Electricity price forecasting and market dynamics

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Synopsis:

The electricity market is a key political tool for affecting the development of the energy system. Future electricity prices are forecasted to increase, which seems in contrast to the effects of renewable energy driving down prices.
This makes it interesting to investigate how the future electricity prices might develop and how the market dynamics create incentives for development of the energy system.
A model is constructed with the aim of forecasting prices on the basis of technical energy systems in the year 2030.
A reference scenario developed by the DEA and the IDA 2030 scenario with more renewable capacity are modelled, and the average electricity prices were 249 kr/MWh and 112 kr/MWh respectively. This is in a much lower range than the forecasted 400 to 500 kr/MWh and too low for most generation to be feasible.
If political interference in the energy system is wanted, then the current market design cannot support investments in the energy system and some changes must be made.

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1 Introduction

The increasing focus on climate change have led to serious concerns over the anthropogenic emission of greenhouse gasses. With the aim of curbing greenhouse gas emissions and keeping the temperature increase well below 2°C, the Paris Agreement is a political signal that climate change is a serious issue that must be addressed [UNFCC, 2017]. The European Union have ratified the agreement and it entered into force on the 4th of October 2016 [European Commission, 2016a]. This makes climate change one of the current political priorities of the EU. In 2014, 30.2% of the European greenhouse gas emissions originated from Energy Industries, including electricity generation [eurostat, 2016]. This makes the electricity sector a potential sector for curbing greenhouse gas emissions from the energy system on both European and Danish level.

The electricity market is one of the key political tools in regulating the development of the energy system and the electricity sector on local levels. The market rules and regulations are important in determining how the price is set and how the money flow between consumers and generators. This creates initiatives for market players to react in different ways and thereby shaping the Danish energy system.

1.1 Background of the Electricity Market

Traditionally the electricity sector have been characterised by monopolies and heavy regulation. In Denmark many power plants have been owned by either municipalities or in co-operatives since the introduction of electricity in Denmark in 1891 [Frederiksen, 2012b]. This trend have persisted up until the 1980s where the first ideas of market liberalisation of the electricity sector were introduced in Chile by the Chicago Boys [Pinson, 2017].

The liberalisation of the Danish electricity sector was a part of a major liberalisation tendency which were present in both the USA and Europe. Typically big state owned companies like airlines, train services and the telecommunications and electricity companies were liberalised in order to foster competition and drive down prices. The EU had an important role in the Danish electricity market liberalisation, where the liberalisation directive from 1996 was implemented through the *el-reformen af 1999*. [Frederiksen, 2012a]

Before the liberalisation, the electricity market was characterised by a large degree of vertical integration. This implied that all parts of the production, transmission and distribution, seen in Figure 1.1, was done by the aforementioned public monopoles. With the deregulation of the electricity sector, this vertical integration was split and electricity generation became an independent business. This meant that the consumers and the distribution companies were no longer linked to a certain power plant serving a limited geographical area which were meant to foster competition and drive down prices. [Frederiksen, 2012a]

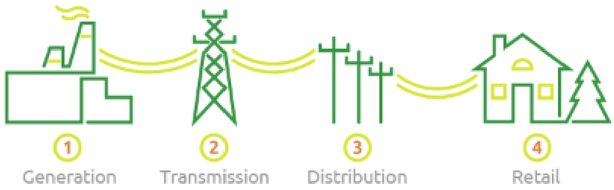

Figure 1.1. General sketch of the flow of electricity in the market. [Spark, 2017]

The Danish transmission system is still under monopoly which is served by the state owned company Energinet.dk. Energinet.dk was established in 2005 with the main responsibility of the transmission system, security of supply and a well functioning market in both the electricity and gas sector. The distribution systems are primarily privately owned in cooperatives where it is the end-users in the geographical area owning the distribution system.

It should be noted that the term deregulation in the context of the electricity market does not mean that the state does not interfere with the market, but that the state is no longer running the power market and instead free competition is introduced [Nord Pool, 2017a].

