til OPF: 20-10-2014 10:46
RWE: 20-10-2014 02:55
Statnett: 20-10-2014 07:09
SvK: 19-10-2014 16:01

Statnett ☐
SvK ☐
RWE ☐
TTG ☐
TTG/15min ☐

☒ Forventet ubalance (drill down) MW

DK1
Balanceansvarlige
Danske Commodities A/S
DONG Energy Thermal Power
E.ON Energihandel Nordic AB
EGL Nordic AS (EGLNORD-V
Energi Danmark, Vest (EDK-V
Energinet.dk, Ikke-prioriteret p
Energinet.dk, Prioriteret prod.
Markedskraft Danmark AS, V

☐ Vis alle aktører

Kategorier
☑ Køreplan (DK1)
☐ Køreplan (incl. min/max) (DK1)

☐ Vis både DK1 og DK2

Timer før driftsdagnet 0
Timer efter driftsdagnet 0

Vælg opløsning 5 minutter

Figure 10: Schedule handling system

With these tools, the dispatcher has a very good overview of the requirement for regulation ahead in time and the available reserves.

3.3.4 Power and heat production in power plants

The first and most important challenge for the low carbon power system is controllable flexible resources. Due to the uncontrollable intermittency wind and solar resources the controllable power and heat production must absorb the variations and be able to respond flexibly. Some of the measures available for increased flexibility are:

1. Rapid response (ramping speed) in thermal power production units
2. Lower minimum outputs in the thermal power production units
3. Shorter start up times for thermal power production units
4. Improved ways of co-producing heat and power
5. Power for heating (heat pumps and electric boilers)

The solutions above are available and already in use and can be integrated in the capacity expansion plans in China. In section 5 a detailed analysis and assessment of the first 3 bullets (flexible power plant operation) above is given. In the next section (3.3.5) a description of the use of CHP plants and power for heating is used.

3.3.5 Options for increased flexibility by integration of heat and power systems

Interaction between power systems and district heating systems based on combined heat and power (CHP) generation can ease the integration of wind. There are several tools available for the district heating system, which helps integration of the variable output from wind. Integration of wind create two challenges; in periods with strong wind and high output from the wind turbines there is usually a need to reduce other generation technologies. The other challenge is the opposite situation where there is no or low wind and limited output from the wind turbines. In this situation there is a need to increase output from other power generation or to reduce demand for electricity.

Heat storage in combination with a CHP generation plant is an option for short term flexibility. Heat storage makes it possible to shift heat production relative to heat consumption. It is simple and cheap to store heat and the energy loss is low - typically around 5%. It is an option which can be deployed with both large scale and small scale CHP. Heat storage facilities are typically sized to store heat for short periods - up to approx. 8 hours of production or demand during winter. In principle heat storage can also be used for seasonal storage but only limited experience is gained with this option until today. However, seasonal storage is seen in recent years primarily in connection with large solar installations.

Electricity to heat

Use of heat storage and use of electric boilers complement each other in the district heating system. Electric boilers has a double function; it is able to increase demand for electricity (when prices are very low) and its able to reduce heat (and thus electricity) generation from the CHP plant.

Though very useful and bringing significant contribution to flexibility of the power generation from the CHP plants this type of application has its obvious limitation for wind integration. This is a short time measure since the typical storage is able to cover around 8 hours of heat generation during winter. Heat storage able to store heat for several days has other advantages but requires larger investments. In a system where the power price is market based, the flexibility driver is the price signal from the electricity market and higher shares of wind and solar could drive demand for bigger heat storages. If electric boilers are installed in the heat tank, it can also be used to provide balancing services to the power system. Investment in electric boilers in Europe is based on the business case where they offer bids for down regulation in the balancing market. It is a rapid and efficient way to regulate the power production. Even with the absence of a market and price signals investment in electric boilers in heat storage can prove feasible compared to other measures.

Heat pumps are at present generally used among private households and only to a limited degree in large scale. The power usage is usually around ¼ to 1/3 compared to the produced heat in the heat pump. It is thus another way of transforming power to heat, which under high RE power production periods serve as a cost-efficient supply of heat.

Besides obtaining increased flexibility by integration of heat and power systems a multitude of different technological solutions exist for power storage. However none of them are widely used in Denmark at present due to the prohibited high costs and loss of energy associated with storage. One of the most widely used is pumped storage, where water is pumped back up in the reservoirs at the hydro power plant (mechanic power storage). Due to significant amount of hydro power in Norway and to some extend in Sweden combined with very high level of wind power in Denmark and northern Germany the case for pumped storage is strong in Norway. Other means for storage is compressed air energy storage, flywheels (kinetic energy storage), power to gas (production of synthetic methane and hydrogen) and batteries etc. (please also see section 4.4.1).

3.3.6 Demand side measures to increase flexibility

In Denmark some of the first demand side measures are being tested in the market at present. One solution is a small scale industry solution (Power Hub) where control of the power usage is sold within some pre-determined boundaries (i.e. how much effect, duration and ramping speed is sold). The customer types are for example water supply companies, waste water treatment plants, cooling storage facilities etc. who can satisfactorily operate even with leaving some control of their power demand to be regulated to supply flexibility in the power system. DONG Energy is offering such a product at the market place at the moment[10]. Another very potential demand-side measure will most likely be electric vehicles (EV) once a significant amount of EV is in the market as well as when an IT solution has been established through which the batteries in the EV can be used as a mean providing flexibility. A third source of demand-side flexibility is from private households whom can either manual or automatically (based on predefined boundaries etc.) supply demand side flexibility through their use of large home appliance devices. An example of this has been rolled out among 2,000 households in Denmark in a pilot project under the European EcoGrid EU project[11].

3.4 Conclusions

Flexibility describes 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. It is important that a proper balance is stroke between at the one hand security of supply and the cost of investing in capacity and flexibility on the one hand.

In Denmark the large share of RE (primarily wind production) in the system has been integrated in the system through different means. The power marked system design in Denmark/Europe with a least cost dispatch in a day-ahead market is a prerequisite for ensuring all RE production is dispatch first, which obviously require a power market system that can provide a high degree of flexibility. In terms of ensuring enough flexibility in the system important actions are the use of increasing size and number of interconnections to surrounding areas and increased grid enforcement. This has among other things increased the production and consumption area thus smoothing the challenges variability from RE production poses to the system balance. Other important action taken has been the development of a more and more sophisticated and precise forecast and scheduling system. Besides these measures increased flexibility at the power plants has been a very important tool in absorbing more and more RE energy production in the system. In addition to these measures a multitude of other means are available to cope with increase share of RE – for example through power for heating and improve ways of co-producing heat and power. Through these measures a very high degree of security of supply as well very low curtailment of wind power has been made possible.

---

[10] www.powerhub.dk

[11] www.eu-ecogrid.net/ecogrid-eu/the-bornholm-test-site

4 Measures taken by the Danish TSO in order to use the grid in a flexible manner

4.1 Deployment of wind power, energy policy and grid flexibility

The first Danish energy plan dates back to 1976, followed by the introduction of an act on electricity supply, an act on heat supply and an act on the introduction of natural gas in 1979. In 1979 investment subsidies for wind power were introduced with up to 30% of the total project costs subsidized. This was a system that was in place until 1989, when it was changed to a feed-in tariff. The next Danish energy plan from 1981 was followed by a moratorium on nuclear power in 1985 and by an agreement between the Danish government and the power producers to install additional wind power capacity.

Through a major change in the electricity supply act in 1989, priority to renewable energy, on behalf of conventionally produced energy, was affirmed in the legislation and a moratorium on the establishment of coal fired capacity was introduced. Taxation of energy consumption based on the content of CO2 was introduced in 1992. A system for power production from independent producers was introduced and followed by a Green Tax Package (SO2, CO2, NOx) shortly afterwards.

In 1963 Nordel was founded, which was a body for co-operation between the TSOs in the Nordics. The objective of Nordel was to create strong conditions for a development of an effective and harmonized power market in the Nordics. Nordel was to present advice and recommendations for an efficient power system in the Nordic region given the specific power production and power system conditions in each country. Nordel thus contributed to an international co-operation and information exchange already from the 1960'ies.

4.1.1 Development from 1990 until 2001

In 1990, a moratorium on new coal-fired power plants was discussed and no new development plans for coal plants were included. The last new coal-fired power plant was commissioned in 1998. The power production capacity based on wind turbines was increased substantially during the period.

Two main contributors to flexibility in the power system in this period was the capacity expansion in combined heat and power (CHP) plants and increased energy efficiency (both heat and power). The government implemented various measures to achieve infrastructure development, i.e. strengthening the transmission grid. Energy savings in buildings and stringent energy efficiency requirements and standard (both heat and power) also contributed to reducing the balancing challenges by reducing peak demand.

4.1.2 Development from 2001 – 2011

The organisation of the Danish energy markets were changed in a market oriented direction. The Danish power and natural gas market were liberalised during the period i.e. competition was introduced in power generation and trade; and the previous horizontally integrated energy utilities were unbundled. Denmark also became member of the Nordic power stock exchange (NordPool) resulting in a very dynamic and volatile development in power prices as shown in section 4.2.

The Danish TSO Energi.net was established in 2005 by a merger of two smaller TSO's and a more integrated planning procedures with larger focus on the connections to Europe were implemented. During this period new interconnectors to the Nordic countries, Germany and Poland was constructed to ease the balancing challenges of the power system.

4.1.3 Recent development

In 2008 the Danish commission on climate change policy was established producing a roadmap of how to achieve an energy system without fossil fuels in 2050. This work was soon followed by a very broad political consensus and agreement regarding the future perspective of the Danish energy system. Specifically the political agreement which all parties (less one) in parliament supported set forth specific energy targets for 2020 and source of funding for the initiatives. In 2013 the government in power put forth a climate plan with additional and more ambitious climate goals – now also covering transportation, agriculture, building and waste industry besides the energy sector. The long term overall goal is a fossil fuel free economy in 2050 with the first milestones for the contribution of renewable energy already in 2020 when large infrastructure investment in off-shore and on-shore wind turbines combined with new and stronger interconnection with the Nordic neighbours (Sweden and Norway), Germany, and Holland and increased use of electricity in the heat and transportation sectors as well as increased use of biomass.

4.2 Wind curtailment rates in Denmark and their explanations

Curtailment of wind is when wind power generation is reduced in order to make room for other kinds of production such as base load coal or nuclear power or if the system is unable to absorb the wind power production. Curtailment of wind power means unnecessary cost for fuel, more pollution and GHG and less value of wind power assets.

In Denmark there are two different kinds of wind curtailment: active wind curtailment when wind power is ordered to stop production due to disturbances or emergencies in the system and market based curtailment when power prices are too low to for wind turbines to cover the marginal costs and thereby be profitable. Active wind curtailment is only used once every third year on average for the Danish power system. Active wind curtailment is used during large scale events such as during a hurricane or if disturbances to the grid prevents the wind power production form being used.[12]

Market based curtailment happens when power prices becomes zero or negative. If the wind power turbines are controllable (mainly goes for newer wind turbines and large wind farms) the wind power plant owner will stop the turbines if power prices becomes zero or negative in order to avoid paying for producing power. In some cases the subsidy scheme promotes production even with power prices below zero. The current subsidy schemes for new wind power production has been designed to avoid this by removing subsidies if power prices become zero or negative.

---

[12] This happens so seldom that there is no statistics. Based on interview with Energinet.dk dispatch operatoers

In 2014 only about 0.2% of possible wind power generation in Denmark was wasted due to market based curtailment.[13]

Negative power price happens when supply of productions capacity with a marginal cost at zero or below zero surpasses demand and capacity to export the energy produced. In Denmark these units could be:

- Wind power plants. Marginal cost is zero or lower than zero if they are subsidized or unable to stop due to technical reasons
- Roof top PV panels
- CHP power plants with no alternative heat production or very expensive alternative heat production such as coal power with oil backup
- Units with high cost of start and stop

In practice this means that in situation with low demand and high wind and CHP production conditions there is a risk of oversupply of power production form wind and CHP. In normal operation the oversupply is exported to Norway, Sweden and/or Germany, but in some cases limitations to usage of transmission capacity or same time oversupply of wind power production in Germany can lead to situations with prices below zero.[14]

Statistics on negative prices are presented in Table 1 and an example of a situation with negative prices is shown in Figure 11.

Number of hours with prices below zero

[h]	DK West	DK East	Norway	Germany
2010	12	6	0	12
2011	18	17	0	16
2012	34	32	0	58
2013	40	30	0	65
2014	46	19	0	64

Average price below zero

EUR/MWh	DK West	DK East	Germany
2010	-5	-25	-5
2011	-10	-9	-9
2012	-54	-57	-58
2013	-46	-61	-52
2014	-12	-19	-16

Table 1: Statistics about negative power prices in DK, Norway and Germany. Norway have not had one hour with negative prices in the statistical period[15]

---

[13] Based on analysis of data obtained from (hourly wind power production and power price): http://www.energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

[14] Since 2005 app. 200 hours have been negative prices (typical just below zero but some are negative 10-100 Euro pr. MWh.) and app. 200 hours with price of zero (0 Euro pr. MWh.) has happened.

