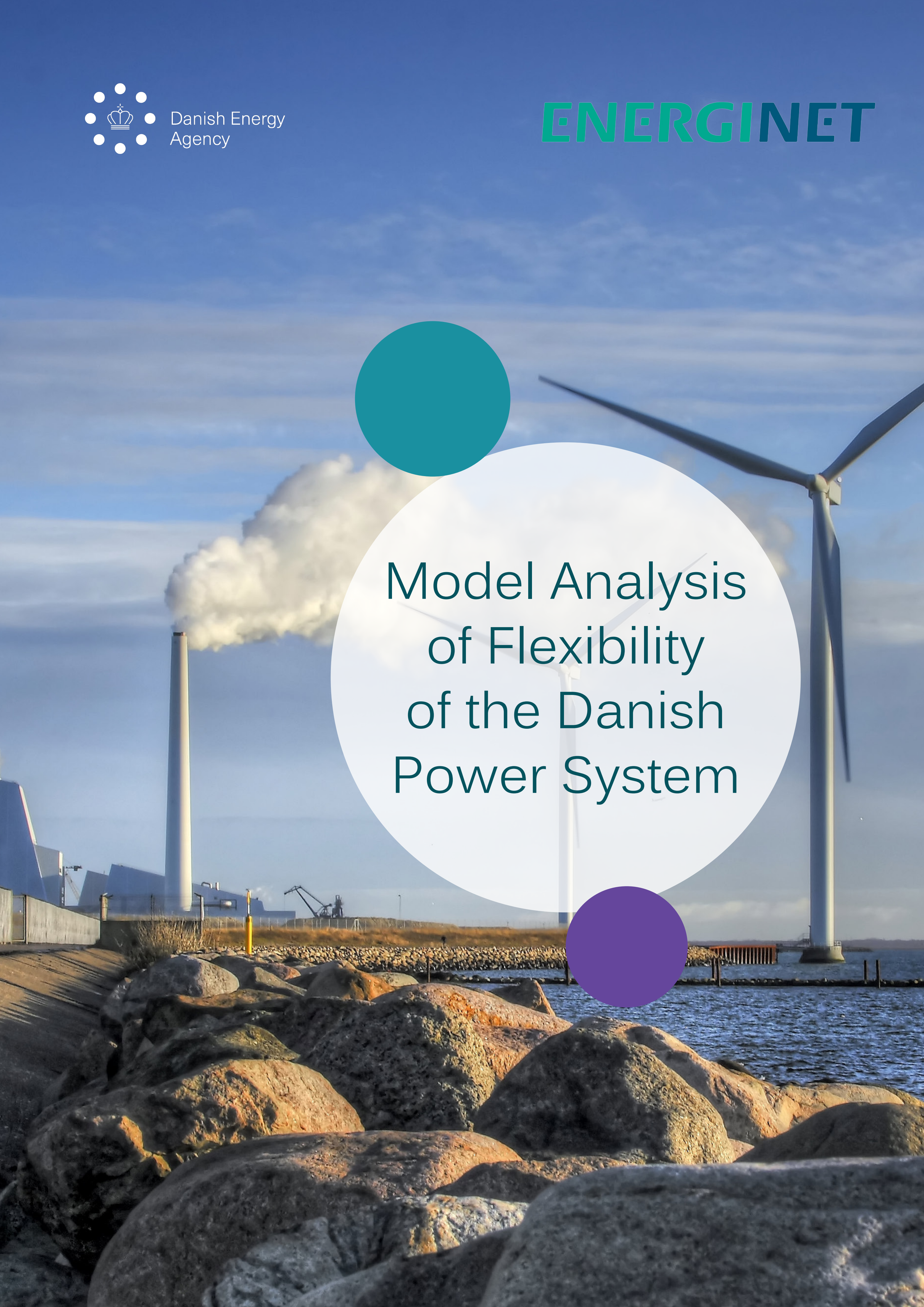
Danish Energy Agency

ENERGINET



Model Analysis of Flexibility of the Danish Power System

Contents

This report has been conducted by the Danish TSO, Energinet, for the Danish Energy Agency and is a contribution to the Clean Energy Ministerial Advanced Power Plant Flexibility Campaign, May 2018.

Executive summary

To support the development towards more flexible power systems through cost-efficient and CO_2 emission reducing measures, a deep and detailed understanding is needed on the value and effect of different sources of flexibility, including transmission grid and thermal power plant flexibility. The present report aims at deepening this understanding.

Based on model analyses, this report analyses the impact and value of flexibility measures in the Danish power system. The measures explicitly investigated are flexible power plants and flexible use of interconnectors to neighbouring power systems. The analyses have been conducted by the Danish TSO, Energinet for the Danish Energy Agency. The model analyses were carried out by Energinet's in-house model named SIFRE.

The choice of using Denmark for illustration of flexibility needs and flexibility sources is quite obvious, as Denmark has the world highest share of variable renewables (VRE, wind and solar) in the power system. In 2017, wind contributed close to 44% of the total Danish electricity consumption while solar photovoltaic panels (PV) contributed with about 2%. Furthermore, wind generation exceeds demand in 5% of hours over the year.

About 5 GW of wind power capacity and 900 MW of solar power capacity are presently installed in Denmark, with a demand peak load at about 6.5 GW and a total yearly electricity consumption of approximately 33.5 TWh. Wind power capacity is divided in close to 4 GW onshore and 1 GW offshore installations. The fossil based thermal generation capacity is declining and amounts today to about 4 GW of large central power stations and 2.3 GW of small scale (local) units. In practice, all thermal plants are combined heat and power plants (CHP). The heat is delivered to district heating systems, which distribute the heat to consumers.

Denmark is one of the countries in Europe with the strongest power system interconnections. The total capacity of interconnectors to Norway, Sweden and Germany amounts to about 6,000 MW, which is close to 50% of the total installed generation capacity.

The model analyses carried out consider four Danish scenarios. The purpose has been to evaluate the consequences of reducing the flexibility of the power system compared to the present system in 2018, which constitutes the base case.

The base case scenario (**scenario 1**) represents the present Danish power system, and is char-acterised by having very flexible thermal power plants and a high degree of flexibility in balanc-ing via strong (6,000 MW) interconnections to neighbouring countries.

Compared to the base case, **scenario 2** has been constructed with highly reduced flexibility of the large thermal CHP plants. In scenario 2, the ramping rates of the large power plants have been reduced (from about 5% of nominal capacity per minute to 1%) and the minimum loads for stable operation have been significantly increased (from 10-30% of the nominal capacity in the base case to 60%). With the aim of further reducing the flexible capabilities of CHP plants, electric boilers, heat pumps and not least heat storage tanks have been removed from district heating systems connected to the large power plants.

Scenario 3 has focus on reducing the system's flexibility by significantly reducing the capacity of interconnectors to the neighbour countries Norway, Sweden and Germany. A flat rate reduc-tion of 80% on all capacities has been assumed, thereby reducing the total exchange capacity abroad to about 10% of the total Danish generation capacity, which is the European Commission's overall minimum target for 2020 for EU countries.

Finally, **scenario 4** is a minimum flexibility scenario, constructed by adding the flexibility reductions of scenario 2 and 3 thereby reducing flexibility both with respect to operation of the large power plants and with respect to balancing the system via import/export.

For the specific Danish power system, large impacts are observed both when large thermal plants' flexibility is reduced and when interconnection capacities are reduced.

The most important consequences of r**educed power plant flexibility** compared to the base case are:

- An increased production at the large thermal power plants leading to an increase in CO2 emissions of 15% from the plants, which result in overall CO2 emissions increase of about 11%.
- A reduction in the power plants' achieved wholesale prices of approximately 5%. This represents a reduction in economic surplus corresponding to approximately 1.1 million euro for a 400 MW plant.

The result shows that the highly flexible thermal power plants in Denmark enable them to reduce power output and thus contribute to lower overall system CO2 emissions. Further, the economic results support the rationale for the Danish power plants to have invested in and become increasingly flexible over time allowing them to better adjust their power output depending on the power prices.

The most important effects of reduced interconnector capacities compared to base case are:

- Curtailment of wind and PV will rise from practicable zero in base case to about 9%. The large power plants will produce about 10% more, which is the main contribution to overall system CO2 emissions increase 7%
- The prices in wholesale market will decline substantially for all stakeholders being studied. Most pronounced is a 30% reduction in the achieved power prices for wind production. The price reduction plus the curtailment leads to an overall reduction in economic surplus for wind at about 20%. The impact of the reduced power prices and curtailment on the economic surplus is softened by subsidies to VRE.
- The overall socio economic result for Denmark (producers, consumers and congestion rents) amount to a loss of 170 million euro per year, which as comparison is approximately 50% of the total revenue generated by all the wind assets in the base case.

It can be concluded, that Danish interconnector capacity is pivotal to integration of wind. Without sufficient exchange capacity the system would witness a clear increase in VRE curtail-ment and CO2 emission. At the same time the system value and market price obtained by wind will deteriorate significantly, which would have resulted in much lower return on investment in wind assets and/or required subsidies to be much higher. This would expectantly have had a large adverse effect on the buildout of wind power.

The *combined effects of interconnector capacity reductions and power plant flexibility reductions* are in general additional however some results are more than additional. Specifically, under low interconnector capacity then reduced power plants flexibility will lead to increase in VRE curtailment from 9% to 12% as well as lead to a larger decline in economic surplus for the power plants. Given a situation with low interconnector capacity then reduced plant flexibility will lead to a decline in economic surplus of 2.6 million euro for a 400 MW plant instead of just 1.1 million euro decline under normal interconnector capacity.

The model results provide an illustration of the importance of flexibility, both in power plants and from interconnection to neighbouring market areas, in the deployment of high shares of VRE in Denmark. The model illustrates well that without the developments in power plant flexibility and transmission capacity with neighbouring countries it would be extremely challenging to integrate VRE to the level Denmark has today. The expansion of interconnection capacity is shown not only to favourably affect the possible integration of VRE, but provides in the model a clear advantage from a society welfare perspective considering CO2 emissions and economic surplus. Furthermore, the current level of transmission capacity in Denmark ensures very limited levels of curtailment of VRE supporting a continued buildout of VRE.

The enhancement of flexibility capabilities and flexible operation among thermal power plants is not driven by a strict command and control regulatory frame, but by a well designed market structure that provide the necessary economic incentives. The power market allows for prices to correctly signal the need for flexibility and therefore rewards power plants that can take advantage of increased flexibility. In this way, the market structure can be seen as a tool that helps align the incentives of the producers with the requirements of the system.