1.2 The Current Market Design

The current electricity market consists of a wholesale and a retail market as seen in the schematics in Figure 1.2. Here it is seen that all generation from the generation companies, genco, is pooled in the wholesale market where retailers and large consumers place their bid for consumption. The end consumers then have free choice of retailers to buy their electricity from in the retail market which in turn gets the electricity from the wholesale market. [Kirschen and Strbac, 2004]

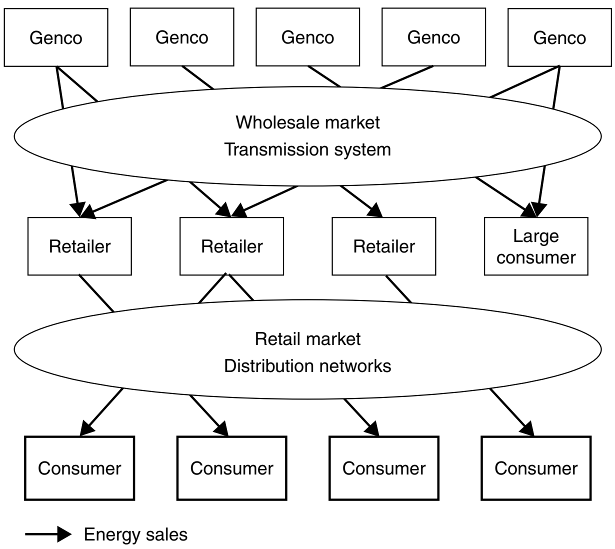

Figure 1.2. The wholesale pooled market. [Kirschen and Strbac, 2004]

This model can from an economic perspective been seen as the most satisfactory since all energy prices are set through interactions in competitive markets. [Kirschen and Strbac, 2004]

The wholesale market is interesting to investigate further, since it is here that the price for electricity is set and the exchange with generators are made. It is the design of the wholesale market that determines the revenue streams to generators and thereby the feasibility of different generating technologies. These incentives have an impact on how the energy system is developed because businesses seeks sectors and niches where they can make a profit.

1.2.1 The Wholesale Market

The wholesale market is designed as a pool where bids for generation and consumption are pooled and used as the foundation for forming supply and demand curves as seen in Figure 1.3. The bids for generation is sorted in ascending order in order and the demands in descending order with the intersection between the two determining the traded quantity and a uniform market price. At this uniform market price all generators sell electricity for more than or equal to their bid and all consumers buy electricity for less than or equal to their bid. The difference between the uniform market price and the willingness to pay is defined as the consumers surplus and the vice versa for the generators with the producers surplus. This method of clearing the electricity market maximises the social welfare defined as the sum of the consumers and producers surplus.

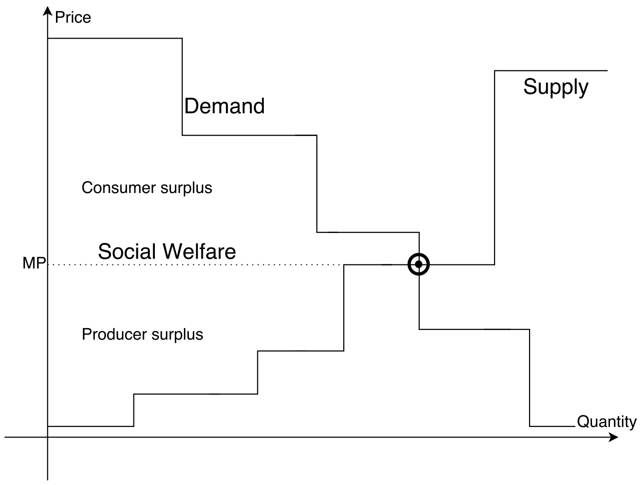

Figure 1.3. Market clearing in the wholesale spot market.

In a Danish context, the market is operated by Nord Pool, which is an enhancement of the Norwegian market, Statnett Market AS, established in 1993 [Nord Pool, 2017c]. Nord Pool is now owned by all the Nordic TSOs; Statnett SF, Svenska kraftnät, Fingrid Oy and Energinet, but is operated as an independent company [Nord Pool, 2017b]. The bids for generation and consumption for energy are set up on an hourly basis and the market is cleared at noon for the forthcoming day. Even though most of the electricity traded in the Nordpool area is traded through Nordpool spot, with a market share of 84% in 2013, generators and producers can form bilateral agreements on trading electricity [Nordpool, 2014].