[15] From: http://www.energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

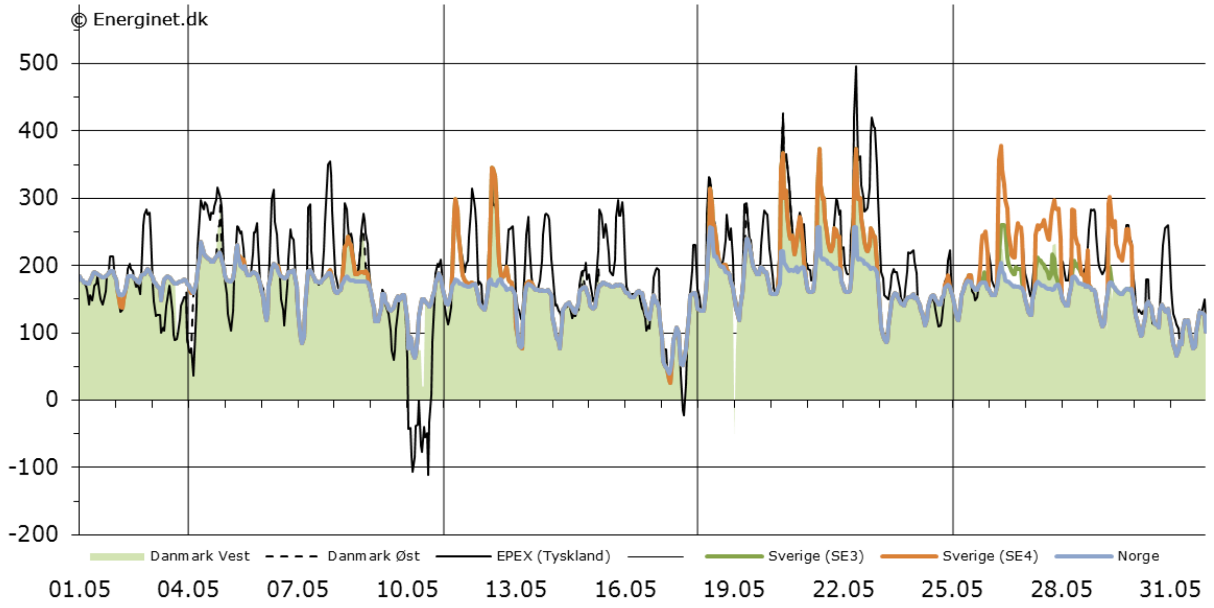


Figure 11: Translation Area prices Nord Pool Spot and EPEX DE May 2015. DK-W (Danmark Vest), DK-E (Danmark Øst), Germany (EPEX), Sweden (Sverige SE3 Sverige SE4), Norway (Norge). Example on the interaction of area prices in Denmark and neigbouring countries. It can be observed that when prices in Germany drop below zero the prices in DK are likewise very low, but not quite as low as for Germany. The unit is DKK/MWh. 100€/MWh is 745 DKK/MWh. [16]

4.3 Examples of ramping speeds from wind energy in Denmark

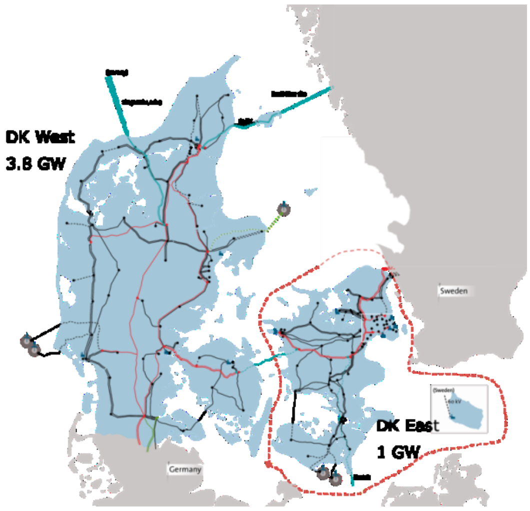


Figure 12: DK West and DK Easy including installed wind power capacity. DK West is comparable in size to Hainan province and DK east is comparable to Tianjin in size

Wind power production is recorded centrally in the control center in 15 min intervals (Western part of Denmark - DK West) or hourly intervals (Eastern part of Denmark - DK East). In the following hourly values are presented. In DK west a total of 3.8 GW wind power is installed and in DK East a

---

[16] Data from: http://www.energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

total of 1 GW wind power is installed. In the following graphs the hourly ramp rates for DK east, DK west and DK in total is presented for 2014[17].

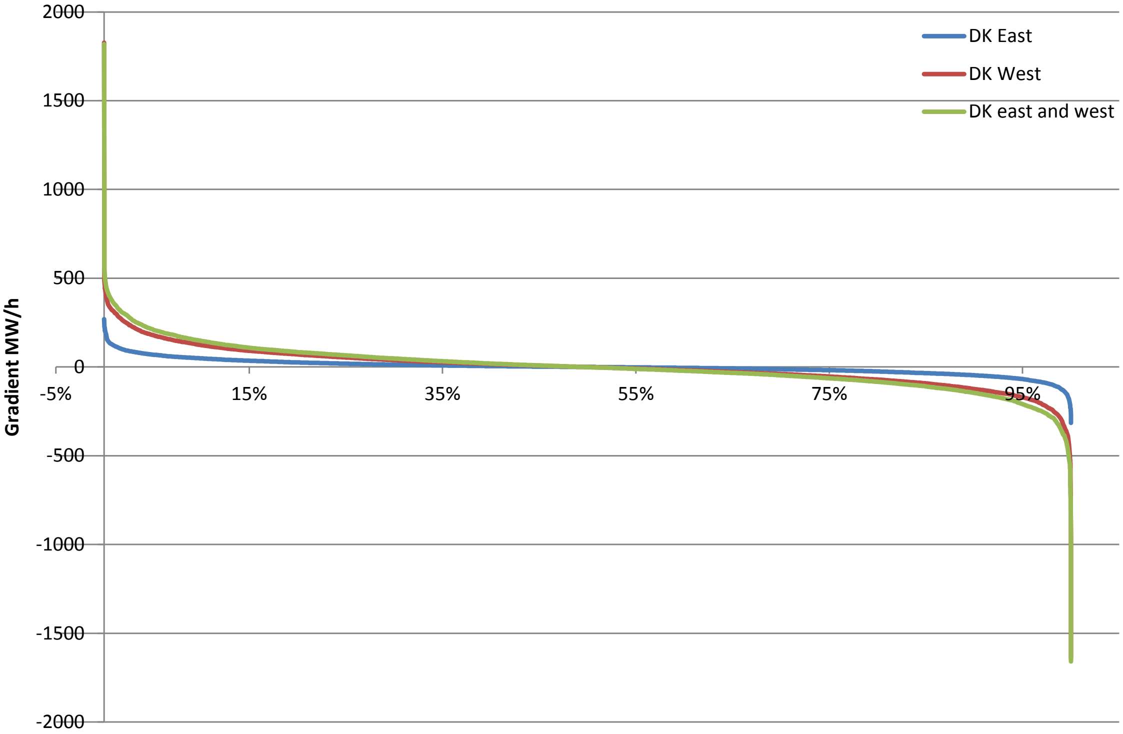


Figure 13: Duration curve of ramp rate of wind power production in DK in 2014. The unit is MW change per hour. Largest and smallest observed values are: DK East 268 MW/-314 MW, DK West 1826 MW/-1639 MW, DK 1817 MW,-1660 MW

As can be seen for most hours ramp rates of wind power production are slow but in about 1% of hours the ramp rates are strong enough to pose a challenge to the system in either upward or downward. In order to be able to compare the values of DK East with DK West and with DK (total) the ramp rates are in the following made relative to installed capacity (MW/h per GW installed wind). It can be seen that ramp rates are reduced when a larger area is considered. The maximum hourly wind power ramp rate for DK in total is approximately +/- 350 MW/h per GW installed wind power. For this reason it is easier to handle and balance wind power production if a large area like North Europe is considered rather than one small country or province.

---

[17] Based on analysis of Energinet.dks database of quarterly wind power production data.

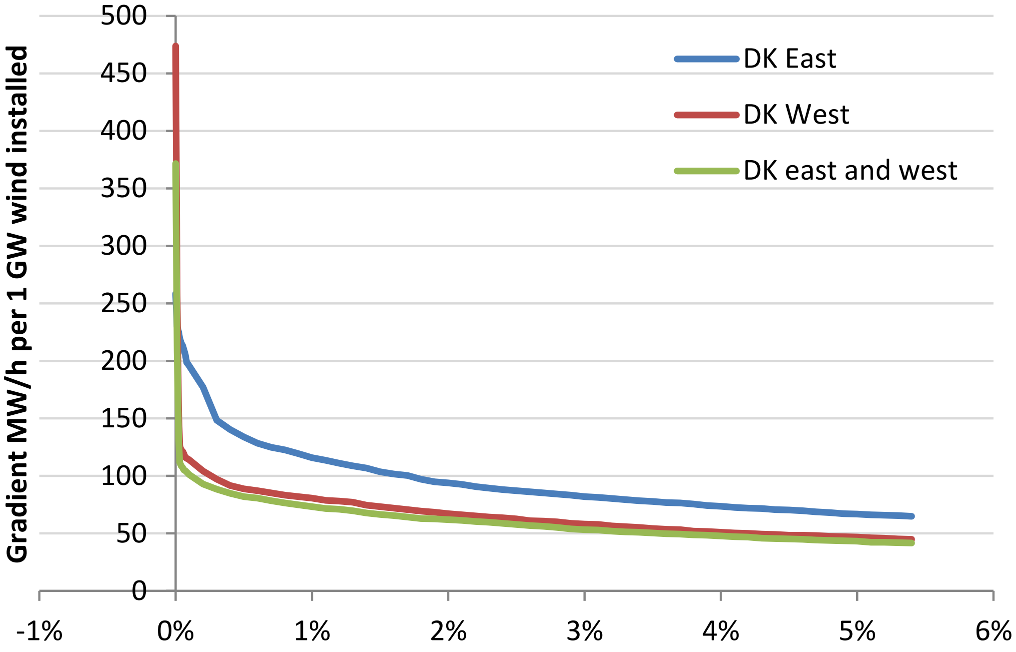


Figure 14: Upward ramp rates hourly. Hourly change of wind power production in MWh per GW wind. Highest value for DK east is 258 MW, for DK west 474 MW and for DK (total) 371 MW.

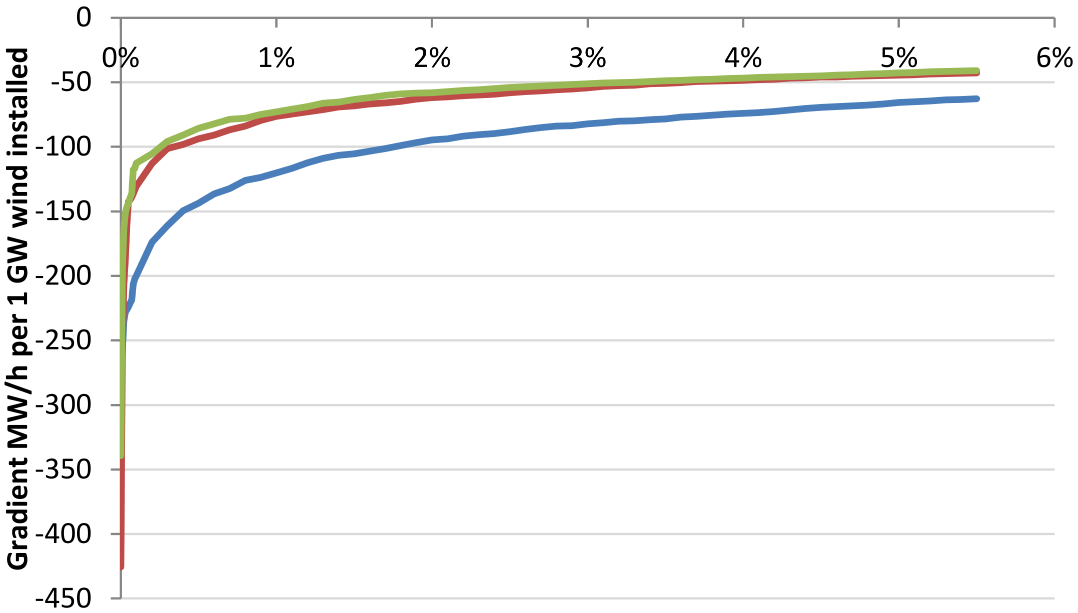


Figure 15: Downward ramp rates hourly. Hourly change of wind power production in MWh per GW wind. Highest value for DK east is -303 MW, for DK west -425 MW and for DK -339 MW.

High wind situations

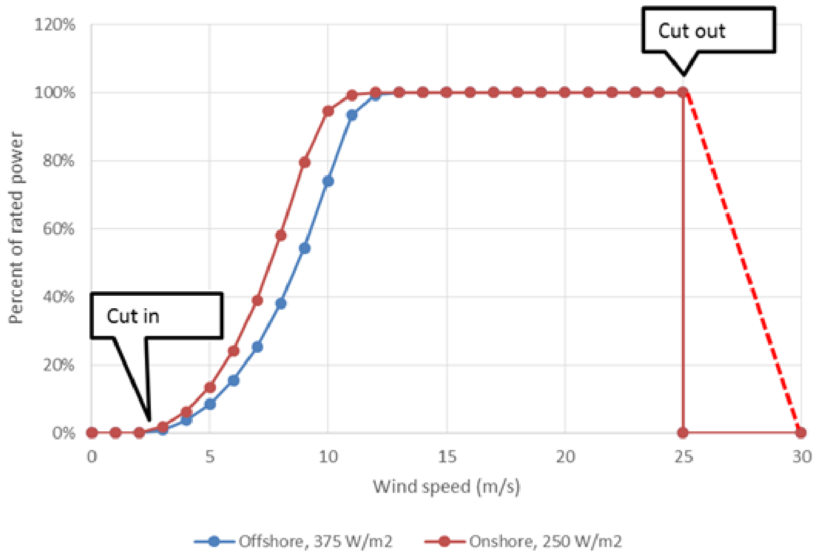


Figure 16: Example: Power curves for wind turbines. [18]

Most wind turbines are designed to cut out (e.g. stop production) production when wind speed reaches 25 to 30 m/s in order to avoid damaging to the wind turbine (Figure 16). Compared the situation when wind turbines stop due to low wind the cut out is very sudden. Production from one wind power plant (e.g. an offshore wind farm) can change from full production to no production within minutes. When wind speeds drops below 25 m/s the wind power plant can ramp up to full power within minutes. The cut out poses a special challenge during hurricane or storm events in the Danish system as the geographical area is so small that large amounts of the installed wind power capacity can cut out during the storm and the exact timing of cutout is difficult to predict. Cut in when wind speeds reduce to below cut out needs to be controlled in order avoid to strong ramp-up. Cut out of wind power has never caused a blackout in Denmark.