While the possibilities for the design of markets and incentives for increasing flexibility in power plants and for increasing transmission capacity are broad, the present study shows that in the Danish context, both sources of system flexibility have granted positive effects. Improving the capacity of the system to integrate VRE not only requires the existence of adequate technology, but also an appropriate market with powerful price signals that reflect the need and true value of flexibility.

1. Introduction

1.1. BACKGROUND

Variable renewable energy (VRE) continues to make up an increasing share of the power pro-duction across the world. This development requires power systems to adapt particular to become increasingly more flexible to cope with the intermittent nature of VRE. In case of Denmark extensive and flexible utilization of interconnectors to neighbouring power systems and very flexible dispatchable thermal power plants are main sources of flexibility. A well suited and appropriate market design is pivotal to provide the necessary economic incentives for reaching an efficient economic dispatch of generation and demand.

In many power systems, regulations, market design, and contractual arrangements may not encourage a flexible operation of thermal power plants nor a flexible or cost-efficient utilization of interconnectors. As a result, there is often a large amount of flexibility on supply side and from transmission that is potentially available from a technical standpoint, but not exploited in reality due to lack of price signals and economic incentives.

To support the development towards more flexible power systems and integrating increasing shares of VRE a comprehensive understanding of the value and effect of different sources of flexibility including interconnectors and thermal power plant flexibility is valuable. The report serves this purpose.

Based on a detailed power system model the report analyses the value of flexibility measures in the Danish power system. The measures explicitly investigated are the flexibility of power plants and the extent of flexible interconnectors to neighbouring countries. The model results give insights on the generation pattern, CO2 emissions, curtailment and the economic implication for the asset owners as well as overall society from these two main sources of flexibility.

The analyses have been conducted by the Danish TSO Energinet for the Danish Energy Agency (DEA). The model analyses were carried out by Energinet's in-house model (SIFRE), which is described in more detail in chapter 2.

1.2. THE DANISH POWER SYSTEM IN BRIEF

1.2.1. Physical system

Denmark has the world highest share of variable renewable energy (not including hydro) in the power system. In 2017 wind contributed with about 44% of the total Danish electricity con-sumption while PV (photovoltaics) or solar production contributed with about 2%. The chal-lenge and need for a highly flexible power system become even clearer given wind generation already today exceeds the total national power demand in 5% of hours over the year.

Looking forward, the Danish national targets aim at wind power production to correspond to 50% of total electricity consumption by 2020 while the political target is to have an energy system independent of fossil fuel by 2050. This will require an even more flexible power system with likely demand response, batteries as well as closer integration with other energy sectors as the transportation sector and natural gas sector – besides the continued increase of interconnector capacity to neighbouring power systems (bidding zones).

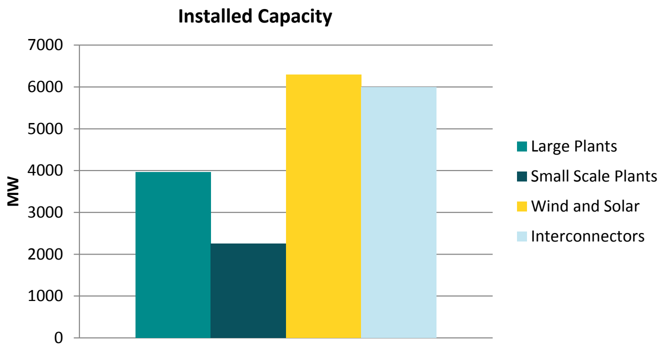
The development of the capacity of Danish thermal power plants and interconnectors have changed much in the last decade as the share of VRE has risen substantially. As the installed capacity of VRE has doubled in the last decade then the installed interconnector capacity has grown with almost 50% while the thermal capacity has declined approximately 30%.

Today the Danish power generation assets are made up by about 5 GW wind power (4 GW onshore and 1 GW offshore) capacity, 900 MW of solar power capacity and a thermal power plant capacity of about 4 GW of large power stations with installed capacity of several hundred MW (often termed "Central" units) and 2.3 GW of mainly 1-50 MW small units (often termed "local" or "decentral" units). In practice, all thermal power plants (both large and small) in Denmark are combined heat and power plants (CHP). The heat is delivered to district heating systems, which distribute the heat to end-consumers.

The Danish consumption peak load is about 6.5 GW, minimum load is about 2.5 GW and the total yearly electricity consumption is about 33.5 TWh.

Denmark is today very well connected to neighbouring countries with a total capacity of about 6,000 MW interconnections to Norway, Sweden and Germany (see figure 1.1 to the right). Presently Denmark is building additional connections to Netherlands (700 MW to be commissioned in 2019) and Germany (400 MW + 1000 MW to be commissioned in 2018 and 2020 respectively). Besides, a new connection to Germany (1,000 MW) and a 1,400 MW new connection to England are being planned, but no final investment decisions have been made.

Looking ahead the development that has taken place in the last decade or so is expected to continue rendering the power system more and more reliant on VRE production and increased interconnection capacity to enhance the system's balancing ability - and less and less dependent on thermal power plants to be the core of the power system. The expected future development is depicted in figure 1.2 below.



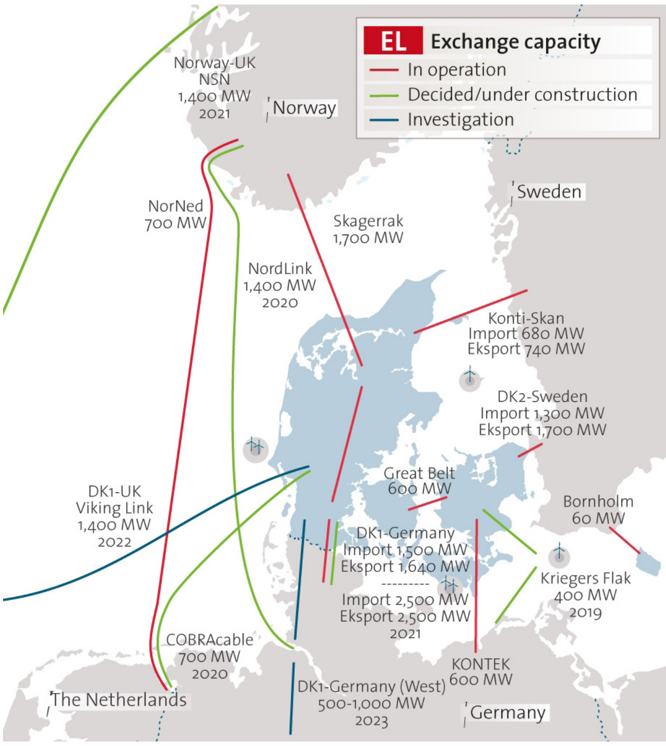


Figure 1:1 Overview of the present Danish power system (2018). Installed generation capacities, and capacity of interconnectors to neighbouring countries (Germany towards south, Norway towards North and Sweden towards East). (Source: Energinet).

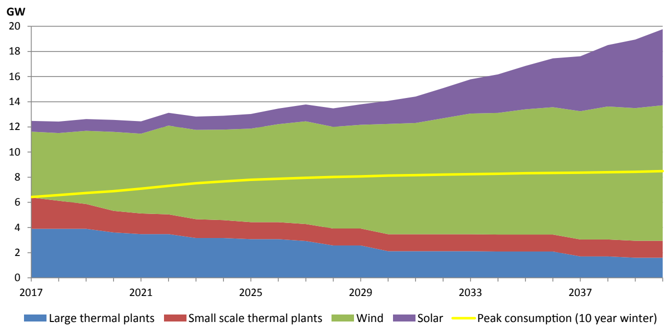


Figure 1.2: Expected future trend in Danish installed generation capacity and peak hourly consumption (Source: Energinet).

1.2.2. Markets

While interconnectors and transmission grids constitute the "hardware" of power systems allowing electricity to flow across national borders then power markets is the "software" that secures an economic efficient allocation of resources based on supply and demand.

The market Denmark is part of is not just one market, but a series of markets encompassing a financial market (price hedging), day-ahead market, intraday market and balancing market (see figure 1.3).

Today the day-ahead market is a pan-European coupled market where all supply and demand bids from north to south of Europe go into the same optimization algorithm. Based on this input a simultaneous and jointly scheduling of generation, demand and interconnector exchange between the different bidding zones is done. This takes place for each hour, each day of the year.

Some of the main results of this market design are:

- A least-cost dispatch prioritizing the marginally cheapest production units (i.e. VRE production) to serve the given demand in each hour.
- A clear price signal for each hour (all generators receive the same market clearing price) signalling the value of producing and thus implicit the value of being able to op-erate in a flexible manner.
- Ensures that power flows from low price areas to high price areas (due to the simul-taneously and jointly scheduling of generation and interconnectors i.e. implicit auc-tioning)

The implication of the above is that the thermal power producers have clear economic incen-tives to avoid producing in hours with low power prices and deliver maximum outputs during hours with high prices. In other words, to produce when the system values production and to reduce/avoid production when not.

Given the zero marginal cost nature of VRE production, day-ahead market prices tend to be lowest when wind production is at maximum and vice versa. This implies that during windy periods the given area (bidding zone) will generally be net exporter and net importer in low wind periods.

The intraday and balancing markets in Europe are today regional or national markets. However in 2018 the intraday markets will be coupled across Europe in a similar way as the day-ahead market is coupled today. The Nordic countries have already common intraday and balancing markets. The balancing market is operated by the system operators, who take over the re-sponsibility for the system one hour before real time.

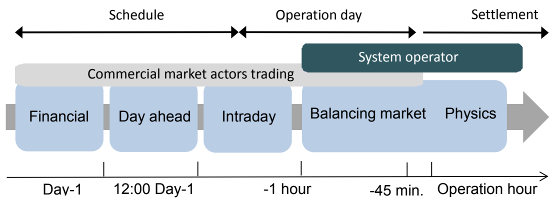


Figure 1.3: Illustration of the Nordic electricity markets (Source: Energinet).

1.2.3. Flexibility of the Danish power system

The dispatch of the Danish system during a week with varying wind power generation in Sep-tember 2015 is shown in figure 1.4. As a weekly average, wind and PV covered 49% and 2%, respectively of the Danish demand.

The figure illustrates over a week the high degree of flexibility[1] in both generation and exchange with neighbouring bidding zones (located in Norway, Sweden and Germany). The residual demand is defined as demand less the variable renewable generation (wind and PV). Thus the residual demand is the demand to be covered by the dispatchable sources: power plants and import.