1.2.2 The Dynamics of the Electricity Market

If the market functions as intended and no operator can exercise market power or form cartels then the market fosters free perfect competition between generators and consumers.

Under these perfect conditions it can often be assumed that most generators bid in with their short run marginal cost [Stoft, 2002]. If they do so, they are sure that if they are cleared, they will at least cover their variable costs linked to electricity production, and if they are not the marginal producer, the price will be set higher than their variable costs, introducing a contribution margin for covering the fixed costs and possibly generating a profit. If generators bid in with their short run marginal costs, then the marginal producer will not make a contribution margin and his operation will be unprofitable in the long term.

In the former fossil fuelled energy system the marginal producer was typically inefficient peak load power plants pushing up the prices so that the large proportions of energy generated in centralised power plants or cogeneration units would have a contribution margin making them profitable. As more and more renewables are introduced in the electricity sector, these technologies drive down prices since their marginal cost is close to zero. If the renewable generation is under a subsidy scheme, they might even bid on the market with a negative price. This effect of the price decreasing when more renewables are introduced is called the merit order effect and can be demonstrated in figure 1.4. Here it is seen that with an additional amount of cheap renewable electricity, Q_{res} the supply curve changes which causes the price to decrease.

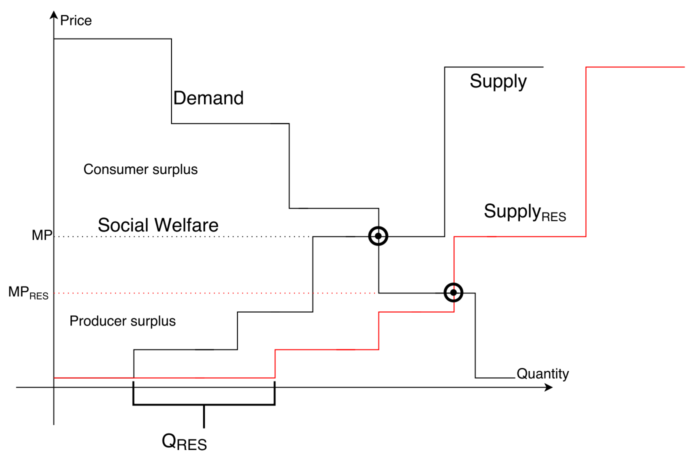

Figure 1.4. Market clearing and the merit order effect.

Therefore it is expected that under the current market design, the merit order effect will be more prominent the more renewable generation is integrated in the electricity system. This will affect the feasibility of different generation units, and in order to investigate the future feasibility of different generation technologies in the energy system it is interesting to investigate how the electricity prices will develop in the future.

1.3 Former Forecasts

Forecasting is extremely important when planning in order to see how future revenue streams will flow. The Danish Energy Agency, DEA, have throughout history made such forecasts of the electricity prices as seen in Figure 1.5 where former forecasts are displayed together with the historical electricity prices. It should be noted that the prices for 2017 are only for the first couple of months, and therefore not representative for the whole year.

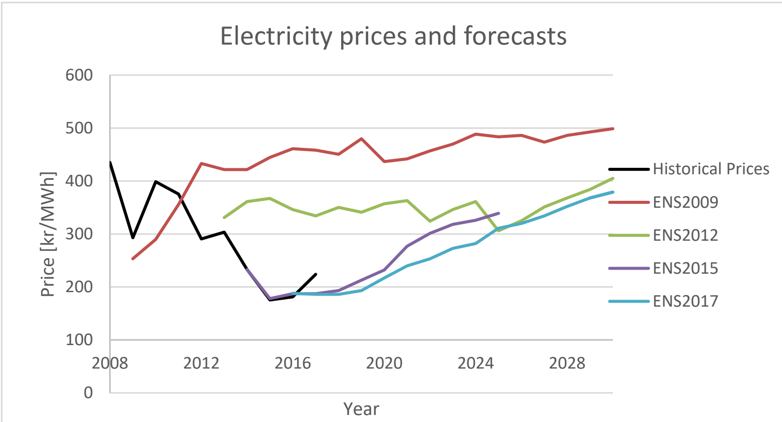

Figure 1.5. Historical prices and electricity price forecasts. Historical Prices - [Energinet, 2017]. ENS2009 - [Energistyrelsen, 2009]. ENS2012 - [Energistyrelsen, 2012a]. ENS2015 - [Energistyrelsen, 2015a]. ENS2017 - [Energistyrelsen, 2017a]