4.4 Long term and future flexibility measures in DK

The long term outlook for Denmark is considerably more wind and photo voltaic power. The target for 2050 is to reduce CO_2-emissions to zero. Wind power is considered to be one of the cheapest technologies for power production when cost of emitting CO_2 is considered. In 2035 the power production is expected to consist of 80% intermittent production and by 2050, 97% of all power production is expected to be produced from wind, solar power and - if the technology is developed – wave power (Figure 17). Such a large share of renewable energy is expected to pose a challenge for the system which will require development of the market models and new technologies in order to reduce the cost of handling the renewable electricity production and maintaining security of supply. It is today technically possible to design the system with 100% renewables based on wind power, a strong transmission network and thermal backup capacity but such a system is expected to be expensive. The challenge is to design a system which delivers a 100% CO_2-netural energy

---

[18] Technology Data for Energy Plants, Danish Energy Agency 2015

system at a cost which is lower or equal to a fossil fuel based power system including negative externalities from the fossil fuel usage.

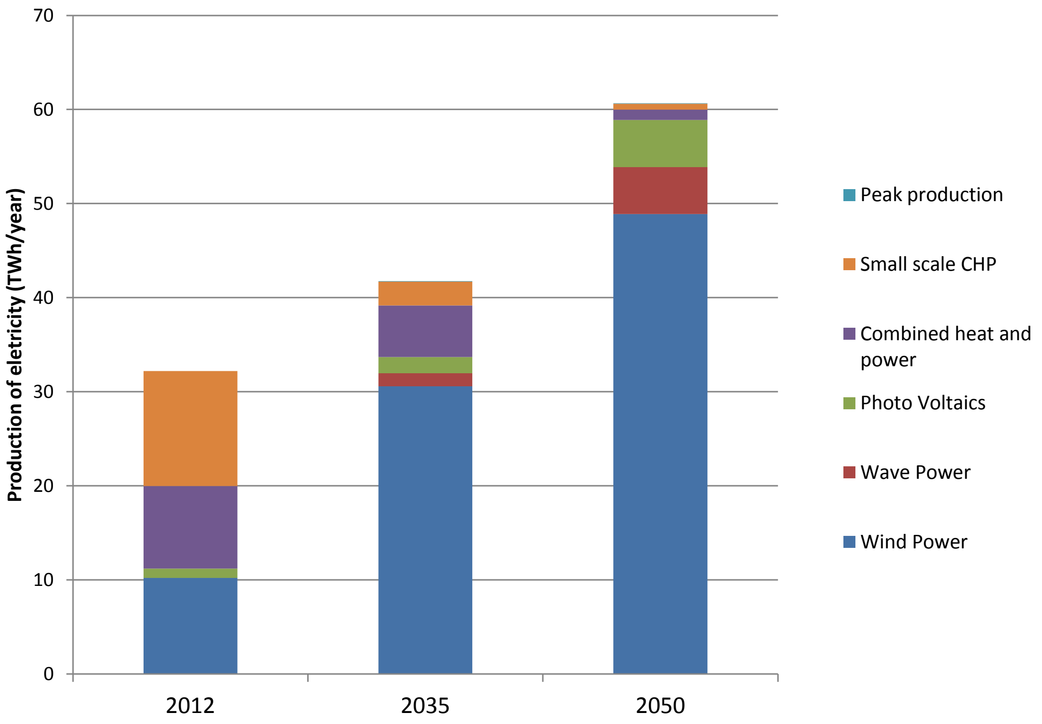


Figure 17: Past and expected future production of electricity in Denmark. [19]

4.4.1 Combined energy systems as a solution for handling fluctuating energy production

The solution to managing an energy system with a majority of intermittent energy production is related to integrate several energy systems. Today heat and power is interlinked via CHP production. In the future heat, power, gas and manufacture of fuel are expected to be linked and electricity will be used whenever it is possible to substitute fossil fuels. The linking of different energy carries is done not only to balance the input of renewable energy but also to provide CO_2-emission neutral fuels for industry and transportation (e.g. planes and cargo ships) and other places where electricity is not an option. An example of the energy flows are show in Figure 18.

---

[19] Energikoncept 2030, Energinet.dk 2015. http://energinet.dk/DA/KLIMA-OG-MILJOE/Energianalyser/Analyser/Fremtidens-Energi/Sider/default.aspx

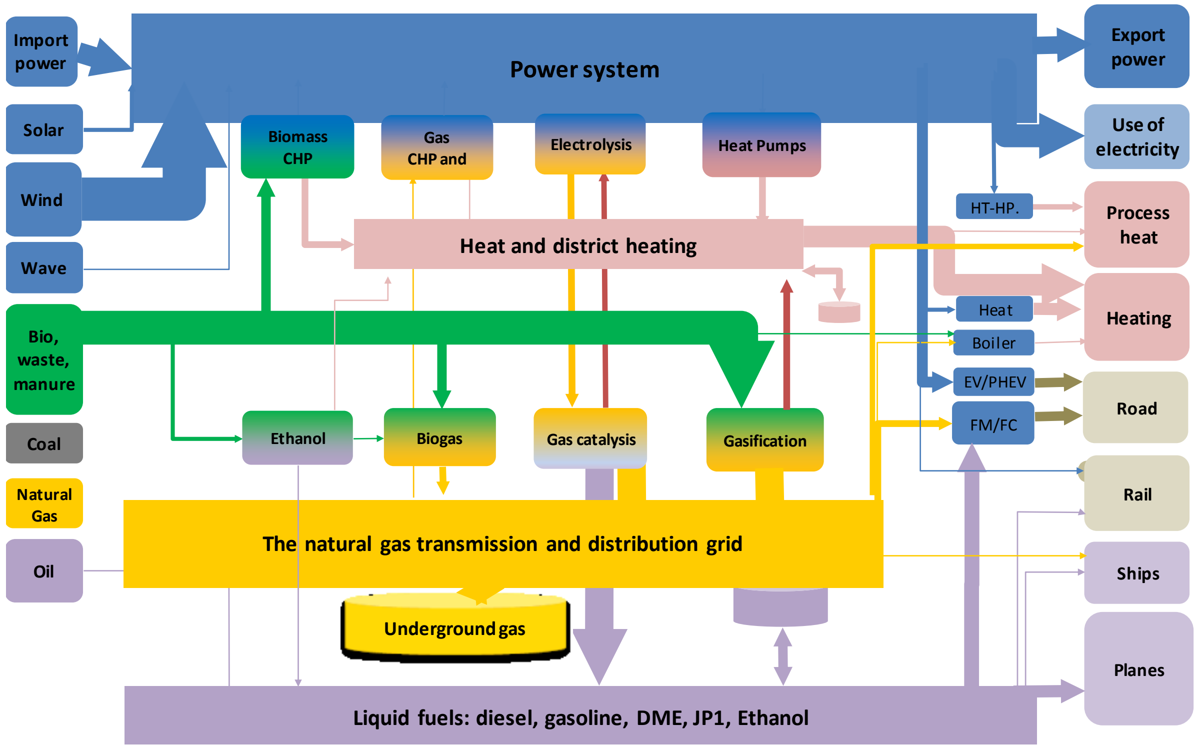


Figure 18: A Sankey style diagram of the Danish energy system in 2050. An energy system with almost no use of fossil fuels. [20]

The core of the energy system in Denmark in 2050 is expected to be the power grid and the gas grid. The power system will handle the bulk of the energy flows from solar power, wind and perhaps even wave power. The expectation is a higher direct usage of electricity for transportation and heating through heat pumps. Surplus electricity is either exported, used for heating with heat storage or converted to fuel via electrolysis. Electricity deficits (when power production from renewable production is too little to cover demand) are handled by import of electricity, increase of power production from biomass and gas and use of demand flexibility.

The gas systems role will be to absorb electricity through electrolysis and mechanization of CO_2, biogas upgraded to methane quality and gasified biomass and to provide fuels for transportation, industry and backup power for the electricity and heat system. The Danish gas system includes two underground storages which provide enough storage capacity to handle the fluctuations in energy production and consumption.

The different elements in Figure 18 are briefly described in the following.

CHP based on biomass and gas

CHP's is expected to still play an important role in the Danish heat and power system in the future but with a more flexible mix of operation modes: Heat & power, heat only & power only. The bulk of CHP's will be based on biomass, but may also use gas to boost production via separate gas

---

[20] Energikoncept 2030, Energinet.dk 2015. http://energinet.dk/DA/KLIMA-OG-MILJOE/Energianalyser/Analyser/Fremtidens-Energi/Sider/default.aspx

turbines, gas engines or dedicated gas fired boilers. All CHP power plants include storage to allow flexibility in production.

Individual heating and heat pumps

Today heating of individual houses and large apartment blocks are based on district heating, natural gas, oil, electricity or wood pellets. Oil is currently being phased out in favor of heat pumps, wood pellets and district heating. Natural gas heating is expected to be converted to either district heating or heat pumps. For the heat pump solution possibly with natural gas as a backup solution to secure flexibility between use of gas and electricity and avoid of using electricity for heating when power production from wind and solar is low.

Electrolysis and power to gas

Electrolysis is a process to convert electricity and optionally heat to produce hydrogen and oxygen from water. Hydrogen can be stored and used as fuel for cars and production of heat and power. Additionally oxygen and hydrogen can be used in industries. Hydrogen is difficult to store and handle and thus it may be more beneficial to use hydrogen to produce methane, fuels or raw materials. One example is through methanisation of the CO_2 (or another source of CO_2) in biogas by a catalytic[21] or organic process[22].

Conversion of biomass & waste to gas and fuels

Biomass and waste can be converted to gas and fuels via an anaerobe digestive process or a thermal gasification process[23]. In both cases the output is a gas that can be cleaned, upgraded or converted (with Hydrogen) to natural gas quality gas or fuels via the Fischer–Tropsch process. Both fuels and gas can be stored and can be used as fuels for transportation. On the longer term isit could be assessed weather there is a stronger case for not spending money upgrading the gas to natural gas quality and instead adjust the production assets and transmission system for gas to handle a different quality gas in stead.

Transportation

Transportation is cars, trains, planes, ships, busses and trucks and so on. Currently most kind of transportation is fueled by oil based products such as diesel, Gasoline, jet-fuel. These fuels can be made synthetically from biomass and hydrogen. Direct use of electricity is however more efficient than combustion of synthetic fuel. This is feasible in cars, trains, busses and even short route ferries but currently not an option for long distance trucks, planes and ships.

Studies and simulations of the future Danish energy system shows that the conversion to a 100% CO_2-netural energy system is possible and can be done with same cost or less compared to a traditional fossil fuel based system if the cost for emitting CO_2 is included. All elements in the system have been shown to work in practice but further research and development is required to increase scale and lower the cost. Furthermore the markets for trading electricity, heat and gas

---

[21] As utilized in the MeGa-stoRE project: http://www.methan.dk/

[22] As utilized in the BioCat project by Electrochea http://biocat-project.com/

[23] As utilized in the GoBiGas project https://www.goteborgenergi.se/English/Projects/GoBiGas__Gothenburg_Biomass_Gasification_Project

needs to be developed further in order to support demand flexibility from many different units and support units that operate in several energy markets (heating, gas, power).

4.5 The functionality and reliability of the Danish network, a case study

Do the increased variable energy sources and the increased flexibility introduced compromise the security of supply? A study hereof was made for Denmark in 2014. The aim of the study is to assess whether the security of supply can be kept at the high level of today as capacity on thermal power plants decrease and capacity on wind and solar increase.

Functionality of the power system is measured by calculating disruptions at demand side. It is apparent that about 3/4 of the disruptions are caused by the distribution network, while the remaining 1/4 are due to the transmission grid and that generation inadequacy has not impacted security of supply historically. It is also evident that cabling of the distribution networks underground means fewer interruptions, and since the distribution network have been largely cabled, the scale of the disruption is decreasing. This trend is expected to continue. The transmission network will be developed to cope with future wind integration developments and be adaptable to on-going developments. New grid components able to deliver ancillary services are also installed as supplement to ancillary services from power plants, as protection against disruptions.

As security of supply is achieved through networks and plants jointly; the analysis assessed development in domestic capacity – controllable as well as wind and solar – and the interconnection capacity from the neighbour countries. However, wind power may not be the only thing missing on a cold winter's day, as thermal power plants are not 100% available. The *likely* availability is what determines security of supply. Security of supply was analysed using a probability model covering all generation plants and cross-border interconnectors. Based on demand profiles, an hour-for-hour Monte-Carlo simulation was run, which using 'roll of the dice' probability models examines whether domestic production and imports from abroad are available. The model measures for each hour whether there is sufficient capacity, including interconnectors, to meet demand. An important finding is that despite the uncontrollable nature of wind and solar these technologies also contribute to security of supply.

Simulations were carried out for the years 2020, 2025, 2035 and 2050. For the first two years, domestic production is projected based on knowledge and assumptions regarding the continued phase-out of centralized and decentralized capacity. These scenarios have been designed so that the level of security of electricity supply is the same as today, i.e. disruptions due to generation inadequacy are expected to occur every ten years, cross-border electricity interconnectors are included on a par with domestic generation capacity, and current interconnectors are included along with planned expansions to Norway, Sweden, Germany and the Netherlands.

The results of the simulations for the risk of generation inadequacy are as follows:

Up to 2025:

- The security of supply is expected to improve in Western Denmark and can be maintained at similar levels in Eastern Denmark up to 2025, in spite of plant closures, as international interconnections, wind and solar power offset the decrease in thermal capacity.

- Developments in Eastern Denmark are more sensitive. In 2020, the security of supply of such selected assumptions could be maintained, while in 2025 there is a risk of marginal deterioration. It means that a delay or postponement of new interconnector projects could prove serious.