It follows from figure 1.4 that the variation during the day of the residual demand by far exceeds the variation in (total) demand. Also the hourly ramp rates (positive and negative) can often be higher for the

1. Flexibility in in power systems can be defined as the ability to handle variability and uncertainty in generation and demand while maintaining satisfactory reliability..

residual demand. Thus the high amount of variable renewable generation adds to the system's need for flexibility provided by dispatchable generators (large and small local power plants) and by exchange (mainly import in this given example) with neighbouring systems (bidding zones).

The 2nd September (Wednesday) was very windy with wind production in some hours covering the whole Danish consumption. This day was remarkable in the sense that the Danish power system for the first time was operated without large power plants.

Also the weekend was very windy with a net export from Denmark. In contrast there was almost no wind production on Monday, where the load was covered by import and generation of large plants and to some extent small local plants.

Figure 1.4 also shows the hourly spot price in the day-ahead market. As expected the price fluctuates over the week with high prices during periods with low wind production and low prices during periods with high wind production and even negative prices for some hours dur-ing Sunday with very high wind generation. There is also a very clear correlation between the power prices and the level of production from the thermal power plants illustrating the ability of the thermal power plants to adjust production accordingly to the market price.

Since 2nd September 2015 there have been several occasions with operation of the Danish power system without large power plants. The longest coherent time period without operation of the large power plants in the western of the two Danish bidding zones was a week in June 2017.

1.3. LIMITATIONS OF PRESENT STUDY

The analyses carried out in this study are limited to simulating the day-ahead market dispatch in the coupled European setup where Denmark has connections to neighbouring bidding zones in Norway, Sweden and Germany. The results in the model therefore reflect the outcome of the hourly clearing of the day-ahead market through the modelling of a joint and simultaneous scheduling of generation, demand and power exchange on interconnectors between bidding zones without considering the succeeding intraday and balancing markets.

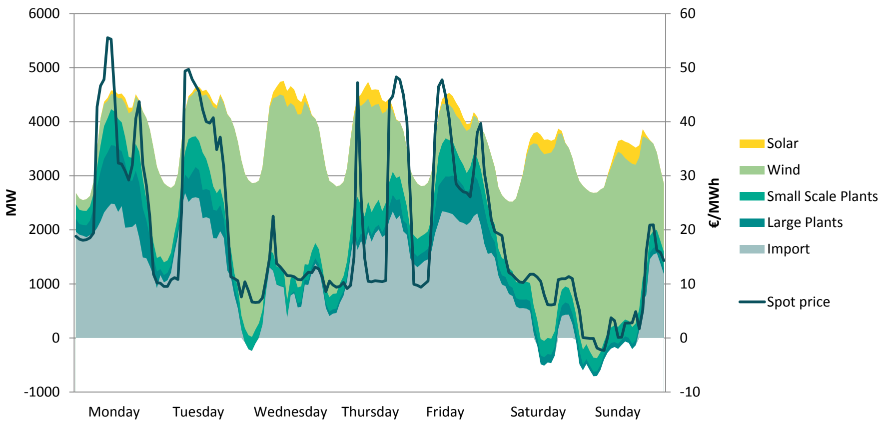


Figure 1.4 Week in September 2015 with high flexibility from both thermal power producers as well through utilizing the interconnectors for import/export (Source: Energinet).

2. Model

The simulation model applied for this study is SIFRE (Simulation of Flexible and Renewable Energy systems). The model has been developed in 2013-2014 and is owned and maintained by Energinet. The model is used for Energinet's analyses of the present and future Danish power system. A specific application is model analyses in connection with development of business cases for new transmission investments.

SIFRE is a simulation tool for spot market (day-ahead market) analyses of power and heat combined systems. The model takes point of departure in the Danish power- and heat system and conducts simulations with an hourly time resolution.

SIFRE is based on the Unit Commitment problem and includes great detail on fuel consumption, on multiple energy types and on connected energy systems. The main purpose of SIFRE is to simulate highly flexible and integrated energy systems in great detail and with a reasonable simulation time, such that the future behaviour of energy systems can be analysed.

SIFRE uses a MILP (Mixed Integer Linear Programming) formulation for the Unit Commitment (UC) problem.

SIFRE supports the analysis of wind power, PV and Combined Heat and Power generation in great detail. The tool is, however, not hardcoded to any specific energy system and can thus be applied however liked.

Input to the model are data describing production units, fuels, consumptions, interconnector lines etc. Output is comprised by production of generators, hourly power prices (day-ahead prices), flexible demands, import, export etc.

Of special interest is that SIFRE can take into account minimum production levels and ramping rates of generators.

The model represents state of the art. SIFRE complements existing models on the market by facilitating multiple energy systems with focus on functionality in thermal power and heat systems, demand side flexibility, unit commitment decisions and future technology through its very generic nature, and ability to handle negative market prices.

Back tests on historical data indicate that SIFRE is capable of producing high quality results within reasonable time (the model setup of SIFRE is illustrated in Annex A). The short-term heat storage introduces a flexibility to the energy system, which is crucial to optimise the total system, both economically and environmentally.

3. Scenarios

The model analyses are carried out for four Danish scenarios. The purpose has been to evaluate the consequences of reducing the flexibility of the power system compared to the present system in 2018, which constitutes the base case.

3.1. RATIONALE AND OVERVIEW OF SCENARIOS

The base case scenario (**scenario 1**) being the present Danish power system is characterised by having very flexible thermal power plants and a high degree of flexibility in balancing the system via large interconnector capacity to neighbouring countries (bidding zones).

Compared to the base case, **scenario 2** has been constructed with highly reduced flexibility of the large thermal power plants, which are all CHP extraction plants.[2] In scenario 2 the ramping rates of the large power plants have been reduced and the minimum loads for stable operation have been significantly increased. With the aim of further reducing the flexible operation of CHP plants then both electric boilers, heat pumps and heat storage tanks have been removed from district heating systems connected to the large power plants.

Scenario 3 has focus on reducing the system's flexibility by significantly reducing the capacity of interconnectors to the neighbour countries Norway, Sweden and Germany. A flat rate reduc-tion on all capacities has been assumed thereby reducing the total exchange capacity abroad from around 50% to about 10% of the total Danish generation capacity. 10% is the European Commission's overall minimum target for 2020 for EU countries.

Finally **scenario 4** is a least flexibility scenario constructed by adding the flexibility reductions of scenario 2 and 3 thereby reducing flexibility both with respect to operation of the large power plants and with respect to balancing the system via the interconnectors by import/export.

In the following the scenarios are described in more detail.

3.2. SCENARIO 1 - BASE CASE

This is a reference scenario describing the present situation in 2018 with regard to generation fleet, demand, interconnector capacities etc.

Generation fleet

The large (also termed 'central') power plants typical have an electric capacity between 200 and 400 MW and are extraction type of CHP plants. Most of the plants are fuelled by coal (50%) alternatively biomass (35%) or gas (15%). Given Denmark's limited size and the dominance of wind power the large plants comprise only about 10 plants representing around 4,000 MW capacity (inclusive reserve capacity).

The other group of thermal power plants are backpressure CHP plants, usually small scale local plants. There are about 500 small scale local plants; most are small with a capacity below 5 MW. About 100 plants have capacities above 5 MW while 50 plants have capacities above 10 MW. The total installed capacity adds to around 2,300 MW. The plants use natural gas, biomass and waste as fuel.

This study focuses on modelling the flexibility of the large thermal plants, which are all individ-ually modelled. The smaller units are modelled after aggregation in lumps. The flexibility parameters of the smaller plants have been kept constant across the scenarios.

The fact that all thermal power plants in Denmark are CHP plants has several implications. Firstly, due to combined power and heat output the overall fuel efficiency is much higher than in case of separate power and heat production. Secondly, the requirement to serve a specific local heat demand forces the plants

2. While CHP backpressure plants have a fixed ratio between power and heat output then CHP extraction plants allows for some flexibility (the degree depends on the given plant configuration) between power and heat output.

to deliver a certain amount of power simultaneously i.e. a forced power production. To allow for a more independent or flexible power output all CHP plants have over time invested in heat storage tanks. Recently some plants have also invested in electric boilers. These two measures constitute important flexibility capabilities among Danish CHP plants allowing for a more flexible combined heat and power output.

An overview of the generation fleet is shown in table 3.1.

Scenario 1 (Base Case)	**MW**	**GWh**
Large (central) power plants	3,959	11,500
Small scale (decentral) power plants	2,255	6,861
Wind power	5,384	14,985
Photo voltaic (PV)	914	961
Total	12,512	34,307

Table 3.1. Generation fleet data (2018). The large (central) power plants in the table are inclusive reserve plants, which do not take part in the daily operation. (Source: Energinet).

Demand

The total Danish traditional electricity consumption is about 33.5 TWh (2018). In addition there is power consumption for heat pumps, electric boilers and electric vehicles etc. which together amount to about 1.8 TWh.

Interconnectors

The total interconnector capacity to foreign countries (Norway, Sweden and Germany) com-prises about 6,000 MW.

Exchange with neighbouring counties

The exchange on interconnectors is determined based on generation costs of Danish power plants and VRE, the interconnector capacities and the presumed day-ahead market prices in neighbouring countries (Germany, Sweden and Norway). The presumed day-ahead market prices for neighbouring countries are taken from forward market prices for 2018 (published on the market platform SYSPOWER 3.0, SKM market predictor as of 17 March 2017). These forward market prices form the basis for Energinet's presumptions of analyses for the future.

3.3. SCENARIO 2 – REDUCTION OF POWER PLANT FLEXIBILITY

Scenario 2 has been constructed with highly reduced flexibility of the large thermal power plants. For this purpose the flexibility parameters: "ramping rates" and "minimum stable loads" have been changed:

- The ramping rates of the flexible "Large power plants" (see table 3.1), which are typi-cally 4-5% per minute of installed capacity have been reduced to a typical international low value of 1% per minute.

- The minimum operating loads of the large power plants (currently varying between 10% and 30% of nominal capacity in base case) have been increased to 60%, which is a rather high value that is typical for base load units not supposed to regulate much up or down.

With the aim of further reducing the flexible operation of combined heat and power (CHP), electric boilers, heat pumps and heat storage tanks have been removed from district heating systems connected to the large thermal plants (but maintained at the small scale plants).

Some of the expected main implications of these changes are that the thermal power plants besides having much higher output when operating at minimum load will be less able to adjust power output to the changing power prices during winter season due to the lack of heat storage tanks. The higher minimum load will incentivize the power plants to shut down more frequently (given sufficiently long low-price periods); however the lack of heat storage tanks will practically disable this option during heating season.

All other assumptions are kept as in scenario 1 (Base case).