Of cause it is impossible to make accurate forecasts under uncertainty, and this is also seen to be the case for the DEA where the forecasts deviate significantly from the historical prices, with the general tendency being that actual prices are decreasing and forecasted prices are increasing.

Some of the important parameters for estimating future electricity prices are variables like the fuel prices, electrical efficiencies, CO_2-qouta price, meteorological variations and interconnections to other markets [Energistyrelsen, 2015a]. All of these are difficult to estimate, but the aggregated estimations are what represents the future electricity price. Further more the DEA uses a *frozen policy* approach meaning that they make their forecast based on the current political situation. [Energistyrelsen, 2017a]

If the tendencies of the forecasts are observed, it is seen that in all scenarios, the electricity prices are expected to increase in the future to a level around 400 to 500 kr/MWh.

This upward trend is not only expected by the DEA but from many actors in Denmark. Another example is the trade association, Danish Energy Association, whom in their electricity price forecast, expects the electricity prices to develop to between 300 kr/MWh and 600 kr/MWh with most of their scenarios around 350-400 kr/MWh [Meibom et al., 2014]. Another example is the Danish TSO, Energinet, who expect in their foundation for analysis, Energinet.dk [2016] that the electricity prices in Denmark will be around 400 kr/MWh in 2030 and increasing to 500 kr/MWh in 2050. This general expectation of increasing electricity prices is very interesting.

1.4 Current Tendencies and Future Expectations

If it is expected that the current market design will be the one used in the future, which must be the assumption under the *frozen policy* assumption, and that the installed renewable capacity in both Denmark and the neighbouring countries will increase, then the logic from the merit order effect dictates that electricity prices will decrease in the future. This is in contrast to the official forecasts presented by the major institutions where the electricity price in 2030 is expected to increase to around the double compared to today, making this inconsistency an interesting area for analysis.

The current development with decreasing prices have introduced some doubt on the development of the electricity prices as the main driver of the future energy system, and sparked discussions on the topic. This is for example seen in the February 25th 2017 edition of the magazine The Economist where the leader discussed "Clean energy's dirty secret" - the merit order effect driving down electricity prices and thereby affecting the feasibility of all investments in the energy sector. Similarly to The Economist, the magazine FORESIGHT which addresses climate and energy, went "In search of a cure for cannibalisation" which is driving down prices making the signal for investors that electricity generation is not feasible.

These two examples underlines the relevance of the problem and the importance of understanding the dynamics of the electricity markets and thereby trying to understand the future development of the prices. Therefore it is interesting to investigate how the electricity prices can develop under the current market conditions.

The climate political ambitions are typically realised through intervening in the market and setting goals for the performance of the energy system. This can e.g. be done through tenders where e.g. a fixed offshore wind capacity is put into a public tender where the developers bid in with a wish for subsidies for the produced electricity, and the developer with the lowest subsidy bid wins the tender and can build the turbines. Thereby the electricity market is left with a technical system that is more or less politically determined. This makes it especially interesting to investigate how the electricity market will function under an inherited technical electricity system.

The expected future electricity system, especially on a short term, can be assumed to be somewhat similar to the reference scenario developed by the Danish Energy Agency. This scenario for 2030 is developed on the assumption that current policies are realised and not changed and therefore gives a baseline for the future of the system. As a part of their climate plan, the Danish Society of Engineers, IDA, made a technical model in the simulation tool EnergyPLAN of the 2030 reference system proposed by the DEA. Furthermore, IDA developed their own scenarios for the development of the energy system with the aim of making an alternative for the reference scenario minimising the greenhouse emission while maintaining socio economic feasibility.