In 2035 and 2050:

- In 2035 and 2050 more thermal capacity is required, but the demand for more thermal capacity depends on the scenario. In the case of a high wind or a hydrogen scenario there is a need to add considerable extra capacity to ensure the status quo for the security of supply, while in the two biomass scenarios only a little extra thermal capacity seems to be necessary. In 2035 and 2050 there will occur interruptions in electricity networks in all scenarios unless additional capacity is added.

There are a variety of options to ensure the security of supply in the future. These include the network, where improvements already today are implemented, and measures on the demand side. When the network is reinforced or distribution networks cabled underground, this alone improves security of supply.

Regional differences in generation adequacy can be offset by new interconnectors. There are also various methods to maintain domestic electricity capacity at a certain level. Such capacity mechanisms typically fall into three categories: strategic reserves, capacity markets and capacity payments. In many countries, different models are either under consideration or have already been decided upon. None of the models are free of costs. There are advantages and disadvantages to all three models. International experiences with capacity mechanisms shows that the costs of capacity payments are generally on the high side. The cost of a capacity market is highly dependent on how they are configured. Strategic reserves seems cheaper, but not necessarily a permanent solution. It has to be emphasised that the experience from various capacity mechanisms still is limited and that costs will differ from country to country.

Flexible consumption offset capacity requirements is an option in countries with an electricity-intensive sectors. However, this could change if the smart grid concept is developed successfully.

The analysis summarizes security of supply with the following headlines:

- Overall, security of supply is to be maintained at the current level without new initiatives for the next 10 years
- Reinforcement of the network will to some extent offset the decrease in thermal capacity
- There are various possibilities to ensure sufficient generation capacity, but is might be expensive
- Any decline in thermal capacity is monitored as closely now as it will be in the future

4.6 Conclusions and lesson learned for China

Market based curtailment happens when power prices becomes zero or negative. In 2014 only about 0.2% of possible wind power generation in Denmark was wasted due to market based curtailment. Having the high level of wind penetration in Denmark integrated into a larger area (Northern Europe) smooth out the production making it easier to handle and balance the wind power production. However, the need to cut out wind production during hurricane or storm events can pose a significant shift in production over a fairly short time horizon.

The long term outlook for Denmark is considerably more wind and photo voltaic power. The target for 2050 is to reduce CO_2-emissions to zero. In 2035 the power production is expected to consist of up to 80% (dependent on the given scenario i.e. biomass or wind etc. scenario) intermittent production, which is expected to pose two interrelated challenges for the system:

The first challenge for the system is the much higher level of variation in RE production, which will require development of new market models and new technologies in order to reduce the cost of handling the renewable electricity production and maintaining security of supply. In the future heat, power, gas and manufacture of fuel are expected to be linked and electricity will be used whenever it is possible to substitute fossil fuels. The expectation is a higher direct usage of electricity for transportation and heating through heat pumps. Surplus electricity is either exported, used for heating with heat storage or converted to fuel via electrolysis. Electricity deficits (when power production from renewable production is too little to cover demand) are handled by import of electricity, increase of power production from biomass and gas and use of demand flexibility

The second challenge is whether the security of supply can be kept at the high level of today as capacity on thermal power plants decrease. The specific study in Denmark points towards a continued high level of security of supply until 2025, while more thermal capacity is required thereafter depending on the given scenario expected for 2035-50. Securing sufficient capacity typically fall into three categories: strategic reserves, capacity markets and capacity payments. In many countries, different models are either under consideration or have already been decided upon. None of the models are free of costs. There are advantages and disadvantages to all three models. Flexible consumption offsetting capacity requirements is an option in countries with electricity-intensive sectors like China.

5 Flexibility in conventional thermal power plants

Within the next five years it is China's goal to triple the energy production of renewable sources like wind and solar[24]. By 2020 a total capacity of 0.43 TW[25] is planned to be online resulting into a penetration of the installed renewable energy capacity with app. 20%. Obviously, this ambitious integration will challenge the existing power system with respect to adapt the fluctuating energy production while providing reliable and affordable energy.

To make use of the capability to operate the existing conventional generation fleet flexible is one of the cheaper ways to ensure power system flexibility at low to medium wind production penetration levels. This is due to the fact that increasing operational flexibility of power plants exploits the potential of an already existing infrastructure to its maximum.

Flexibility enhancement of conventional power plants consists of various tasks and operational flexibility is just one of them. Other flexibilization tasks, which European power generators currently are facing are; flexible maintenance, driven by the demand to counteract decreasing revenue; flexible utilization of different types of fuel, driven by subsidy regimes, as example for biomass; flexibility on emissions, driven by more rigorous regulations and increasing emission taxes. The following only addresses the task to enhance the operational flexibility, but one should have in mind, that the power generators must optimize their fleet with respect to all aspects.

Operational flexibility of conventional power plants can be defined by the following flexibility parameters.

Flexibility parameter	Description	Denmark	China
Minimum load	Minimum stabile net output when operating on the primary fuel source. Periods with a high contribution of renewable production require lower minimum load, as start of conventional steam power plants are time consuming and costly.	Min. load primary fuel: 15-25% Boiler Maximum Continuous Rating (BMCR)	Min. load primary fuel: 30% Boiler Maximum Continuous Rating (BMCR)
Load ramping	Increasing or decreasing of the net power output in order to balance the fluctuations between production (as example renewable production) and demand.	Load ramping: approximately 4%/min	Load ramping: 1 %/min
Start-up time	Short power plant start-up times are beneficial, as the forecast error of renewable energy production decreases when reaching the actual production hour and retention to order a unit started is of interest for the grid operator.	Start-up time (from ignition to 90% base load, warm start): 170 min	Start-up time (from ignition to 90% base load, warm start): 170): 180 min

---

[24] Introduction to Electric Industry, EPPEI presentation April 2015

[25] Introduction to Electric Industry, EPPEI presentation April 2015

Efficiency	With decreasing load the efficiency[26] of a steam power plant decreases. It is of importance to optimize the part load efficiency and to keep part load OPEX (operational expenditure) at a low level, in order to maximise the revenue.	Efficiency (range 100% - min load): 45-37 %	Efficiency (range 100% - min load): 44-43 %

Figure 19: Flexibility parameter definition

With an increasing penetration of volatile renewable energy the operational profile of the conventional power plant fleet changes. The trend is that conventional power plant load operation with high number of operating hours (typical > 7500h) and few starts per year (typical < 2) will go towards more peak operation with a high number of starts per year (typical > 250) and low operation time (typical < 2500h). When shifting from base load to peak load regime, the specific power production price increases, while the plants revenue decrease. Increasing OPEX is among others caused by start-up costs and decreasing unit efficiency both at low and high loads (high loads because of increasing heating losses when being synchronized for only a few hours). The plant revenue decreases partly because of the increasing OPEX, but mainly because of the decreasing operation hours and hereby the associated loss of revenues.

This shift in the operational profile from base load to intermediate and peak operation can currently be observed for many power plants in Europe. The decreasing revenues of European power generators create a decreasing incentive to invest into new capacity, which in the long term is not beneficial for the operation of the power system. The shift in the operational profile varies from country to country within the European Union depending on the country specific CO_2 reduction goal, as well as other political decision, as example phase out of nuclear energy production.

In Figure 20 below the expected development of the operational profile for a hard-coal fired steam power plant and a combined cycle plant with gas turbines (CCGT) in Germany is shown. Germany's goal is to reduce CO_2 emission up to 80% until 2050, a nuclear phase-out until 2022 and to increase renewable sources up to 40% [27]. The figure shows number of unit starts and operation time on the grid referenced to 2010 as baseline year. Of course the numbers depend on calculation boundaries, like fuel and emission prices.

	2020	**2025**
CCGT number of starts	-40 %	-35 %
CCGT operation time	-71 %	-44 %
Steam power plant hard-coal number of starts	+7 %	+17 %
Steam power plant hard-coal operation time	-55 %	-24 %

Figure 20: Operational profile comparison for two units in Germany[28]

It is the purpose of this section to summarize the impressions regarding the potential for enhancing the operational flexibility of Chinas thermal power plant fleet with respect to the in Figure 19

---

[26] Defined with fuel LHV (lower heating value)

[27] Integration of large-scale renewable energy sources: Challenges to thermal generation in Germany, Ziems et al. Milano September 2011

[28] Integration of large-scale renewable energy sources: Challenges to thermal generation in Germany, Ziems et al. Milano September 2011

defined products. The impressions are based on a meeting with experts from EPPEI (Electric Power Planning & Engineering Institute) and, in advance of the meeting, exchanged questions between EPPEI, DEA (Danish Energy Agency) and AV (Added Values). As that the following must only be regarded as a starting point for the analysis of the Chinese fleet's operational flexibility capability, capacity and related costs. Based on the discussions it is possible to evaluate the capability of a typical Chinese power plant from an overall point of view, but without further analysis and knowledge concerning the detailed design and operation of the Chinese steam power plants, it is impossible to estimate the specific capacity, volume and price of enhanced operational flexibility accurately. This assessment, which results are an important input for the long-term power system planning, should be carried out soon, as the integration of renewable energy is expected to develop rapidly.

Beside evaluation of the typical power plant capability for enhanced operational flexibility a possible path for the development of enhanced operational flexibility is presented. This path follows the goal to exploit a least-cost approach, where the operational flexibility of the conventional fleet is developed using a stepwise optimization approach for each phase matching the increasing penetration level with renewable energy sources. A phase by phase optimization will keep the necessary investment in operational flexibility for the conventional power generators at the lowest possible level.

5.1 Danish energy policy and development of flexibility in power plants since 1990

Enhancement of the operational flexibility of Danish thermal power plants has been in focus for more than 20 years. The motivation to enhance the operational flexibility was not only given by an increasing penetration with renewable energy, but also by changing market conditions, when the liberal power market was established.

Figure 21 shows the evolution of the power production in Denmark. Decreasing separate power production in connection with a rapid development of renewable production (mainly wind power) can be observed from 2005 and onwards.

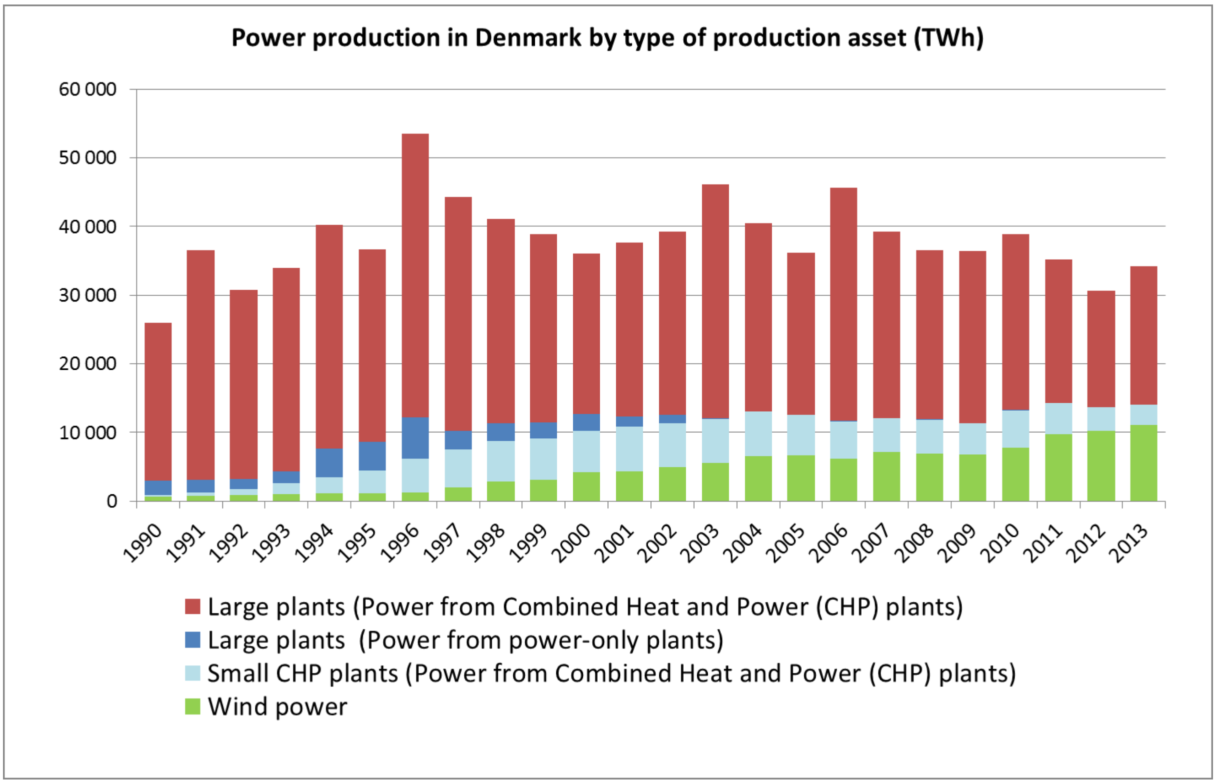


Figure 21: Evolution of power production in Denmark[29]

Table 2 shows the increasing penetration with renewable energy as percentage of total power consumption. In the early 1990's the penetration was app. 2%, reached 10% in 2000 and 20% in 2010. With the latest energy development plan of the Danish government (Energy Agreement of 2012) an ambitious goal concerning expansion of renewable energy sources was decided and the following strategic expansion reached a current record breaking penetration of 39% (of total power consumption) in 2014[30].

	Penetration with renewable energy
1995 – 2000	From 4% to 10%
2000 – 2010	From 10% to 20%
>2010	From 20% to 39% (2014)

Table 2: Penetration of renewable energy in Denmark[31]

5.1.1 First optimization 1995-2000

The first optimization of the conventional power plant operational flexibility was driven by the change of the marked price when entering into the liberalised power marked. The liberalization forced Danish generators to compete against cheaper production capacity from Norway, Sweden and Germany. Due to the fact, that almost all thermal power plants in Denmark are CHP (combined heat and power) plants, a decreasing power price could be observed during periods with high district heat demand, explainable by the high rate of forced power production in Denmark. In

---

[29] Danish Energy Agency
[30] Danish Energy Agency
[31] Danish Energy Agency

order to counteract this price development the first operational flexibility optimization was launched with the aim to improve the decoupling of heat and power production. The enhanced decoupling was implemented using the existing plant components in a different manner and no investment in new hardware was necessary. It should be mentioned, that district heat storage tanks already before this optimization step were in operation and utilized to take advantage of the fluctuating prices over a day/night 24 hour cycle. The typical storage capacity is equal to one day's heat demand during winter time or one weekend's heat demand during summer time.