3.4. SCENARIO 3 - REDUCTION OF INTERCONNECTOR CAPACITY

In this scenario focus is on reducing the system's flexibility by reducing the capacity of interconnectors.

In base case the capacity of interconnectors corresponds to about 50% of total generation capacity. This number is very high compared to the general European level. In comparison large countries like UK, Italy, Germany and France all have interconnection numbers around or below 10%. The European Commission's target for 2020 is that all EU-countries should have at least 10% interconnection capacity.

Following this a 10% interconnection capacity value for Denmark has been assumed in scenario 3. This represents a strong reduction in exchange capability with neighbouring countries thereby limiting the flexibility of the Danish power system very severely. The reduction from 50% to 10% is done as an 80% flat rate percentage reduction on all interconnectors.

The expected key consequences are in periods of net export (often due to high wind production) that the Danish power system will experience lower power prices and possibly limited alternative sources of flexibility leading to curtailment of VRE. Similarly, periods of low or absent VRE generation in Denmark will presumably result in higher prices due to reduced import capability and activation of higher marginal priced generation to fulfil demand.

3.5. SCENARIO 4 - COMBINED REDUCTION OF POWER PLANT AND INTERCONNECTOR FLEXIBILITY

Scenario 4 is a minimum flexibility scenario analysing the combined flexibility reduction means of scenario 2 and 3. This means that the flexibility of the Danish power system is constrained both with regard to the reduced flexibility of the large power plants and with regard to interna-tional exchange capability.

This scenario serves two purposes. Firstly the scenario gives insights to how the Danish power system would be impacted by lack of flexibility from both much smaller interconnection capacity and from much less flexible power plants.

Secondly, comparing the results of scenario 4 and scenario 3 will show the effect of lacking highly flexible thermal power plants in a situation where the system's interconnections to neighbouring countries were at a level of 10% instead of the current 50%. Given a situation with much less flexibility due to highly reduced Danish interconnector capacity, the value and impact of flexible power plants are expected to be much more pronounced.

4. Modelling results

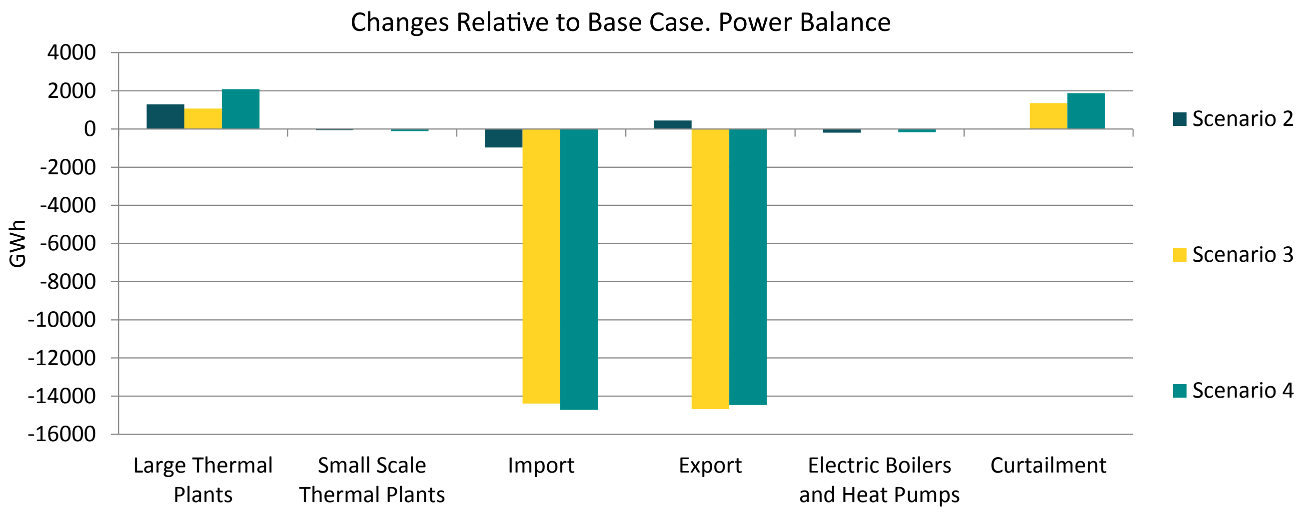
4.1. OVERVIEW

In this chapter the modelling results for the described Danish scenarios are presented and discussed. The presentation is intended to be kept consistent in the sense that focus is on changes in absolute and percentage values for scenarios (2), (3) and (4) compared to base case (1). Unless otherwise stated all presented results are yearly values or yearly averages.

4.2. RESULTS CONCERNING POWER BALANCE

The main results for the three alternative scenarios regarding the balancing of the overall power system compared to the base case are shown in figure 4.1.

Figure 4.2 depicts the same results as figure 4.1, but with a change in scale and showing just the net changes in import/export.



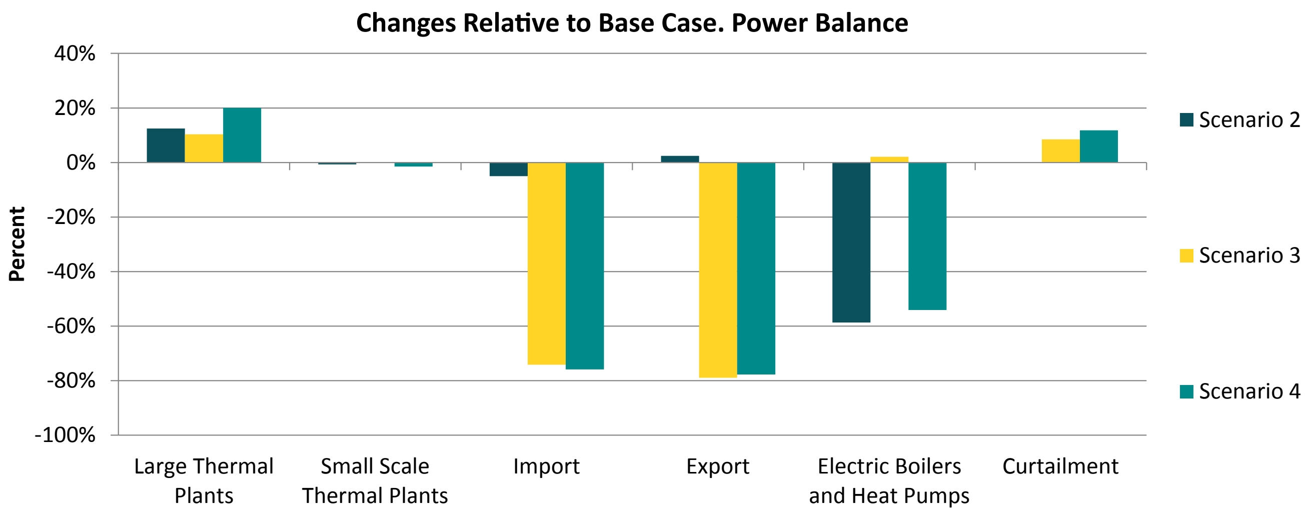


Figure 4.1: Changes in overall power balance in GWh and in percentage compared to base case.

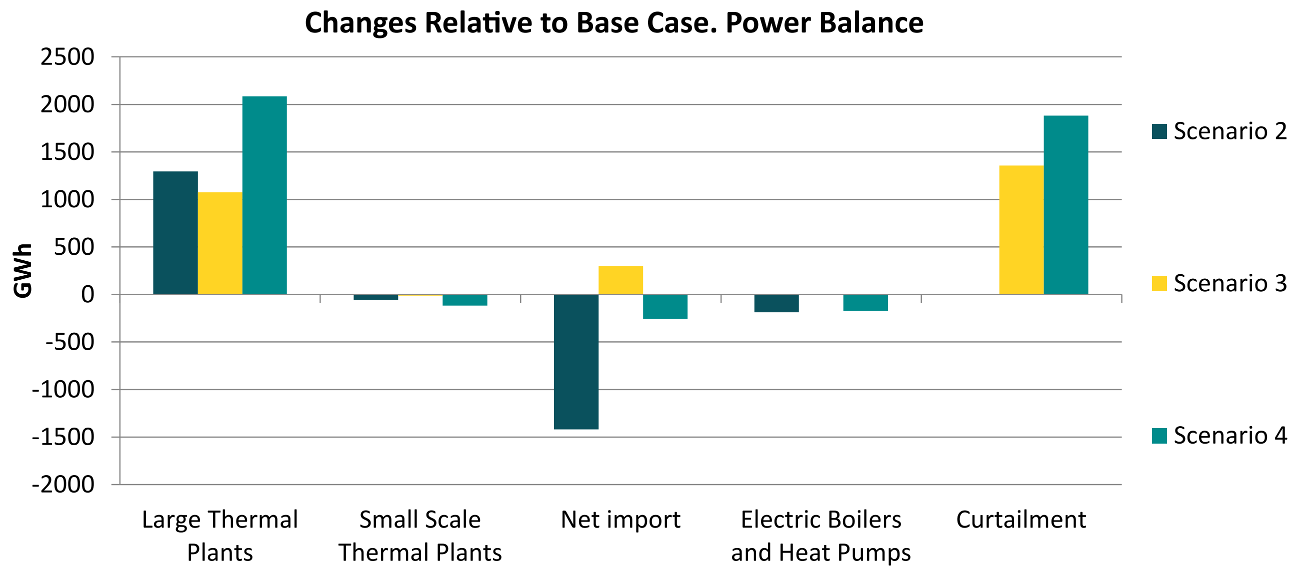


Figure 4.2: Same as figure 4.1, but with change of scale and showing changes in net-import.

The effects on the large power plants are summarized below:

- The less flexible large power plants in (2) will lead to an increase in their power production by about 12% while the heat production is practically unchanged.

  The reason for this outcome is that it is still economically optimal to produce the heat on the large power plants instead of producing at separate heat-only boilers and that the higher minimum loads of the plants and the lack of heat storage tanks result in higher power production with fewer start/stops.

  In other words: less flexibility of the large power plants result in higher power production from the plants. This is consistent with a less net import in (2), see figure 4.2. The reduced amount of net import has about the same size as the increased power pro-duction of the large thermal plants.

- Reduced exchange capacity to neighbouring systems in (3) also leads to increased power production from the large power plants with about 10% while the heat production also here remains unchanged. With both import and export opportunities being heavily reduced there will be hours with higher domestic generation when import is constrained from one or more countries and hours with less domestic generation when export is similarly constrained. The two situations will to a certain degree balance each other leading to modest change in net import.

  With minor changes in net import and generation from the small thermal plants then the increase in generation from the large power plants must outbalance the increased curtailment that arises due to the constrained export possibilities. Consequently the increase in generation from large thermal plants plus the increase in net-import is about same size as the increased curtailment of wind and PV.