This makes the reference scenario for 2030 very interesting to investigate as well as alternatives like the IDA 2030 scenario.

Research Question 2

The electricity market is an important political tool that can be used to shape the development of the energy system. The liberalisation in the electricity market have led to a design meant to foster efficient generation, but which drives down prices as more renewable energy is integrated in the market. This is seemingly in contrast with electricity price forecasts made by e.g. the DEA. This makes in interesting to investigate:

How is the electricity prices expected to develop under the current market conditions and how does the market dynamics create incentives for development of the energy system?

In order to answer this research question, the following sub-questions must be addressed:

- How is the current electricity market designed?
- How can the market be modelled in order to make a forecast for the electricity prices based on a technical model of the reference system?
- How will the prices react under other scenarios than the reference scenario?
- What market dynamics affect the prices and incentives for investors?

Limitations

The aim of this project is to investigate the dynamics of the future of the electricity market under the current market conditions and use this as a foundation for discussing possible consequences linked to this design. Therefore the aim is not to make the most realistic or precise forecast on the electricity prices and to use this as the basis for decision making in navigating in the market, but rather to inform and point out dynamics so that the consequences of market designs are visible.

The project will only operate with the day-ahead market, and revenues gained from balancing markets or long term contracts are not included in this project.

The developed model for electricity prices uses technical energy systems as input, since the aim of the project is to investigate market dynamics, and not to model energy systems. The technical systems are from [Mathiesen et al., 2009a].

Outline of the Project

Based on the problem analysis, the theoretical framework of the project is presented in Chapter 3 where the approach and the world view is displayed while the theoretical foundation of the market design is presented. This forms the basis for Chapter 4 where the developed model is presented. Here the methods used for developing the model are presented together with the key assumptions and functions of the model. The generated results from the model is presented in Chapter 5 where the forecasted electricity prices will be presented based on a technical energy system of the 2030 reference scenario. A scenario analysis will then be carried out in Chapter 6 which investigates the market dynamics. These dynamics and results will then be discussed in Chapter 7 and put into relation to the development of the energy system. The project will be concluded with a discussion of the methods, a conclusion and proposes for further studies.

Theoretical Framework 3

The purpose of this chapter is to present the foundation for the analysis made in the report; the theoretical framework. This framework is presented in order to give the reader an understanding of the rationality and logic which lies behind this project. First the electricity market in a political context will be presented. This will be used to present a delimitation of the focal points of the project. Then the current electricity market design will be elaborated and the methods of calculation will be discussed.

3.1 Electricity Markets and Its Role in the Energy System

The electricity market is throughout this projects seen as a political tool that can be used to achieve certain goals. The market should not be legitimised in it self through either strict or lose regulation and its monopolistic or competitive nature, but rather by its ability to assist in the achievement of societal goals in an effective manner.

3.1.1 Political Context

The foundation of the theoretical framework used in this project is the description of the innovative democracy presented by Hvelplund which is presented in Figure 3.1. From the Figure it can be seen that the policy makers can change the ways markets function, through different political initiatives, in order to fulfil certain goals of society.

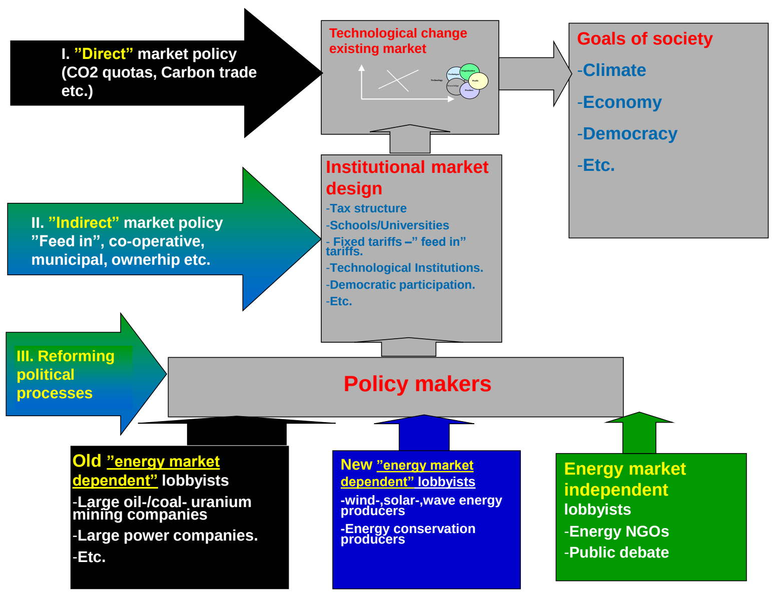

Figure 3.1. Overview of the innovative democracy. [Hvelplund, 2016]