5.1.2 Second optimization 2000-2010

During the first decade of the new century increasing penetration with renewable energy changed the marked. The operational profile of the conventional power production changed towards decreasing load utilization and as time periods with low energy prices increased partly due to the merit order effect created by more wind power with low marginal costs, an interest in improved low load operation capability grew. Typical operational flexibility enhancement measures applied during this second optimization were low load operation optimization, load gradient boosting and further decoupling of heat and power production. Low load operation capability was optimized and the power output can now reach values as low as 10-20% of the nominal power output. Low load operation is typically applied for shorter periods (varying between overnight up to one weekend), as the start-up costs are balanced if time periods with low power prices gets longer. Load gradient capability, as well as primary and secondary control capability was improved, in order to balance decreasing revenue of power production by harvesting higher revenues on the ancillary market. The focus on efficient plant operation grew and performance monitoring systems were introduced on all units, given the plant operators the possibility to optimize daily operation in order to reduce losses suggestible by changes of operational parameters. Key performance indicators (KPI) were introduced in order to benchmark the performance of the power plant fleet.

This optimization was done with no to low investment in new hardware and the main costs of this optimization phase were related to plant re-commissioning, which among others included optimization of the DCS control system, combustion optimization, steam turbine cooling steam and thrust calculations, or in other words mainly engineering costs.

5.1.3 Third optimization after 2010

Since 2010 the renewable energy penetration increased, reaching a current record of 39% of power consumption in 2014. Although (since 2000), app. 2 GW thermal power production was decommissioned and another app. 1 GW is on long-term stand-by[32], this growth resulted into a rapid decreasing operation time for the remaining conventional power plants, even though all these plants are CHPs. In order to keep the plants revenue at an acceptable level, further and even more drastic flexibilization measures were needed. Implemented measures were; complete turbine bypass (bypass of main/reheat steam directly into a district heat exchanger); electrical boilers for conversion of electrical power into heat, especially for periods with electricity overflow (higher production by renewables than the demand); increasing focus on efficiency enhancement and decreasing maintenance costs. This was the first optimization step which required medium investment into new plant equipment, like investment in bypass heat exchangers, electrical boilers, piping, etc. Furthermore start-up optimization is now getting more focus. Start-up optimization

---

[32] Danish Energy Agency, Capacity evaluation of thermal power plants, February 2014

decreases not only the start-up costs, but also the necessary operation time during low periods with power prices, in order to be able to reach base load and harvest the revenue of attractive high price periods.

Summarizing the Danish power plants was optimized in phases matching the required needs for flexibility during each phase. This phase oriented optimization allowed to keep the necessary investment for each phase at the lowest possible value.

5.2 Technical parameters for flexibility on Chinese Power Plants

Based on discussion with experts from EPPEI, as well as in advance of the meeting exchanged questions, it was possible to compare technical parameters relevant for the enhancement of the operational flexibility of Chinese and Danish power plants. By comparing the key technical design parameters, the potential for operational flexibility enhancement of a typical Chinese power plant can be estimated. The, for this estimation considered key design values are summarized in Table 3. It can be noticed, that several design values with key relevance for the enhancement of the operational flexibility are identical.

	Typical Chinese Power Plant	Typical Danish Power Plant
Fuel/Coal	90% of installed steam power plant capacity: hardcoal [33] 10% of installed steam power plant capacity: lignite	70% of installed power plant capacity: hardcoal[34], some units with biomass co-firing (up to 15%) 30% of installed power plant capacity: natural gas or biomass
Firing system	n-1 coal mill configuration mills: XRP, MPS with rotating classifier low-NOx burner in tangential or boxer configuration	n-1 coal mill configuration mills: MPS, BBD with rotating classifier low-NOx burner in tangential or boxer configuration
Flue gas cleaning	NOx: SCR (selective catalytic reduction). SOx: wet FGD (flue gas de-sulfurization) Dust: Filter bag	NOx: SCR SOx: wet or dry FGD Dust: Electrical participator
Boiler type	Once through	Once through, tower design
Once through (Benson) operation load point	30% BMCR (Boiler Maximum Continuous Rating)	Max. 35% BMCR
Minimum load primary fuel	30-40% BMCR	15-25% BMCR
Load range secondary fuel	0-30% BMCR	0-100% BMCR
Use of secondary fuel	Unit start-up and mill start/stop	Start-up, flame stabilization during low load operation, since 2012 fuel oil for coal mill start is abolished
HP and IP/LP Bypass station capacity	30-40% Cannot be operated	100% Can be operated continuously

---

[33] Mainly domestic hardcoal sources

[34] World-marked hardcoal, mainly from Russia, Poland, South America

	continuously	
Turbine configuration	Combined HP/IP casing, except units <150 MW which are in single casing configuration	Single casing configuration
Turbine	HP turbine start-up line	Only few units do have HP turbine start-up line
Turbine operation	Sliding pressure between 40-90% Pressure control: 80-100 bara	Sliding pressure between 30-100% Pressure control: 90-100 bara
Combined heat and power plants	30% of installed steam power plant capacity Steam turbine extraction from IP/LP cross over or the IP exhaust. IP/LP cross over equipped with valve to adjust extraction steam pressure.	100% of installed power plant capacity Steam turbine extraction, at the exhaust of IP2 turbine. LP's can, during district heat production, be shut off with cross-over valves, only cooling steam is send through.
Operation profile	1 start per year Base load or intermediate load (app. 8000h/year)	Starts per year > 20 often weekend stop during summertime. Cyclic operation (app. 4000-6000h/year)
Design life time	30 years	30 years or 200.000 hours. Life time extension when above this number.
Forced outage rate	0.3 - 0.4 %	0.2 % (this number also includes stand-by operation time)
Unit size	1000 MW or 600 MW USC (ultra supercritical), SC (super critical)	600 MW or 400 MW USC, SC
Grid code requirements	Primary response: 5% Load gradient: 1%/min Minimum load: 40%	Primary response: 5% (within 5s) Load gradient: 2%/min for load area 20-50% and 90-100%, 4%/min for load area 50-90%. Min load: 35% (for coal)

Table 3: Comparison of key technical design parameters between Chinese and Danish power plants

Impact of the power plant size

The relative optimization potential of the majority of the flexibility parameters is independent on the power plant size. Load gradient and start-up optimization might although be limited by the unit size, as steam pipes and valve bodies might have reached wall thicknesses limiting the permissible temperature gradient significantly. However, although the typical Danish power plant is about ½ the size of the Chinese power plants, the relative optimization potential can be expected to be comparable with the obtained operational flexibility of Danish power plants, because the technical design features are almost identical. It is important to have in mind that the absolute flexibility figures, will vary from plant site to plant site. This variation can be explained by differences in applied components, component configuration and boundary conditions (as example coal quality and characteristics) which do determine the limitations and obstacles met during optimization. To give an example; the lowest obtainable boiler heat input is typically defined by combustion stability, i.e. coal quality (coal calorific value and volatility).

Minimum load reduction potential

Reduction of the minimum load highly depends on the possibility to reduce the boiler heat input, but also the capability to provide sufficient firing rate gradient to get back into the normal operation area. The transition point from once through operation to circulation operation (Benson point) of Chinese power plants is comparable to that of Danish power plants. This allows for operating the typical Chinese units between Benson minimum (30% BMCR) and base load (90% BMCR) in cyclic operation without any limiting factors given by the boilers firing or hydraulic system. As the typical Danish power plant, the typical Chinese power plant does have a boxer (burners located at the front and rear wall) or tangential burner configuration, having the advantage of providing a more even flue gas temperature distribution towards the heating and SCR catalyst surfaces even in part- and low load operation. Furthermore the combustion flame stability is higher, as the flames of the individual burners do support each other, allowing reducing the heat input while burning primary fuel only, i.e. without using aux. burner/fuel oil for flame support. It is expected, though depending on the flame stability, determined by the coal quality, that low load operation down to safe one-mill operation should be obtainable. However, it must be mentioned, that one-mill operation sets high requirements conc. the air damper positioning accuracy in order to control the combustion air excess, as well as purge air damper positioning accuracy for the burners out of operation, as unwanted high air leakage through the purge system not only reduces the boilers efficiency, but because of the formation of cold air streaks also the CO emissions might increase. With the XRP/MPS coal mills it should be possible to reduce the mill load to app. 25-30% of its capacity, which in n-1 configuration would allow reducing the firing rate with 2 mills in operation to app. 20-25% of the nominal firing rate. However, the latter depends on the coal quality in terms of hardgrove-index, calorific value and the fraction of volatile parts, as the mill turndown ratio is limited by the minimum required grinding bed thickness and coal/air ratio. At this load the boiler will be in circulation operation with significant decreased main and re-heat steam temperatures. Transition from once through to circulation operation can cause rapid temperature gradients, which might be problematic for the boilers thick-walled components or the circulation pump itself. For optimization it is important to have temperature measurement equipment, which allows monitoring tube overheating and especially temperature gradients between neighboured tubes, which might result in not acceptable high stress levels. Based on experience the low firing rate will require; 1. combustion optimization in order to reduce flue gas temperature profile distortion as much as possible, 2. optimization of the coal mill start/stop control and 3. feed water pump switch over optimization. Both coal mill and FWP pump start/stop should be as smooth as possible. Furthermore re-programming of the boiler and steam turbine protection must be foreseen.

Flue gas treatment system – emission limits

It is expected, that the existing flue gas treatment systems can be operated from 30% to 100% load without any limitations. When extending the load range towards lower loads the flue gas temperatures upstream the SCR catalyst decrease. With decreasing flue gas temperature the reaction degree of the catalyst decreases and a higher specific NH3 dosing is required, which also will increase the slip and might increase fouling of the catalyst and the boilers heating surfaces. Depending on the load and/or boiler heating surface configuration the flue gas temperature might even be outside of the specified operation window for the SCR. In order to increase the flue gas temperature at low load different techniques can be applied. These techniques vary in their complexity from operating with increased air excess or flue gas recirculation to installation of additional HP heating surfaces or economizer bypass. If none of these techniques can be applied effectively, it might be necessary to introduce a time limitation for low load operation when the flue gas temperatures upstream the SCR is below the specified window. Usually the catalyst can be regenerated if a low load operation is followed by a period of high load operation. The FGD functionality depends on the flow velocity within the absorber and therefor the specific deposition efficiency will be reduced at low loads. This can be compensated by changing the liquid/gas ratio towards higher values, only affecting the FGD power consumption, while keeping the de-sulpherization ratio at a high level above 90%. The challenges of increased operational flexibilization with respect to the flue gas treatment system are well known and can been resolved. It is therefore expected, that the flue gas treatment system, with some minor changes, can be operated at low loads, i.e. the Chinese regulations concerning NOx and SOx emissions will not be jeopardized when enhancing the operational flexibility.

Steam turbine operation

The Chinese and Danish steam turbines are operated in sliding pressure operation. Normally the load range for sliding pressure operation can be reduced to the Benson load or a main steam pressure of app. 90-100 bar. However the latter depends on the requirement to deliver ancillary services in terms of primary/secondary control reserve. Further decrease of the load shortens the steam expansion with increasing turbine cylinder exhaust temperatures as result, usually called turbine ventilation. In order to control the turbine exhaust temperature within the required range a certain amount of cooling steam is required. As the typical HP turbine of a Chinese power plant is equipped with a start-up line, ventilation of the HP turbine can be avoided and the total required amount of cooling steam can be reduced to values even lower to those of steam turbines on Danish units. This allows reducing the generator power output.

Typical Chinese steam turbines of higher power output are designed with combined HP/IP casing, while Danish units usually are equipped with separated HP and IP casings with individual bearing. Separated casing guarantees an excellent thermal flexibility with short start-up time and fast load change capability. Combined HP/IP casing design might due to the permissible temperature gradient limit turbine bypass operation, start-up and ramping rate optimization.

While the Danish CHPs have asymmetric IP turbine sections designed for district heat extraction, the typical Chinese CHP produces district heat using extractions at the IP turbine cylinder exhaust or IP/LP cross over. The units are equipped with valves for control of the extraction pressure. Concerning flexibilization of the CHP's operational envelope it can therefore be expected, that the heat and power production can be decoupled over a wide range compared with the normal load area diagram. This requires that some components, as example HP heater train and HP turbine, are operated in a different manner. When extracting a high amount of steam, valves in the IP/LP cross over, which can be used to control the IP exhaust pressure at the required level, allow to improve the decoupling between heat and power production, as steam can be redirected towards the district heat condensers instead of continuing through the LP-turbine. This allows converting power into heat production until the minimum cooling steam demand for the LP turbines is reached.

Load gradient optimization potential

The Chinese grid code requires a load ramping capability of 1%/min, while the European grid code requires 2%/min (Note: Danish units are designed for 4%/min). The design ramping capability and the corresponding temperature gradients determine the choice of material and the thickness of the thick-walled components like headers, main and reheat steam lines and valves. Depending on the applied wall thickness and materials load ramping optimization might be limited and without further detailed design knowledge it is impossible to judge the optimization potential. However, as Danish power plants are designed for ramp rates in the range of 4%/min, it is also expected that the ramp rates of the typical Chinese power plant to some degree can be optimized.