- The results for scenario (4) show that the effects on power production on the large power plants in scenario (2) and (3) are approximately additional. The combined effect of reduced flexibility of power plants and interconnector capacity thus lead to about 20% increase in power production from large power plants.

Large power plants power production – weekly illustrations

Figure 4.3 and 4.4 illustrate the different scenarios' effect on the large thermal power plants' generation pattern over a week – but under two different situations during the year. These illustrations show how the dynamics of the system work and illustrate respectively a weekly result that is fully in line with the average yearly results as well as a weekly result that yields a different outcome due to the specific situation in the given week.

Figure 4.3 shows the production pattern of large thermal plants in a windy winter week (week 2) for all scenarios (1)-(4).

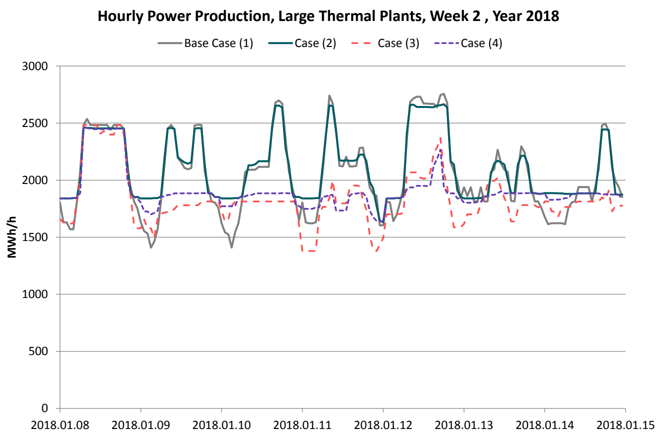


Figure 4.3. Production patterns of large thermal power plants during a windy winter week. All 4 scenarios (1)-(4).

In line with the yearly results the large plants are producing more in this week when being inflexible (2) than in base case (1). In figure 4.3 this shows up as higher generation minimums.

However, the thermal power plant generation in (3) and (4) is less than in base case for this week in contrast to the yearly results. The explanation for this is that the week is a windy week where the reduced exchange capacity constrains the export and thereby also reduces the scope for generation from the thermal plants (see also succeeding figure 4.6).

Figure 4.4 presents the results for another type of week (week 18 in May), which - contrary to the previous week 2 - only has modest renewable generation. The generation in (2) is higher than in base case (1) due to higher generation minimums. The generation of the large power plants are in this week now also larger in scenario 3 and 4 reflecting the yearly results. The reason is that reduced exchange capacity in (3) and (4) constrains the import from one or more countries. Besides, the total generation in this week is higher in (3) and (4) than in base case (1).

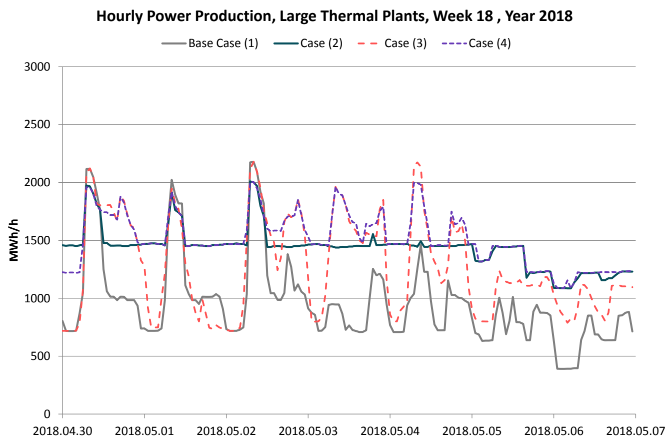


Figure 4.4 Production patterns of large thermal power plants during a week in May with modest wind. All 4 scenarios (1)-(4).

Curtailment

The effect the different scenarios have on curtailment of VRE is highlighted below.

- There is no curtailment of wind and PV in base case (1) and negligible curtailment in (2). Base case represents a highly flexible power system, which can handle large varia-tions of variable renewable generation from wind and PV. As an example figure 4.5 shows the balancing of the system during a windy winter week in base case (1) showing the operation of the system without curtailment. The balance is a result of the simu-lated day-ahead market dispatch.

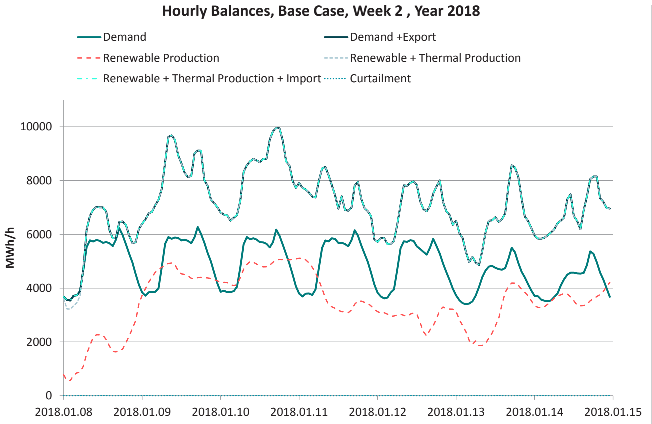


Figure 4.5 Balancing the Danish power system in a windy winter week in base case scenario (1).

- It follows from figure 4.5 that except for the first few hours of the week export is prevailing. (The upper curve in the graph is "demand+export", which equals "renewable+ thermal production+ import". As import is zero except for the first hours of the week the upper curve also equals "renewa-ble + thermal production" in the remaining hours). The week is characterised by large variations in renewable generation (2-5 GWh/h) and also variations in thermal generation and export – and curtailment does not happen in base case.

- With reduced flexibility of power plants in (2) the balancing of wind (and PV) is still possible to obtain through plentiful exchange capacity to neighbouring systems.

- However, the reduction of exchange capacity (3) has severe consequences for cur-tailment. Thus, in (3) the total curtailment of wind and PV amounts to 9% of the po-tential generation of wind and PV. The reduction in exchange capacity is so severe that even operation of flexible large thermal plants in (3) cannot avoid curtailment.

About 99% of the GWh-curtailment is wind. This is because the potential wind genera-tion is about 15 TWh, while the number for PV is much less and about 1 TWh. Also PV is solely generated dur-ing day hours where demand is high.

Figure 4.6 illustrates the situation in the same winter week as figure 4.5, now in sce-nario 3 with reduced exchange capacities.

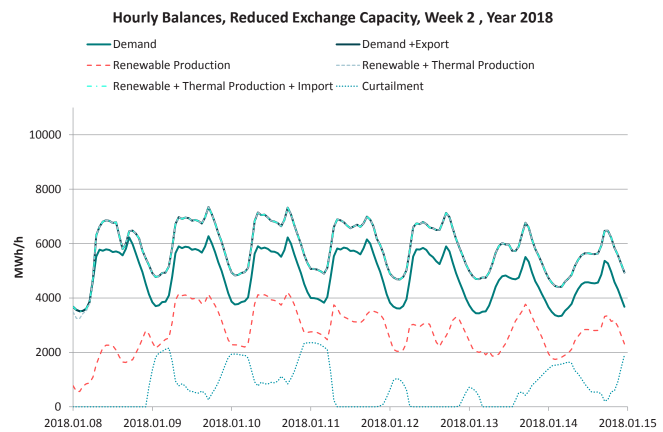


Figure 4.6 Balancing the Danish power system in a winter week in scenario 3 with reduced exchange capacity on interconnectors.

It follows that high curtailment will take place, in some hours more than 2 GW (or very large share of the total VRE production). Besides, as expected the export is much less than in base case (1).

- It also follows from the results in figure 4.1 and 4.2 that given reduced exchange ca-pacities on interconnectors then a reduced flexibility of the power plants will lead to increased curtailment. Thus, in (4) the total curtailment amounts to 12% (of potential generation).

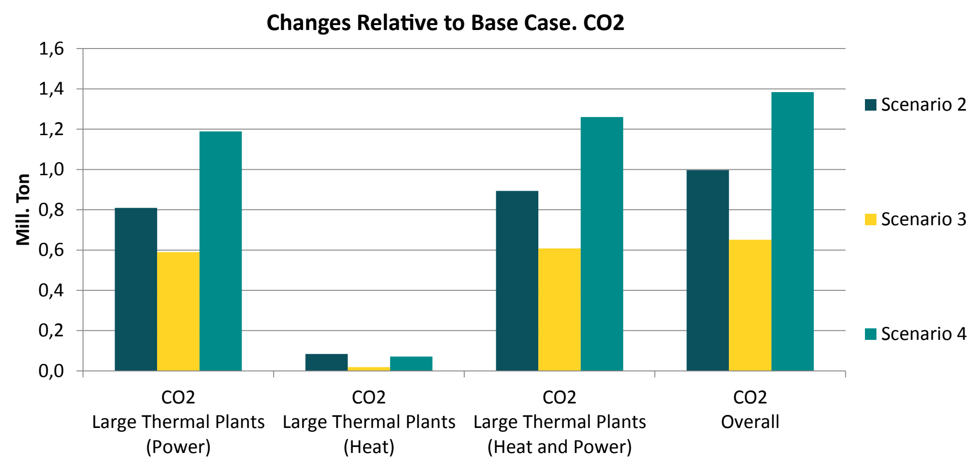
So, when curtailment is already taking place due to reduced interconnector capacity then reduced power plant flexibility will lead to increased curtailment. In other words, given reduced flexibility from interconnectors then inflexible power plants will lead to (additional) curtailment of VRE production.

4.3. IMPACT ON CO2 EMISSIONS

The results concerning consequences for CO2 emissions are shown in figure 4.7. From the discussion of results in section 4.1 it follows that in the Danish power system the large power plants increase their production when flexibility is reduced. This applies both to flexibility of power plants and flexibility in regard to reduced exchange capacity. That explains rising CO2 emissions in figure 4.7.