In the top of the figure is the market, which in this case would be the electricity market. This market is affected and shaped political through either direct or indirect measures. One of the direct measures is the CO_2 quota system in EU. Here the externalities from CO_2 emissions are internalised and the price is set on a market [European Commission, 2017].

Besides the direct measures affecting the market, there is some indirect measures affecting the market which is defined by the market rules such as taxes, tariffs and rules for participation. It is harder to predict the impact in the market from these indirect measures since it might have unpredictable consequences when altering the institutional market design. Different technologies have different characteristics when it comes to factors like predictability, controllability and flexibility which affect their room to manoeuvre in the market. This is underlined by Keay [2013] where it is stated that:

> *Markets are not technology-neutral; such apparently arbitrary factors such as the timescales chosen, the balancing requirements an so on can have a big effect on the potential for access by different technologies.* [Keay, 2013, p. 8]

As seen in the lower end of Figure 3.1 it is the policy makers which shapes the institutional market design through reforms and legislation. This process is affected by stakeholders wanting to either change or maintain characteristics of the current market design. The market dependent stakeholders are represented and counts both the ones dependent on the old, fossil fuelled energy market and the new renewable energy market and these are often represented through trade organisations or if big enough, they navigate the political arena individually. Furthermore there is the market independent stakeholders like NGOs or other civil society organisations. These organisations might have more difficulty in mobilising and competing with the market dependent actors [Saurugger, 2008].

All of this discussed above is part of shaping and forming the markets so that market participants act in specific ways. These actions take part in forming society, why it is important in the whole of this process to keep the goals of society, displayed in the upper right corner of Figure 3.1, in mind. The actions taken on the market will have effect on aspects like the climate and the economy, and there might be barriers in the market that hinders some actors in participating.

3.1.2 Market Delimitations

This project focuses on the electricity market and forecasting the price under the current market conditions. Therefore a lot of the surrounding aspects and foundation for the market is not discussed in order to maintain a focused scope of the project. While Figure 3.1 presents the foundation for the market and the political landscape around it, Figure 3.2 has zoomed in on the essential parts for this investigation which is the current market design and its internal dynamics.

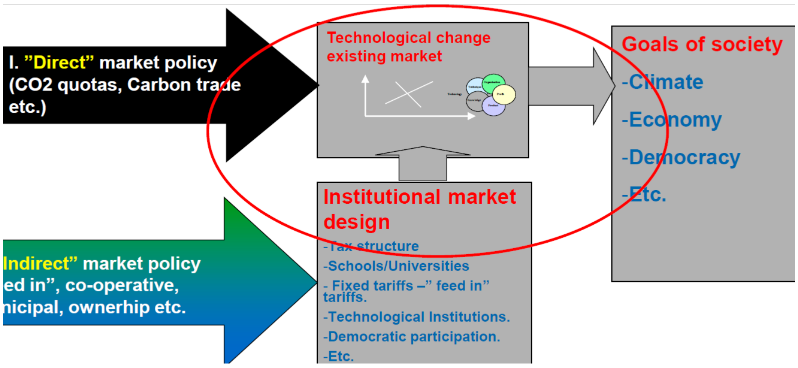

Figure 3.2. Focus area for this project.

It is seen that the market is in the focus of the project where it is modelled and used as the foundation as forecasting the electricity prices. Besides this, the near surroundings are also included, in order to maintain the link with the political aspects and the impact on society. This will make ground for the investigation of the dynamics of the market design and how it affects the development of the energy system. In order to so, the current electricity market conditions and dynamics needs to be investigated.