HP and IP/LP bypass capability

There are different design philosophies conc. the sizing of HP and IP/LP turbine bypass stations between Chinese and Danish power plants. While the typical Chinese bypass capability is identical to the European (as example German) design philosophy, Danish units are in general designed for 60-100% continuous bypass operation. The different design philosophy does only have a consequence for the operational flexibility optimization of CHP plants, but not for units operating in condensing mode. By exploiting HP-turbine bypass capability, also at higher loads, it is possible to decouple heat and power production even at high heat supply demands. However, based on the discussions with experts from EPPEI, the bypass stations are not designed to be operated continuously. As turbine bypass for CHP units might be of interest in order to obtain a complete decoupling of heat and power production, it should be investigated, if this bypass station operation limitation is mandatory or could be relaxed.

5.3 Assessment of the flexibility potential of power plants in China

Based on the comparison of the overall technical design figures it can be concluded, that the approach for obtaining higher flexibility in China and Denmark is the same. Because the average age of the Chinese power plants is much lower than that of Danish power plants it is highly probable, that the starting potential is even better, as the DCS (Distributed Control System) of the Chinese power plants are modern, easier programmable, and as that the control and protection functionality can be easier adopted to a changed operational envelope. When comparing the key design figures shown in Table 3, a high degree of similarity between the Chinese and Danish power plants can be found and it is therefore expected, that many of the technical obstacles found during optimization of the Danish power plants also will be met during the optimizing phase of Chinese plants.

Beside the technical challenges it is necessary to resolve the regulatory challenge. Chinese power plants have a fixed feed in tariff well above the current marginal production costs and as such have no incentive to increase their operational flexibility. As increased operational flexibility will increase the production costs and thus reduce the revenue, it will be necessary either to introduce new regulatory interventions or to introduce a liberal marked in order to compensate for the plants revenue loss.

As the Chinese power plants do have a once through transition point at a relative low load, as well as they according to the grid code are required to be able to operate stabile down to 40% power output, it is very roughly estimated that the Chinese power plants can be operated relative smoothly in the intermediate load range (between 30% to 100%) in cyclic operation. It is expected that this flexibility enhancement can be transposed without any investment in new hardware. Just like the Danish power plants all Chinese power plants were originally designed as base load units and as such the main focus during unit commissioning was solely on the optimization of base load. In order to allow smooth and safe operation in the intermediate load regime it will be necessary to carry out a unit re-commissioning adopting the new load range. Based on experience some DCS control functions, as for example the boiler and steam turbine protection, which originally were designed for start-up, will trigger alarms or even prevent flex-optimization. Therefore re-design / re-programming will be necessary in order to adopt the safety functionality of the unit to the enhanced operational envelope. Depending on the behaviour of the firing system it is probable, that the units can be optimized to operate in the load range between 20/25% to 100%, but this requires high coal quality and proper design of the air/fuel systems.

Increased flexibility will not necessarily lead to significantly increased maintenance costs. The thick-walled components will experience a higher degree of fatigue, but, based on experience, an analysis of operational data will probably show that increased life time consumption mainly is caused by discrete events, as for example inadequate tuning of a feed water pump start/stop or inadequate bypass-station ad-temperator operation. Increasing a unit operational envelope might increase the frequency at which these events are triggered and it is therefore important to carry out a component life time consumption analysis in parallel with the optimization process in order to identify the reasons for increased life time consumption. If these events can be removed or smoothened the additional life time consumption from flexible operation can be reduced. On older units the thick-walled components already have experienced a high degree of creep and additional fatigue might be the reason to trigger component failure causing increased maintenance costs. On these units component life time consumption analysis is of even greater importance.

Compared with the Danish power plants some differences in design could be found. They will not necessarily limit the optimization of the operational flexibility, but they will lead to new and different challenges. It is recommended to investigate the already addressed differences in more detail.

Danish experience with increased decoupling of heat and power production for CHP's show, that these, in connection with district heat storages, do have an excellent starting point for increasing operational flexibility. As shown in Figure 22 the operational envelope can often be improved without additional hardware investment, just by operating the existing equipment in a different manner. With additional investment in new equipment, as example heat pumps or electrical boilers, it is possible completely to decouple heat and power production. According to Danish experience such flexible units are more robust to the increasing penetration of renewable energy, as they have the necessary infrastructure to convert electricity into heat and hereby harvest revenue not only by power, but also by district heat production.

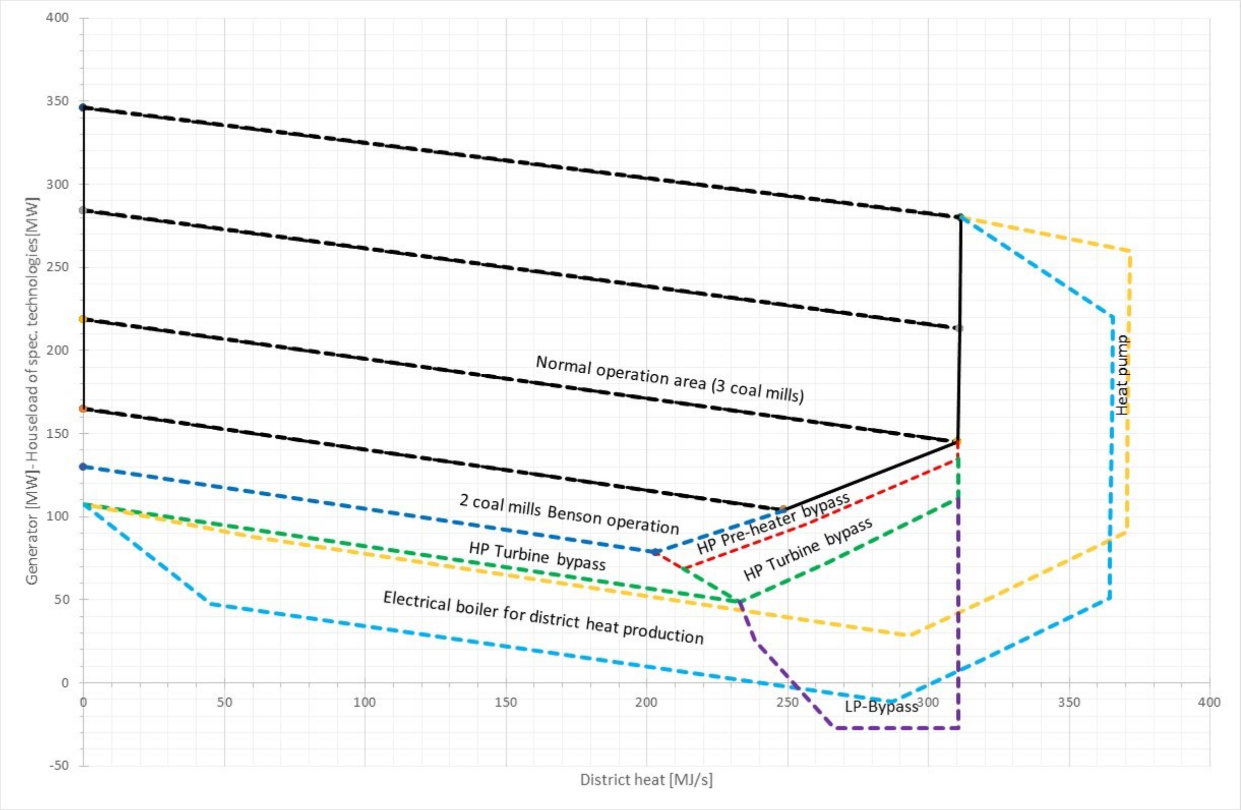


Figure 22: Example of the operational flexibility enhancement of a CHP (in black the original envelope, in colour extension of the envelope using different techniques)

All in all it can be concluded, that the Chinese power plant flexibilization capability can be expected to be (almost) that of Danish power plants. Based on this first overall assessment it is of course not possible to give accurate expectations concerning the achievable operational flexibility, but Table 4 gives a very rough appraisal of the expected operational flexibility, which entirely is based on the experience with the optimization of Danish power plants combined with the comparison of key technical design figures between Chinese and Danish power plants.

	Current operational flexibility	Expected operational flexibility
Minimum load	50-70% TMCR. (Current limit defined by economical rather than technical constrains.)	20-40% TMCR (turbine maximum continuous rating)
Load ramping	1 %/min	2-3 %/min
Start-up time (from ignition to 90% base load)	180 min	150 min
Flue gas emission after SCR and FGD (range 100% - min load)	NOX: app. 60 mg/Nm3 SO2: app. 20 mg/Nm3	NOX: app. 60 mg/Nm3 SO2: app. 20 mg/Nm3
Efficiency (range 100% - min load)	44-43 % (load 100-50/70%)	44-33% (load 100-20/40%)
Reliability	FOR 0,3-0,4 %	Unchanged FOR

Table 4: Current and expected operational flexibility of a typical Chinese power plant, as well as expectations conc. other important Chinese requirements

Besides having focus on safe, smooth and reliable operation, in order to reach the demand of a low and unchanged FOR (Forced Outage Rate), it is also of importance to focus on efficiency. As shown in Figure 23, the power plant efficiency decreases in part load. Main efficiency optimization areas are of course optimization of the combustion and firing system, but also optimum operation of auxiliary equipment among others the aux. air preheater, FGD, etc., should be in the focus in order to reduce the part load efficiency loss as much as possible, as this will increase the revenue.

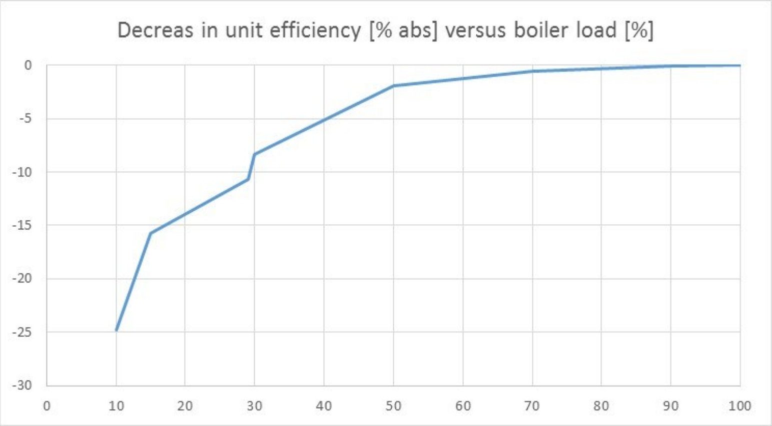


Figure 23: Expected efficiency loss in part load operation

5.4 Possible path to reach enhanced operational flexibility

Based on the experience with operational flexibility enhancement of power plants in Europe, in the following section a possible path to reach enhanced operational flexibility is presented.

Table 5 shows an outline for enhancement of the operational flexibility. The table includes target numbers to be reached depending on the penetration level with renewable energy sources. These targets are based on experience rather than the actual technical capability of the typical Chinese power plants. Depending on the growth rate of renewable energy sources within the different geographic areas of China some flexibility products might be of more interest than others. Only a long-term power system analysis can give the best guess concerning the required target numbers, as well as the flex product priority list for the individual Chinese power grids.

Based on experience a step by step optimization of the individual flex products should be foreseen. In a step by step optimization approach the single flex products are improved until an obstacle is met. An example for an obstacle could be an increasing number of alarms and unit trips. Solutions for removal of these obstacles should be developed and implemented, as example optimization of the control logic in order to address the alarms and trips. After removal the optimization is continued until the next obstacle is met. This approach is repeated, until a limiting, not removable obstacle is met. Figure 24 shows this optimization strategy schematically. It is important to notice that flexibility optimization is a multidisciplinary task, which requires the involvement all power engineering disciplines, among others materials, thermodynamics and control technology, as the obstacle characteristic is interdisciplinary.

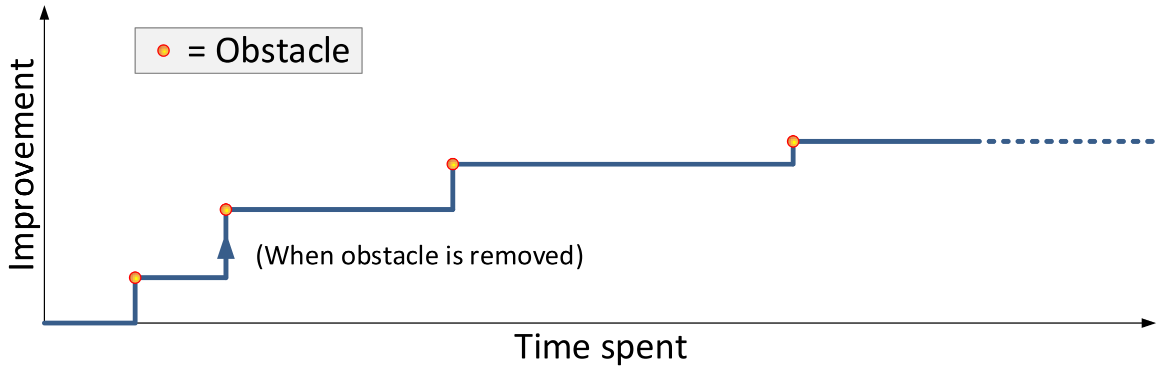


Figure 24: Stepwise optimization approach

As discussed the development of the operational flexibility in Denmark was conducted in different phases, driven by both changes in the market set-up, and increasing penetration with renewable energy. This phase by phase optimization does have the advantage of keeping the necessary investment and in the end the power price at a low level.