The figure shows CO2 emission changes for the large power plants (allocated into production of power and heat) and the system overall changes in CO2 emissions, which are obtained by adding the changes of emissions from all other units in the system (small scale local plants and heat boilers in district heating systems). The main results related to CO2 emission in the different scenarios are outlined below:

- When reducing the power plant flexibility (2) the CO2 emission of power production (excl. heat production) from the large plants increases with



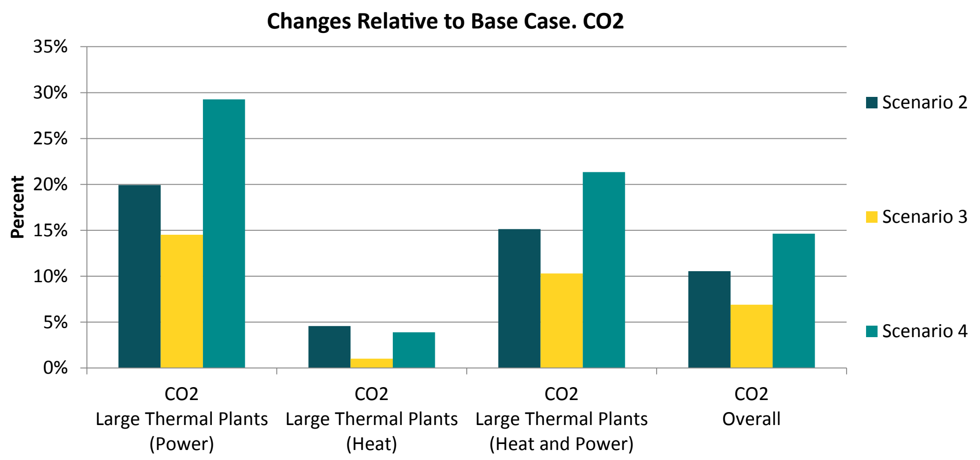


Figure 4.7. Change in CO2 emissions (absolute values and percentage) compared to base case.

about 20%. The detailed results show that about 2/3 of this increase is due to increased generation and 1/3 is due to the plant operating with lower efficiency[3] and other conditions compared to base case. This is in good consistence with the power generation increases with 12% in (2).

- The power generation from large plants increases with about 10% when reducing the exchange capacity in scenario 3. The corresponding CO2 emission from the power production becomes about 15% larger. Detailed results show that also in this case 2/3 of the increase is due to increased production, while 1/3 is due to lower efficiency and other conditions.

- The results for scenario 4 show that the effects from scenario (2) and (3) are somewhat less than additional when it comes to CO2 emissions from large power plants' power production.

- Changes in CO2 emissions allocated to the heat production from the combined power and heat production at the large plants are negligible in absolute values. This corre-sponds to the fact that the heat generation from the large plants is very close to be the same in all scenarios.

- CO2 emission overall is the total emissions from large thermal plants and the smaller local plants and small scale separate heat boilers. While the large power plants are extraction units, the local plants are back pressure units with a fixed relation between power and heat generation. The small scale local plants' generation and CO2 emissions are primarily governed by the local heat demand, which is unchanged in the scenarios. This explains the modest changes in CO2 emissions from the small scale local plants plus separate heat boilers in figure 4.7.

- In scenario 2 the increased power production from large thermal plants is compen-sated by the same amount of reduced import and the specific emission of the increased generation is about 600 kg/MWh. As a comparison power production from coal gives an emission of about 800 kg/MWh and the corresponding number for natural gas is about 500 kg/MWh. The CO2 emission of 600 kg/MWh is higher than the emission from reduced import from neighbouring systems as the main import is from Norway (hydro based system) and Sweden (generation from nuclear, hydro and thermal). Therefore reduced flexibility of Danish large power plants tends to increase the regional CO2 emission with an amount up to about 1 million ton. This is corresponding to about 10% of the total CO2 emission from the Danish power and heat system.

- In scenario 3 it follows from the discussion in section 4.2 that the increased power generation from thermal plants mainly replaces curtailed wind and PV. This is also the case in scenario 4. That implies that the net increase in the regional CO2 emission in (3) and (4) is about 0.6-1.4 mill ton CO2 and generally reflects increased thermal power production to offset the curtailment of VRE production. It corresponds to about 5-15% of the total CO2 emission from the Danish power and heat system.

4.4. IMPACT ON WHOLESALE POWER PRICES

Having less flexibility in the power system naturally also affects the whole sale power prices. Figure 4.8 summarises the main results for power prices obtained for different producers as well as whole sale consumers under the different scenarios:

- With less flexibility in both scenario 2 and 3 the prices are reduced for all large stake-holders. For the large power plants price reductions are observed with less power plant flexibility (scenario 2). An example of this was discussed earlier and

3. Larger fuel consumption per MWh produced power

shown in figure 4.4, where inflexible power plants produce more when they are less able to down regulate during low prices. The corresponding average price reductions for the large power plants amount to 5% in (2). As expected when plant flexibility in (2) is reduced, then the power plant producers are the group being most impacted on their achieved power price.

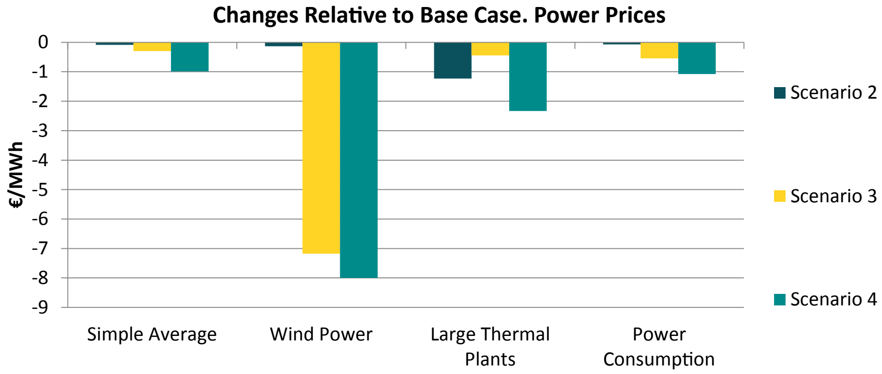
- The largest changes for wind power and consumers occur with less interconnector capacity in scenario 3 and in the combined scenario 4. With less exchange capability the system has “too much” wind generation (due to highly reduced export capabilities) in many hours, which will depress market prices significantly. Prices obtained by wind power are on average reduced by 30-34% in scenario 3 and 4. This will also influence prices for large power plants with a 2% price reduction in scenario 3 and 9% price reduction in the combined scenario 4. For consumers weighted whole sale prices decline by 2% in (3) and 4% in (4).

- The impact of having less flexible thermal power plants is thus a 5% price drop in sce-nario 2, but under reduced interconnector capacity the price drop increases from 2% to 9% (i.e. 7%-point) due to reduced power plant flexibility (difference between sce-nario 3 and 4). In order words, the impact on the achieved power prices for the thermal producers become more pronounced in a situation with less flexibility from other sources.

- Similarly, given reduced interconnector capacity (scenario 3 and 4) it can be observed that less flexible power plants will influence the achieved power prices for wind power by increasing the price reduction from a drop of 30% to a drop of 34%. In other words, when the system is less flexible (due to reduced interconnector capacity) then the impact on achieved power prices for wind producers of flexible power plants will be more noticeable.

- An interesting observation is the substantial decline in prices for wind when the inter-connector capacity is reduced in scenario 3. This is because the very high reduction of 80% on exchange capacity and the relatively high amount of wind in the Danish system. These factors together will result in many hours with low prices and even curtailment where supply exceeds demand. While wind power producers will experience these depressions in price, they will not experience the high prices, when they occur, as high prices typical occur in low wind or no wind hours.

- The price reduction of 30% for wind producers in scenario 3 clearly shows that with limited power system flexibility then the value of zero marginal costs assets (i.e. VRE) is highly diluted. This will reduce investors’ return on investment in VRE and/or require VRE subsidies to be higher – both



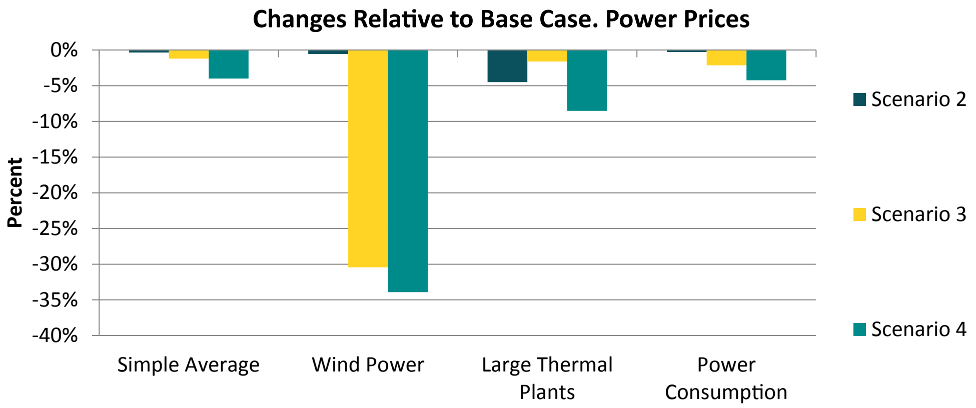


Figure 4.8 Changes in power prices (absolute values and percentage) obtained by different stakeholder categories in the market. (Prices for "Power Consumption" are consumption weighted).

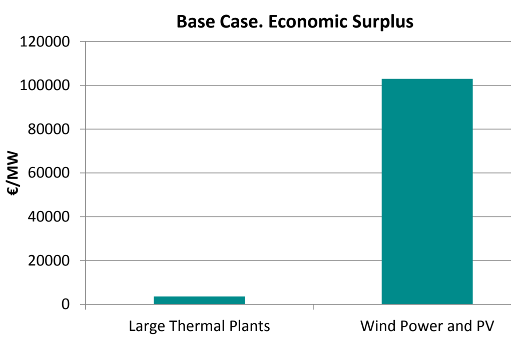
effects would expectantly have an adverse effect on the buildout of VRE.

4.5. IMPACT ON ECONOMIC SURPLUS

The calculated economic surplus (contribution margin) in base case for large power plants (coal- gas- and biomass-fired) and for aggregated wind and PV is shown in figure 4.9. The economic surplus is defined as variable revenues (including subsidies for the VRE producers) minus the variable costs.

The thermal power plants producers have relative low economic surplus (approximately 3,600 euro pr. MW) reflecting that the achieved power prices on a yearly basis in base case only is marginal higher than the variable costs associated with the power production (earnings from the heat side are not included here). Given the relative high initial investment costs and zero marginal cost nature of wind and PV the contribution margin among this class of asset is much higher.

Figure 4. 9. Economic surplus (contribution margin) in base case per MW for different generation units.



The effect the different scenarios have on the economic surplus of respectively the large power plants (coal- gas- and biomass-fired) and for aggregated wind and PV are shown in Figure 4.10.

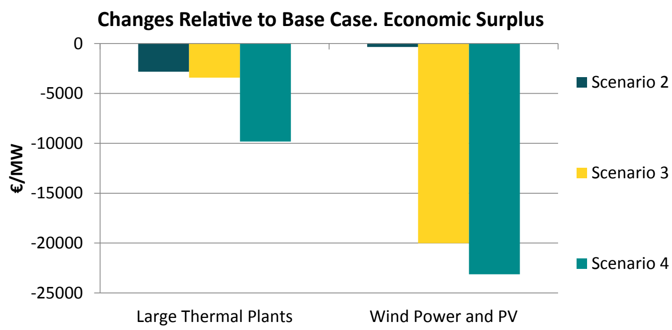


Figure 4.10. Changes in economic surplus (from producing power) per MW generation capacity for large plants and wind & PV in the different scenarios.

The main results are:

- The economic surplus for the large thermal power plants in scenario 2 decline with around 2,800 euro pr. MW. This translates to a decline of around 1.1 million euro per year for a 400 MW plant.

- Comparing the economic surplus for the large thermal power in scenario 3 with scenario 4 shows that the thermal power producers under a situation with limited interconnector capacity will witness much lower economic surplus if they are inflexible compared to a situation where they are flexible. More specifically there is a decline in the economic surplus for the thermal power producers of around 6,400 euro pr. MW (difference between scenario 3 and 4) due to reduced thermal power plant flexibility. This translate to a reducion in economic surplus of around 2.6 million euro per year for a 400 MW plant.

- Following the large impact on the achieved whole sale prices for wind and PV producers in scenario 3 and 4 it is evident that the economic surplus drops very significantly. More specifically the economic surplus in scenario 3 drops 20,000 euro pr. MW – translating to around 8 million euro per year for a 400 MW wind portfolio. Approximately half of the economic surplus in base case (i.e. roughly 50% of the 100.000 euro pr. MW) is subsidies why the percentage reduction in economic surplus for the VRE asset owners is somewhat smaller than the reduction in whole sale prices.

The model results clearly show that the thermal power plants would realize a significant loss in their economic surplus if they were less flexible. Or in other words there is a clear economic incentives for the thermal power sector to become more flexible. This is true both under the current interconnector capacity and even more pronouced given a less flexible system due to reduced interconnectors.

Further, the model results show that the economic surplus of the VRE assets in scenario 3 (and 4) is highly influenced by the extensive interconnection to neighbouring power systems. As metioned in section 5.4. the economic incentives for investors in VRE – or alternative the need for VRE subsidies – is significantly challenged when the system's flexibility is reduced.

The detailed impact on costs and revenue for the large thermal power plants are shown in figure 4.11. The results show:

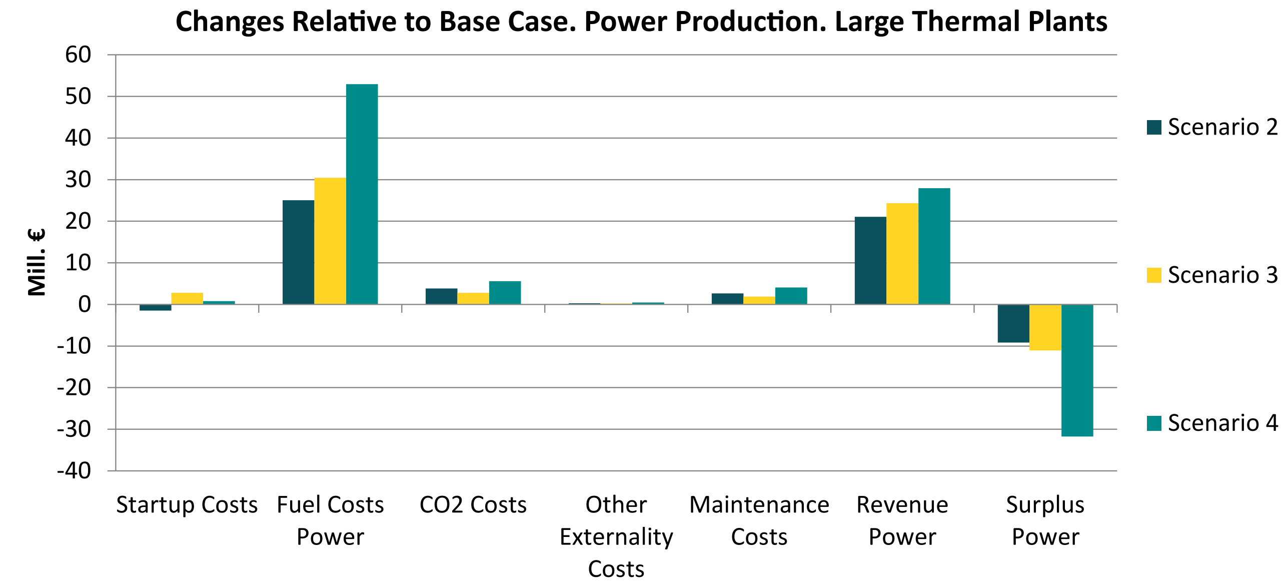
- Fuel costs increase in all scenarios due to larger production of power. The fuel costs increase more in scenario 3 than in scenario 2 even though the generation is slightly higher in scenario 2. Analysis of the detailed results shows the reason is that the added generation in scenario 2 and 3 is not taking place at the same power plants. In scenario 3 the added generation is to a higher extent taking place at power plants that use more expensive fuels like gas and biomass. This result - changing the dispatch pattern of power plants - is due to the large effect on the power system arising from an 80% reduction of interconnector capacities. .

- The CO2 costs also rise in all scenarios because of larger generation and lower effi-ciency. In all simulations a CO2 price of 4.7 euro/ton (reflecting current prices) has been assumed.

- The revenue increases in all scenarios following increased production, but due to the reduced achieved power prices the extra revenue does not make up for the increased fuel costs.

- As the revenues rise less than the costs the surplus will become less than in base case. The very high percentage loss in surplus in scenario 2 and 3 is due to a modest surplus from the power production of 12 million euro in base case and reduced surpluses in (2) and (3) (the percentage changes calculated with a low reference value can easily be very high).

- In the combined scenario 4 the generation changes in (2) and (3) can be added. This is also true for the fuel costs. However the revenue is only slightly improved due to sharp decline in power price in this scenario. Therefore an enhanced decline in surplus is observed in scenario 4.



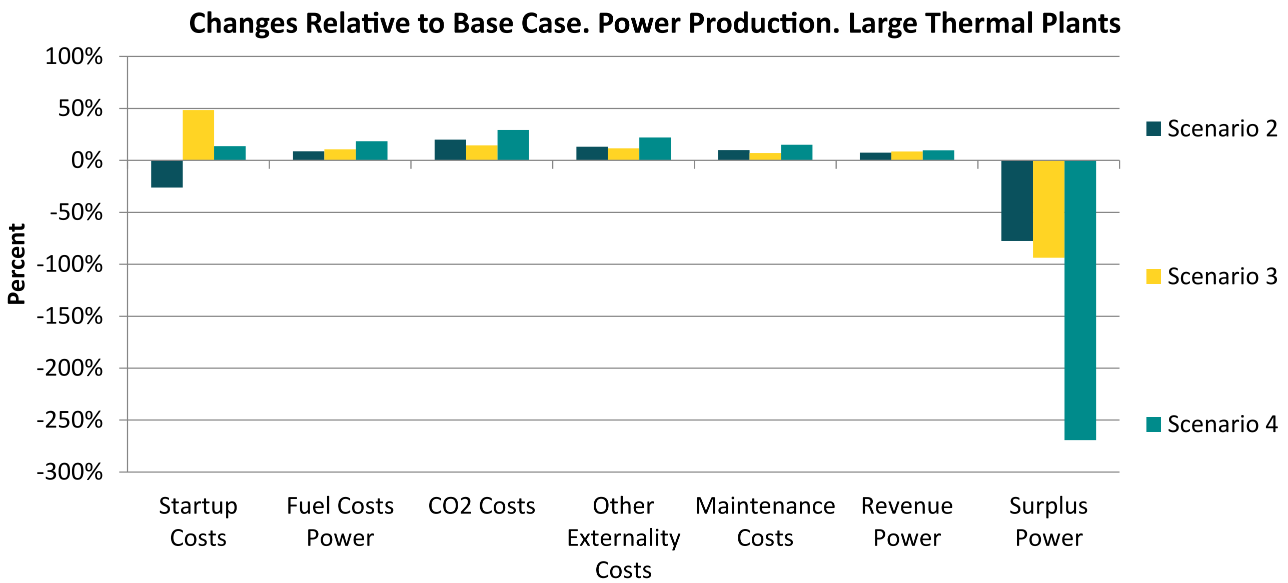


Figure 4.11. Impact on costs and revenue for the large thermal power plants.

4.6. OVERALL ECONOMIC CONSEQUENCES FOR SOCIETY

The economic consequences for all relevant stakeholders are summarized in figure 4.12. The total value is the summation of all columns and represents a proxy for the change of the overall socio economic surplus (it is a proxy because subsidies to wind, PV and biomass fuels are included).

Besides the changes in economic surplus for the different producers then figure 4.12 shows that:

- Congestion rents[4] are reduced with about 30% in

4. Congestion rents represent the earning the interconnector owners (in Europe typical the TSOs between the connected

(3) and (4) compared to base case. The reason is the markedly reduction in interconnector capacity of 80% compared to base case. When the capacity on interconnectors is reduced, congestions will rise and also price differences between areas being connected will on average increase. These two conditions would lead to increased congestion rents, but the effect is too small to counteract the effect of the reduced exchange capacity.

• In (3) and (4) there is an overall economic loss to society of 170-190 million euro compared to base case. To get an idea of the relative magnitude of this amount it could be mentioned that in base case the fuel cost for power producing on the large power plants amount to 287 million euro and the total revenue for wind (5,400 MW) in base case excluding subsidies is about 350 million euro. While the power producers will witness much lower prices in particular (3) and (4) then the consumers will gain in their economic surplus due to lowered cost of consumption driven by consumer prices are reduced 2-4% in (3) and (4), while prices are nearly unchanged in (2). It is obvious that while the consumers will gain from the

areas) will make by exchanging power from a low price bidding zone to a high price bidding zone.