	Flex product	Power plants in condensing operation	Combined heat and power plants
Current situation	Minimum load	50-70% TMCR	Following the heat demand
	Ramping	1 %/min	1 %/min
	Start-up	-	-
	Efficiency	High, as units are operated in base load	High, as units are operated in base load
	Reliability	Excellent, FOR: 0.3-0.4%	Excellent, FOR: 0.3-0.4%
	Requirements for the detailed analysis: • Regulatory or marked defined incitement under consideration • Only existing equipment is used, no investment • Only pilot projects on few but different units (as example for the following units: condensing USC 1,000 MW unit, condensing USC 600 MW unit, CHP unit)		
Phase 1 - Detailed analysis concerning capability and costs	Minimum load	>30 % TMCR	Decoupling heat and power production using existing hardware.
	Ramping	1.5 %/min	1.5 %/min
	Start-up	-	-
	Efficiency	Decreasing as more part load. Efficiency improving measures to be investigated.	Decreasing as more part load. Efficiency improving measures to be investigated.
	Reliability	No change, FOR: 0.3-0.4%	No change, FOR: 0.3-0.4%
	Requirements for step2: • Regulatory or marked defined incitement exist		

	• Mainly existing equipment is used, investment into new balance of plant equipment, i.e. heat storage tanks, must be foreseen. • Medium to intermediate optimization of power plants in areas with low to medium penetration of renewable energy (<20%)		
Phase 2 – Introduction of operational flexibility in areas with low to medium penetration with renewable energy (<20%)	Minimum load	<30% TMCR	Further decoupling heat and power production using components of the plants auxiliary system. Investment into heat storage tanks.
	Ramping	2.0 %/min with gradient boosting	2.0 %/min with gradient boosting
	Start-up	-	-
	Efficiency	Enhancement of efficiency at low load.	Enhancement of efficiency at low load.
	Reliability	No change	No change
	Requirements for step3: • Regulatory or marked defined incitement exists • Step2 has been completed • Mainly existing equipment is used, investment into new equipment, i.e. heat pumps, must be foreseen. • Intermediate to large optimization of power plants in areas with medium to large penetration of renewable energy (>20%)		
Phase 3 – Introduction of enhanced operational flexibility in areas with medium to large penetration with renewable energy	Minimum load	<20% TMCR	Further decoupling of heat and power production using modified equipment. Investment into heat pumps or electrical boilers.
	Ramping	2-3 %/min	>2-3 %/min
	Start-up (warm start)	Shortened by 60-90 min	Shortened by 60-90 min
	Efficiency	Enhancement of efficiency at low load.	Enhancement of efficiency at low load.
	Reliability	No change	No change

Table 5: Possible path aiming for larger operational flexibility

Phase 1

It is the purpose of this phase to develop a profound knowledge concerning the costs and capability of enhanced operational flexibility of Chinese power plants. The result of this analysis will be an important input value for the long-term power system planning tool, in order to determine the cost optimum development of the power system while increasing the penetration with renewable energy sources.

It is proposed to conduct the analysis as pilot projects on several and different power plant sites, varying in size, configuration, location and renewable energy penetration of the grid. With respect to the in Table 5 stated target values it should be mentioned, that the single flexibility products should be optimized until the first limiting obstacles for further optimization is met, so the stated targets are only guidance values. Solutions to overcome the met obstacles and the expected enhanced operational flexibility after removal should be determined and used as input for the power system planning tool.

In order to determine the costs for enhanced operational flexibility accurate, life time consumption analysis before and after optimization should be carried out. It is expected, that already this phase will require a partly re-commissioning of the unit, as well as re-programming/optimization of the control loops within the DCS.

Beside actual optimization of the operational envelop this phase will give experience in operational flexibility which should flow into plant specifications for new build projects. Among others experience concerning adequate storage capacities of the condenser hotwell, feed water storage tank, heater train bypass capability, etc. can be collected.

Phase 2

Based on the experience collected in phase 1, the operational flexibility of power plants in regions with low to medium and medium to high penetration levels of renewable energy are optimized for a larger number of units. Beside costs for unit re-commissioning in order to adopt the new operational envelop investment costs for district heat storage tanks at CHP sites should be foreseen. Based on experience extensive re-programming of the control logic in order to operate smooth, save and reliable within the new operational range must be foreseen.

As shown in table 6 and compared with phase 1 the target values for the single flexibility products are improved. However, the actual obtainable operational flexibility will be site specific and the regulatory incitement should be able to consider the differences between the sites.

Because of the reduced power plant utilization in terms of power output and operating hours, measured to enhance the part load efficiency, among others combustion and firing system optimization, but also optimum operation of auxiliary equipment like aux. air preheater, FGD, etc., should be introduced in this phase in order to increase the plants revenue. Performance monitoring systems and KPI follow-up should be introduced in order to reduce losses suggestible by changes of operational parameters.

As a larger number of units are optimized, this phase will provide excellent experience concerning the optimization limitations and how these can be removed, but also operational experience, while operating in a widen operation envelope and this experience should be use in order to alter plant specifications and guarantees for new build projects.

Phase 3

Based on the experience collected in phase 2 the operational flexibility of power plants in regions with medium to high penetration levels of renewable energy is enlarged further. Beside costs for unit re-commissioning investment into new equipment, i.e. heat pumps, electrical boilers, etc. should be foreseen.

Compared with phase 2 the single flexibility products are optimized to their final limitations, which will vary from site to site.

5.5 Conclusions on power plant flexibility

Based on discussions with experts from EPPEI, as well as in advance of the meeting exchanged questions, a comparison of key technical parameters for operational flexibility enhancement between Chinese and Danish power plants has been developed. When comparing the overall design values it can be concluded, that several key design values with relevance for the enhancement of the operational flexibility are identical. Based on the comparison of the overall technical design figures it can be concluded, that the approach for obtaining higher flexibility in China and Denmark are the same. It can furthermore be concluded, that the Chinese power plant flexibilization capability, in relative terms, can be expected to be identical with the exploited potential on Danish power plants. Compared with the Danish power plants some design differences could be found, which not necessarily will limit the optimization of the operational flexibility, but will give new and different challenges.

Based on this first overall assessment it is of course not possible to give accurate expectations concerning the achievable operational flexibility and it is proposed to conduct an analysis in form of flexibility enhancement pilot projects on several and different power plant sites, varying in size, configuration, location and penetration of the grid with renewable energy sources. It is the purpose of this analysis to develop a profound knowledge concerning the costs and capability of enhanced operational flexibility. The result of this analysis will be an important input value for the long-term power system planning tool, in order to determine the cost optimum development of the power system while increasing the penetration with renewable energy sources.

Based on experience with flexibility enhancement of European power plants a phase by phase stepwise optimization approach could be applied, having the advantage of keeping the necessary investment costs in enhanced power system flexibility and in the end the power price at a low level. It is believed that the cheapest way to ensure power system flexibility at low to medium penetration levels with renewable energy is to make use of the capability to operate the existing conventional generation fleet flexible, as increasing operational flexibility of power plants exploit the potential of an already existing infrastructure to its maximum. Further increasing penetration levels will then of course require the use of other balancing measures.

6 How Danish power plants dispatch its power

Over the last decade a significant change has taken place in the power plant industry in Denmark. As described previously a significant amount of installed capacity has either been decommissioned (2 GW) or set on long-term stand-by (1 GW) within the last decade. Furthermore operation time and production for the remaining power plants in operation has also decreased significantly. For example the total power production from the central power plants in DK West was on average 13 TWh pr. year in the 5 year period 2005-09, while it was average 10 TWh pr. year in the 5 year period 2010-2014. In the same period the number of hours with prices in the Day-ahead market (Spot prices) under 250 DKK/MWh or 200 DKK/MWh has increased. This has put pressure on the economics of the power plant owners. For example the largest power plant owner in Denmark (DONG Energy) has seen EBITDA from thermal power plants activities been reduced from around 300 EURm pr. year in the period 2008-11 to around 100-150 EURm pr. year in the period from 2012-14[35].

These changes (less power production, lower average power prices and general larger variability in the power prices) has required the power plants owners to use its load ramping capabilities and change operation from maximum to minimum load more and more often in order to have the best possible economic performance as well as increase earnings in the ancillary service market.

Almost all of the large power plants in Denmark are CHP extraction plants with large heat accumulators (heat storage), and some of them have option to partial or full bypass power production[36]. Given the power and ancillary service market form in Denmark is as described in the report '*Power markets and power sector planning in Europe*' the dispatch process and optimization – i.e. sales to the general power market as well as sales to the ancillary service market - are in general terms as described in the following sections[37].

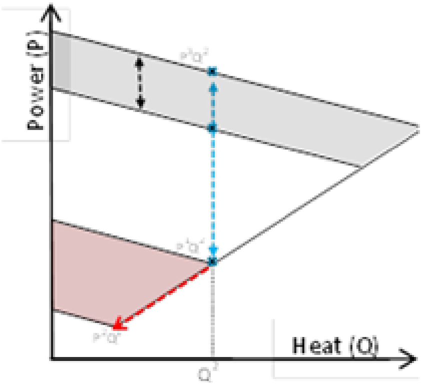
Firstly each CHP plant makes a heat demand forecast for the next 24 hours with a forecast for each hour. In this process the plant naturally takes into consideration its flexibility measures such as the amount of heat left in the heat accumulator (heat storage facilities) etc. Given this and the plant's combined heat/power production extraction limits (minimum/maximum power and heat) it's minimum and maximum power production capacity is thus determined on an hourly basis. Then the plant dispatch in the power and ancillary market in the following chronological steps to maximize value.

---

[35] Large fluctuations in EBITDA from year to year can happen due to the large impact on power prices due to large difference in temperature and hydro production in Norway and Sweden. EBITDA (Earnings Before Interest Taxes Depreciations and Appreciations). However at the same time DONG Energy have invested heavily in and grown a very large business from off shore wind parks which gave an EBITDA of 800 EURm in 2014.

[36] Most of them are today fuelled by coal, but biomass (wood pellets and chips as well as straw) are taken a larger share due to implemented policies support biomass

[37] A description of the Danish and European ancillary service market is described in the report "Power markets and power sector planning in Europe'



A typical extraction plant production envelope with partial bypass (the red squared area) is depicted to the left in Figure 25.

The possible power production is to a large extent constrained by the given heat demand that must be fulfilled by the specific plant (local heat supply). With a heat demand of Q² the possible power production (Y-axes) are given somewhere between P1 and P3.

However, in hours with low power prices the plant minimizes power production to optimize its economics. If the plant has flexibility measures such as partial bypass and heat storage then it is possible to follow the red arrow by moving from P1Q2 to P2Q1 using partial bypass and then meeting the heat demand (Q2) using the heat storage. Using the plant's flexibility in this way thus supports the plant's economics by reducing power production during hours with negative gross margin between power price and marginal power production costs.

Figure 25: Extraction plant production envelope

Step 1: Offers in the Secondary reserve capacity market (only Western Denmark)

Secondary reserve capacity is offered in an auction on a monthly basis to the TSO (Energinet.dk). The offer is typical given the last Wednesday in the month for the following calendar month. The plant receives a payment for the reserved capacity if the offer is accepted by the TSO. The TSO can then make a direct order to down- or up regulate production within the limits of the sold capacity during the whole month. If up-regulation is ordered the plant receives a price equal to the larger of either the day a-head market price in west Denmark (DK1) plus 100 DKK/MWh or the Nordic Regulating power market price for up regulating.

The way the plant derives at the "correct" pricing for offering secondary reserves is looking at the opportunity loss that arises from reduced MW capacity. The opportunity loss from selling reserve capacity is in Figure 25 illustrated with the grey area. The way the opportunity loss is calculated is by comparing how much gross margin the plant is forecasted to make in the day ahead, intraday and regulated power market with all MW capacity (production area including the grey area) compared to how much it is forecasted to make with a reduced MW capacity (production area excluding the grey area). This is done through a model that forecasts the power market prices on an hourly basis. Comparing the two alternatives thus signals how much the plant needs to earn from offering reserves to the TSO.

Step 2: Offers in the tertiary reserve capacity market (manual reserves and regulating power)

Manual reserve capacity can be offered in a daily auction to the Danish TSO (Energinet.dk). The offer compromises a certain MW capacity for some or all or the hours the next 24 hour period. The plant receives a payment for the reserved capacity if the offer is accepted by the TSO – at present the payment is extremely low due to very high competition. Once the reserve is sold it is forced to give offers in the Nordic regulating power market when regulation is called upon. All generation assets can however voluntarily offer regulation in the Nordic regulating power market, but will then not receive payment for securing a fixed manual reserve to the TSO.

Step 3: Offers in the day-ahead market (Spot market), Intraday market (ELBAS market) and in the Nordic regulating power market (NOIS)

After the plant operator knows how much of its production capacity that is reserved to one or more of the above products it can then offer its power production in the Day-ahead market at marginal costs. Marginal cost is by large the sum of all fully variable costs such as fuel incl. transportation, CO2 quota costs, emission taxes (NOx, SOx emission), raw material use such as chalk, ammoniac, water use, ash deposit and removal costs and small contribution to operation and maintenance (O&M). Depending on how much production is sold in the day-ahead market the plant operator will then offer production in the intraday market (also at marginal costs). Finally the plant operator will be able to offer production which is left available to the Nordic regulating power market. If the plant operator has sold reserves in the tertiary reserve capacity market it is forced to offer bids in this market. If not the plant operator can voluntarily offer bids in the market.

The capabilities of Danish power plants to move between max load and a low minimum load enables them to optimize economics (either through reducing power production when there are negative power spread or increasing power production when prices are high) as well as participate and earn in the ancillary market. From the TSO's point of view the primarily coal based power plants in Denmark can often provide cheaper ancillary services than would be the case if those services should be provided by investments in new assets or be provided by more expensive fuels in oil or gas fired plants. Furthermore, faster regulating reserves are general more expensive than the slower reserves why increased ramping rates at the Danish power plants enables the plant owners to offer more and higher priced ancillary services to the TSO.

6.1 Recap – technical possibilities for down-regulating Chinese power plants

The assessed current situation of Chinese power plants in condensing operation is that the minimum load is app. 50-70% TMCR and a ramping rate of app. 1% pr. minute. It was further assessed that without further investments the plants can be operated with a minimum load of >30% TMCR (Benson point) and at a ramping rate of app. 2% pr. minute. In the next section it is illustrated - given a market situation where wind power is curtailed – what the value of down regulating a Chinese coal-based condensing power plant is.

6.2 Value of down regulation power plants compared to wind curtailment

The value of down regulating a Chinese coal-based condensing power plant is in the following section illustrated through a simple case. In general the case looks (randomly chosen) at a 8 hour long period where there is a need for reducing load / power production within a given power system from 10,800 MWh to 9,072 MWh in the 8 hour period. For the sake of simplicity it is assumed that only a wind power producer and a coal-based condensing power producer exist in a closed system (no interconnector to surrounding price zones is available to provide regulation).