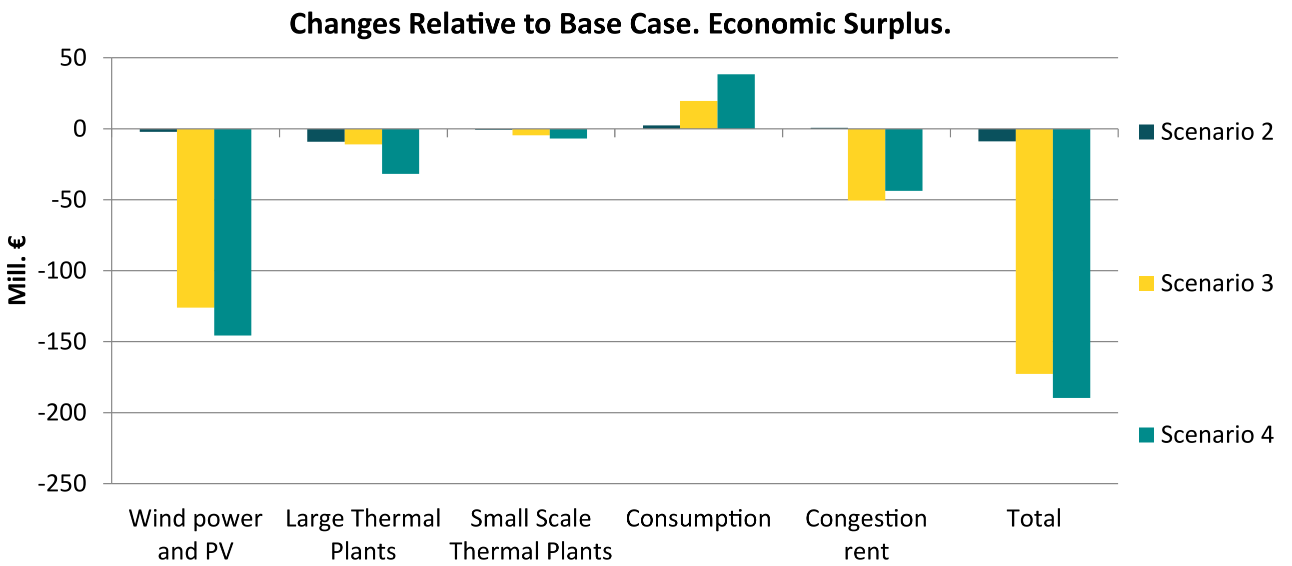


Figure 4.12. Overall economic changes concerning power (absolute values) for stakeholders and society as a whole (total.

5. Conclusion

The impact of reduced system flexibility compared to the current status of the system (base case) has been investigated along two main lines:

Firstly, by assessing the impact of reduced flexibility of the large power plants. This is done by reducing ramp rates (from actually about 5% down to 1% of installed capacity per minute) and by increasing minimum loads for stable operation (from actually 10-30% up to 60% of nominal capacity) on these plants. With the aim of further reducing flexible operation of combined heat and power production, electric boilers, heat pumps and heat storage tanks have been removed from district heating systems connected to the large thermal plants.

Secondly, by analysing the impact of significantly reduced interconnector capacity to neighbour power systems. An 80% flat rate reduction for all interconnector capacity has been assumed, thereby reducing the total exchange capacity to about 10% of the total Danish generation capacity. This value was chosen since 10% is the European Commission's overall minimum target for 2020 for EU countries.

For the specific Danish power system, large impacts are observed both when the flexibility of large thermal power plants is reduced and when the interconnection capacity is reduced.

The most important conclusions from the model results regarding reduced power plant flexibility are related to changes in the level of production, and thus CO2 emissions, and the impact on the economic results of the power plants.

Overall CO2 emissions from power and heat generation rise about 11%. This is mainly due to a 12% increase in generation from the large power plants and less efficiency in generation leading to about 15% CO2 emission increase from the large thermal plants. The reason for increased generation from the large thermal plants is the higher minimum loads of the plants and the lack of flexibility measures on the heat side.

The result of the analysis shows that the highly flexible thermal power plants in Denmark enable them to reduce power output and thus contribute to lower overall system CO2 emissions.

It can also be observed that reduced flexibility in large thermal power plants result in a reduction in their achieved wholesale prices of approximately 5%. This results in a reduced in economic surplus corresponding to approximately 1.1 million euro for a 400 MW plant. This economic result supports the rationale for the Danish power plants to have invested in and become in-creasingly flexible over time. The enhanced flexibility enables them keep serving their local heat demand while allowing them to better adjust their power output depending on the power prices resulting in higher achieved power prices and thus increased profits.

There are several significant effects of reduced interconnector capacities compared to base case. While the curtailment of VRE is practically zero in the base case, it increases significantly to about 9% of potential generation of wind and PV when considering reduced interconnector capacities. The system overall CO2 emissions increase about 7%, mainly due to increased production and thereby CO2 emissions from the large thermal power plants.

The prices in the wholesale market decline substantially for all stakeholders. Most pronounced is the 30% reduction in whole sale prices for wind. This price reduction plus the curtailment leads to an overall reduction in economic surplus for wind producers of 20%. Consequently, the value of zero marginal costs assets (i.e. VRE) is highly diluted, which would either reduce investors' return on investment, and/or require VRE subsidies to be higher.

The overall socio economic result for Denmark (producers, consumers and congestion rents) is a welfare loss that amounts to 170 million euro. In comparison, the total revenue for 5 GW wind (5,400 MW) in the wholesale market is about 353 million euro in the base case.

It can be concluded, that Danish interconnector capacity is pivotal to integration of wind. Without sufficient exchange capacity the system value and market price obtained by wind will deteriorate and business cases for wind power investors will be eroded.

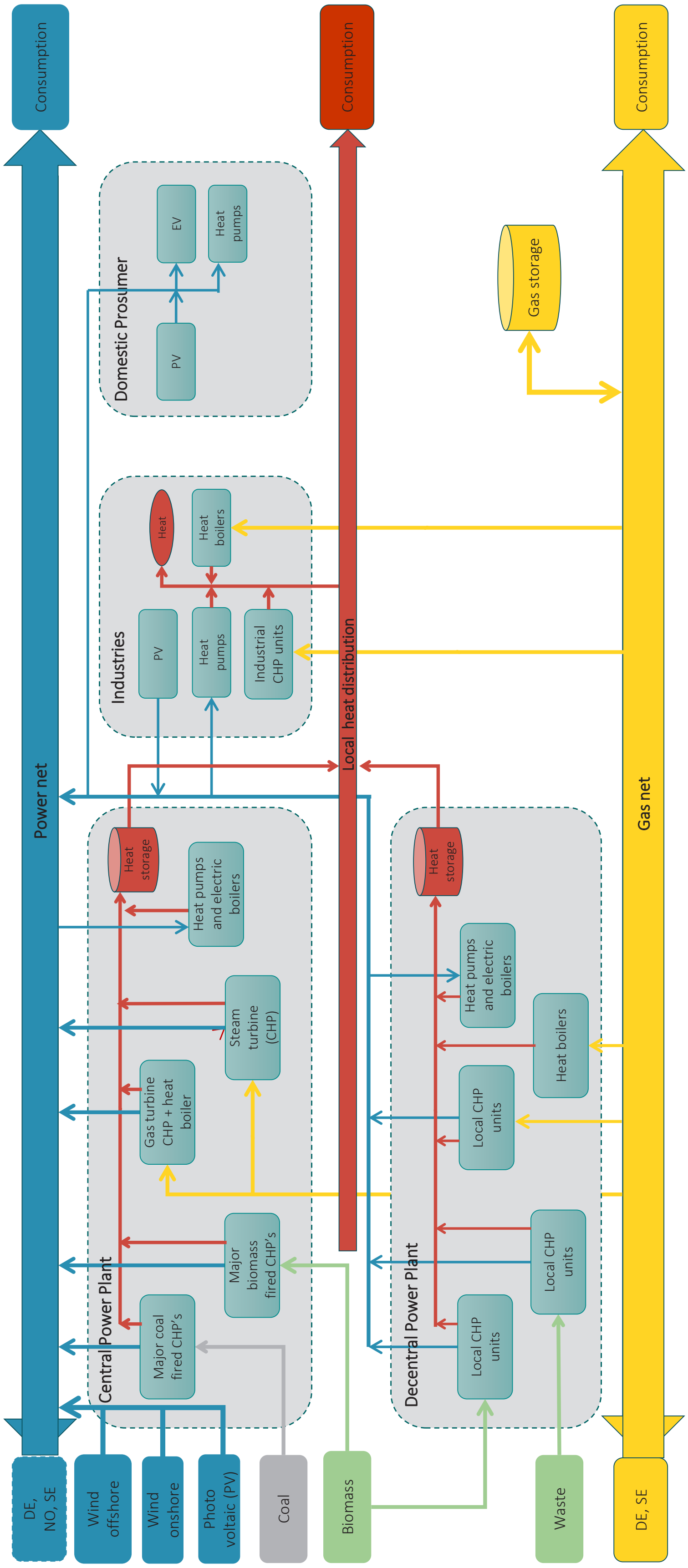
The combined effects of interconnector capacity reductions and power plant flexibility reductions are in general additional. For some parameters the effect of reduced power plant flexibility is enhanced when the interconnector capacity has been reduced. Specifically, under low interconnector capacity then reduced power plants flexibility will lead to increase in VRE cur-tailment (from 9% to 12%) as well as lead to a larger decline in economic surplus for wind and PV, but particular for the power plants who will experience a decline of 6,400 euro pr. MW equivalent to 2.6 million euro for a 400 MW plant per year.

Altogether, the results obtained from the model provides an illustration of the importance of flexibility, both in power plants and from interconnection to neighbouring market areas, in the deployment of high shares of VRE. The model result illustrates well that without the develop-ments in power plant flexibility and transmission capacity with neighbouring countries it would be extremely challenging to integrate VRE to the level Denmark has today. The expansion of interconnection capacity is shown not only to favourably affect the possible integration of VRE, but provides in the model a clear advantage from a society welfare perspective considering CO2 emissions and economic surplus. Furthermore, the current level of transmission capacity in Denmark ensures very limited levels of curtailment of VRE supporting a continued build-out of VRE.

While increased flexibility of thermal power plants in Denmark has significant positive effects in the reliability of the system and the ability to integrate high shares of VRE, it is not driven by a strict command and control regulatory frame, but by a well-designed market structure that provide the necessary economic incentives for them to enhance their flexibility capabilities and operated flexible. The power market allows for prices to correctly signal the need for flexibility and therefore rewards power plants that can take advantage of increased flexibility. In this way, the market structure can be seen as a tool that helps align the incentives of the producers with the requirements of the system.

While the possibilities for the design of markets and incentives for increasing flexibility in power plants and for increasing transmission capacity are broad, the present study shows that in the Danish context, both sources of system flexibility have granted positive effects. Improving the capacity of the system to integrate VRE not only requires the existence of adequate technology, but also an appropriate market with powerful price signals that reflect the need and true value of flexibility.

Appendix A



SIFRE model setup for 2018 (Source: Energinet).


ENERGINET
Danish Energy Agency