The case is illustrated by comparing the value of a "**Reference**" scenario with the value of an alternative "**Business**" scenario. The difference in value between the Reference scenario and the Business scenario is termed "**Delta"** scenario, which represent the case.

The market condition assumptions are:

1. The power price is fixed and similar for both the power plant and wind producer (even though this does not represent current power prices)[38]
2. The power demand/consumption is 9,072 MWh in the 8 hour period
3. No compensation is paid to the wind producer for the curtailed production in the Reference scenario
4. The power plant is contractually "entitled" to produce and sell all power production produced at full load in the Business scenario

In the Reference scenario the need for reduced power output (the difference between the 10,800 MWh and 9,072 MWh) is met by curtailing wind production. The power production is reduced from 600 MWh (pr. hour) to app. 300 MWh (pr. hour) for a period of 5 hours. In the Business scenario the need for reduced power output is however met by assuming that the coal based power plant reduces their load by ramping down to app. 50% of max load with a ramping speed of app. 1%-point pr. minute[39]. As a consequence the coal power producer lose gross margin[40] when comparing to the Reference Scenario. On the other hand the wind power producer is no longer curtailed and sells all production. The Reference and Business Scenario as well as the Delta Scenario are summarized in Table 6 below.

	Reference Scenario	Business Scenario	Delta Scenario (Business - Reference)
Wind power producer	- Curtailed production - No compensation from ordered curtailment Production: 3,672 MWh	- No curtailment i.e. full production - Power revenue earn on full production Production: 5,400 MWh	- Increased revenue/gross margin - Increased prod. (1,728 MWh)
Coal power producer	- Full production (100% load) - Fixed price and all production contractually sold beforehand Production: 5,400 MWh	- Reducing load to app. 50% - Reduced revenue, costs and gross margin Production: 3,672 MWh	- Reduced gross margin - Reduced prod. (1,728 MWh)
Total Production (MWh)	Production: 9,072 MWh	Production: 9,072 MWh	- Constant production (0 MWh)

Table 6: Scenario overview

The case is furthermore based on the power plant assumptions given in Table 7 below. The case is calculated without any taxes or costs associated with emissions (SOx, NOx, CO_2 etc.). Once taxes or costs (negative externalities) are included in the case the coal based production cost will rise and better reflect true cost and consequently the results will show an even larger benefit from reducing the power production from the power plant instead of curtailing wind. It is assumed that variable OPEX and life time of the plant is not affected by change in production (i.e. variable OPEX is similar pr. MWh produced in both scenarios for the power plant producer).

---

[38] The National Development and Reform Commission (NDRC) on-grid tariffs for coal-fired power plants in China indicates a power price of app. 390 RMB per MWh for plants in Hebie Province while feed in tariffs for onshore wind lies around 490-610 RMB per MWh.

[39] The power plant's technical specifications are assumed to reflect the "Current situation" as defined in section 5.4. For simplicity sake it is assumed that the ramping rate at the power plant and the wind park are similar.

[40] Gross margin is defined as revenue less variable production costs

Assumed plant specifications and power price, coal and O&M		
600 MW USC plant	600	MW
Net efficiency at 100% load	43%	
Boiler load 90	0%	point
Boiler load 70	-1%	point
Boiler load 50	-2%	point
Boiler load >30 (benson)	-8%	point
Boiler load <30 (circulation)	-11%	point
Boiler load 15	-16%	point
Present state load ramping	1%	pr. min
Step 1 - Target values for load ramping	2%	pr. min
Present state min. load possible	50%	TMCR
Step 1 - Target values for min. load	30%	TMCR
Average power price Hebie province	388	Yuan / MWh
Coal price (Qinghuangdao)	20.64	Yuan / GJ
Variabel O&M costs	25.50	Yuan / MWh

Table 7: Power plant assumptions

During a meeting with EPPEI in April 2015 a somewhat similar picture of the variable cost structure as given in Table 7 was presented. The costs structure presented by EPPEI showed that coal costs usual represent approximately 55%-65% of the power price, while other variable costs represent approximately 5-10%. The cost estimate used in this case (see Table 7) shows that coal and other variable costs represent approximately 45% and 5% of the power price in the Hebie province.

Case results

The overall result of the case is intuitively straight forward. It is much more valuable to reduce power production from the power plant than the wind park as the power production costs at the power plant is much higher that power production cost of the wind park, which can be assumed to be zero.

The monetary results from the case (Delta Scenario) are shown below in Table 8. Given the specific assumptions – particular regarding the power price and the coal and O&M costs, the total gain (sum of producers) from changing from curtailing wind to reducing power production from a coal based condensing power plant is app. 0.36 million RMB for the 8 hour period.

Delta Scenario	MWh	Revenue Mill. Yuan	Variable cost Mill. Yuan	Gross margin Mill. Yuan
Wind power producer	1728	0.67	0.00	0.67
Coal power producer	-1728	-0.67	0.36	-0.31
Sum of producers	0.00	0.00	0.36	**0.36**

Table 8: Result of Delta scenario

As already noted earlier the specific results above are based on the following market condition:

- No compensation is given to the wind producer for curtailing it's wind production in the Reference scenario
- The coal power producer lose otherwise secured profitable production when down regulating in the Business scenario

Given the market condition assumptions above (and plant assumptions as well) the price that would motivate the coal power producer to provide down-regulating should be larger than 0.31 million RMB (equalling the coal producer's gross margin loss from the foregone production).

The variable cost per MWh for the coal producer is in this simple example cost of coal and variable O&M costs which is 198 RMB pr. MWh.[41] Assuming the wind producer has zero variable cost the gain from changing the reduced production from wind to coal is thus 198 RMB per MWh. Multiplying this with the reduced production in the period of 1,728 MWh result in app. 0.34 million RMB. This simple calculation does not take into consideration the reduced efficiency arising from reduced load. The reduced efficiency at lower load produces the difference of app. 5% between the result of 0.36 million RMB as displayed in the table and 0.34 million RMB (when using an efficiency of 43% for all production). The exact loss deriving from reduce efficiency at lower loads naturally depends on how much production / time the plant needs to operate at reduced load.

Further conclusions

The total gain (sum of producers) from changing the down regulation from the wind producer to the power plant changes linear with the variable cost of producing power from the power plant as well as the quantity of power reduction needed. Rising variable coal based power production costs – either through emission taxes or direct costs - thus increases the total gain. Hence there is a large value in ensuring properly priced economic incentive for down regulating power production from power plants so wind curtailment is avoided and any needed downregulation is fulfil by fossil fuelled power plant production. In a market situation as described above – i.e. where power plant producers are guaranteed a fixed off-take of production and fixed power price - a minimum payment equalling the opportunity loss is needed in order to motivate the power plant to reduce load. A positive payment to the power plant producers for reducing load is based on the current situation where the producers are guaranteed a fixed production and price (i.e. guaranteed a gross margin). However if such a guaranteed production/price regime is abolished in the future a different economic incentive in form of economic penalties for producing fossil fuelled based power in periods of sufficient RE power production could be envisioned instead.

With a wind curtailment of approximately 13 TWh in 2014 and if China achieves the current goal for 2020 the amount of curtailed wind energy is estimated at around 25 TWh in 2020. If all the assumptions used above in the case are applied and coal based power production from condensing plants technically could provide the down regulating instead of curtailing wind the following key economic conclusions can be made for 2014 from the producers' point of view:

---

[41] (20.6/0.43)*3.6+25. This simple calculation does not take into consideration the reduced efficiency arising from reduced load.

The power plants will:

- Loose the production of 13 TWh at approximately 450 RMB per MWh[42]. In total 5,850 million RMB
- Saved production costs of roughly 200 RMB per MWh. A saving of approximately 2,600 million RMB
- Have a reduced gross margin of app. 3,250 million RMB

The wind producers will:

- Get an increased gross margin of 5,850 million RMB assuming same power price of 450 RMB per MWh.[43]
- Getting an increased gross margin of 7,150 million RMB assuming an average on shore feed-in tariff price of 550 RMB per MWh.

The net increase in gross margin (sum of power and wind producer) naturally equals the saved variable cost of 2,600 RMBm plus any difference in power prices between the wind and power plant producers. The 2,600 RMBm is in a sense the social welfare gain (not taking cost of emission and pollution into consideration) obtained from avoiding wind curtailment as it assumes the value/price of the power production is similar for wind and power producers. The payment to motivate the power plant producers to provide the down regulating should - everything else kept constant - be at least 3,250 RMBm (the gross margin loss from forgo producing by down regulating power plant production). The wind producer will - everything else kept constant – gain a gross margin of 5,850 RMBm. The chosen structure of the economic incentive to provide down regulation and redistribution between the wind and power plant producers through pricing of their production is however ultimately a matter of the desired policy.

To sum up, a presentation of the above general conclusions are given below in Table 9. The higher the coal-based variable power production costs are and thus the smaller the gross margin loss from foregone production is - the larger the total welfare gain from having the power plant producers providing down regulation is (**when** the alternative is curtailment of wind or other RE production with zero variable costs) and the smaller the incentive payments needed to provide sufficient economic incentive for the power plant owners to provide down regulating is.

Coal based power Variable production costs	Coal variable costs pr. MWh / Total welfare gain	Power price pr. MWh	Coal - gross margin lost RMB pr. MWh / Needed economic incentive size for providing down regulating	Wind producer gross margin gain RMB pr. MWh
Low	200	450	250	450
Medium	300	450	150	450
High	400	450	50	450

Table 9: Displays correlation between coal-based variable production costs and respectively total welfare gain and needed incentive for the power plant owners to provide down regulation.

Consequently introducing costs on the generators from emission such as NOx, SOx and CO2 emission will - besides ensuring production costs reflect true social costs – increase coal based variable production costs thus moving downward in the table. Power plants with higher emissions (assuming there is a cost associated with the emissions) will as a consequence be more willing to forego production and provide down regulation. Likewise, differences in efficiency (and thus

---

[42] It is roughly estimated that the average power price in 2015 is around 400-500 RMB pr. MWh thus 450 is used as a rough average.

[43] Given on shore feed-in tariffs are between 490 and 610 RMB per MWh depending on wind resource site the gross margin increase would in reality be correspondently higher.

variable production costs) among different power plants will also have an impact on which power plants that will be willing to provide flexibility (for example down regulation) at lowest price. A low efficiency and high emission emitting plant will everything else constant have larger variable costs leaving them with a larger incentive for providing down regulation than more efficient plants. This is however, only the case under the given market condition assumptions all-ready mentioned that

(i) no compensation is given to the wind producer when order to curtail its wind production and (ii) the coal power producer loose otherwise secured profitable production when down regulating (i.e. it has an opportunity loss when providing down regulation).

A supplement to the above is that in general the faster the down regulation speed needs to be the more expensive it is as the technologies and fuel types (typical oil and gas) that can supply faster regulating is more expensive than coal fired power plants. Hence improving the ramping speed of the Chinese power plants from the current 1% pr. minute to 2% pr. minute should increase the earnings of the most flexible power plants.

6.3 Conclusions and lesson learn for China

In section 5 an assessment of the Chinese coal based power plants in general and their potential for providing flexibility was given. Given the high degree of similarities between Danish and Chinese coal based power plants and the fact that in general the Chinese power plant portfolio is newer than the Danish it was assessed that Chinese power plant fleet can provide as much flexibility to the power system as has been the case in Denmark. It was further assessed that using the existing power plant fleet in a more flexible manner is one of the cheapest ways to provide power system flexibility at low to medium wind production penetration levels as there will very limited costs associated with it. It was for example deemed possible to reduce minimum load to as low as 30% of TMCR and increase ramping speed without any direct investment in new equipment. It was suggested (in a first phase) to conduct pilot tests on a few, but different types of plants in order to gather data and experience on operating the plants more flexible – i.e. go down to around 30% minimum load and ramp up and down faster etc.

To sum up; the overall assessment from a technical perspective is that it is deemed possible to increase flexibility in the existing power plant fleet at very low costs and this is probably the cheapest way of providing more power system flexibility (at low to medium RE production penetration).

In section 6 it is presented how the Danish power plants dispatche their production both to the general power market and to the ancillary service market. Secondary reserves are for example sold on a monthly basis to the TSO so they can use the reserve for ensuring sufficient flexibility. Other flexibility is offered by the power plants in the tertiary reserve capacity market through offering regulating power auction on an hourly basis. Both offering of reserves on a monthly basis as well as bidding in the power regulating market is fundamentally based on economic optimization – i.e. providing the product and services that gives the best return and profits. From a Chinese perspective a simple case illustrating the value of having the power plants down regulating their production instead of curtailing wind power production (or other RE production with zero marginal costs) was given. In general it was concluded from the very simplistic example and crude data that the overall total welfare gain was the saved variable coal based production costs, while the economic incentive (i.e. payment) needed to create sufficient economic incentive for the power plant producers to down-regulation was given by the lost gross margin from the foregone production[44].

To sum up; from an economic perspective there are clearly and unambiguously a total welfare gain to be obtained by ensuring sufficient incentive for the coal based power plant producers to down regulate their production in situations where RE production is curtailed as result of oversupply of power in the system.

In conclusion; from both a technical and economical perspective there are very solid reasons for developing a political and regulatory framework, which supports both the technological development of flexibility on the power plants (perhaps through use of pilot cases to begin with) as well as create the right economic incentives for the power plant producers to provide the needed flexibility. One of the central prerequisite for ensuring that the cheapest (least-cost) flexibility products are offered from the power plants is to ensure that sufficient cost and price information is provided and shared in the market in order to send clear and unambiguous signals to the providers to steer their operation after. In other words relevant price signals (i.e. payment for providing down regulating) must be available in the market to ensure the most cost efficient production and operation.

---

[44] This conclusion however rest on strong assumptions about the current market conditions in China (as described in bullets under Table 8)