3.2 Market Design

In order to understand the market dynamics it is important to investigate the market design and elaborate on the fundamentals presented in Chapter 1. The wholesale market introduced in Section 1.2 will be the focus point of the project. Besides the electricity traded on the wholesale market, or day-ahead market, as it is also called, generators and users can make bilateral contracts on the forward market months or years in advance. [Energinet, 2017]

3.2.1 Market and System Operation

As presented in Section 1.2.1 this market design respects all offers and the willingness to sell and buy electricity as the price is set so that no generators get paid less that their offer and no buyer have to pay more than their offer [Kirschen and Strbac, 2004]. At the Nordpool sport market, this calculation is done on an hourly basis with the electrical energy measured in MWh as the commodity. [Energinet, 2017]

All offers for generation and consumption must be handed over to Nordpool no later than 12:00 on the day before generation. The offers can be on an hourly basis or in blocks of at least three hours. The possibility of making block offers is very beneficial for power plants with high start-up costs, which is typical for large thermal units like centralised coal fired combined heat and power plants [Energinet, 2017]. When Nordpool receives the offers, they make the market clearing, forms the price in all hours in the forthcoming day and schedules generators and consumers throughout the day. This is displayed in Figure 3.3 as the day-ahead block. Besides bidding energy on the day ahead market, generators and consumers can also make bids for balancing on the intra-day market. Bids for balancing reflects that the generator or consumer have capacity to either introduce or remove energy from the market at a certain price if called upon. [Pinson, 2017]

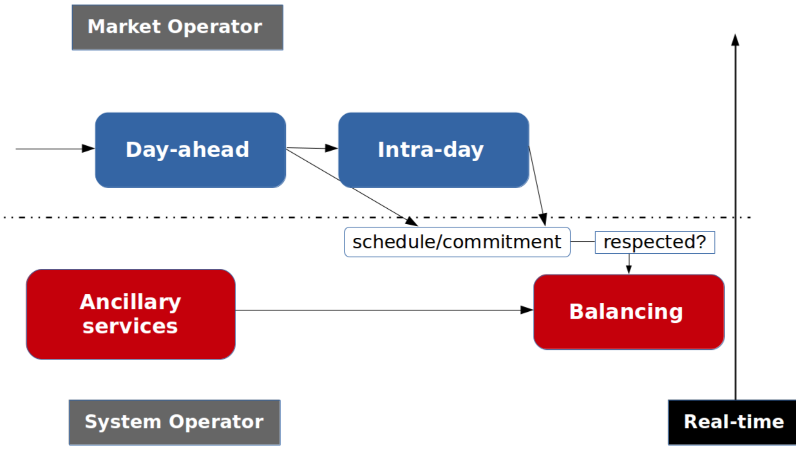

Figure 3.3. Operation of the electricity market. [Pinson, 2017]

When the day ahead market is cleared and the generators are scheduled for the forthcoming day, the system ought to be in balance with generation and consumption levelling out. If this is not the case, the responsibility for balancing the grid is handled by the Transmission System Operator, Energinet, who can utilise either ancillary services or the balancing market to level generation and consumption.

This mismatch between scheduled and actual market conditions can to some extend be caused by the difficulty of forecasting demands, but is to a large extend caused by the high generation from renewables, which is also very hard to predict accurately. Even small changes in wind patters over Denmark, can have a large impact on the generated electricity from wind turbines. [Morales et al., 2014]

It should be noted that the market operator Nordpool is responsible for the market clearing and scheduling, while the TSO is responsible for the more technical aspect of the operation, matching generation and consumption. This is indicated in Figure 3.3 by the broken line between the blue market operation and the red transmission system operation.

The topic of intra day and balancing markets is out of the scope of this project and only the day ahead market will be analysed. This is chosen because the majority of the electricity is traded on the day ahead market making setting both prices and quantities to be traded.

3.2.2 The Day-ahead Market

As introduced in Section 1.2.1 the Danish wholesale electricity market is operated by Nordpool as a energy only market with uniform price formation as displayed in Figure 3.4 where the price formation is shown.

The day ahead market is what can be defined as an energy only market, where electricity is traded as the commodity at the basis of MWh of electrical energy.

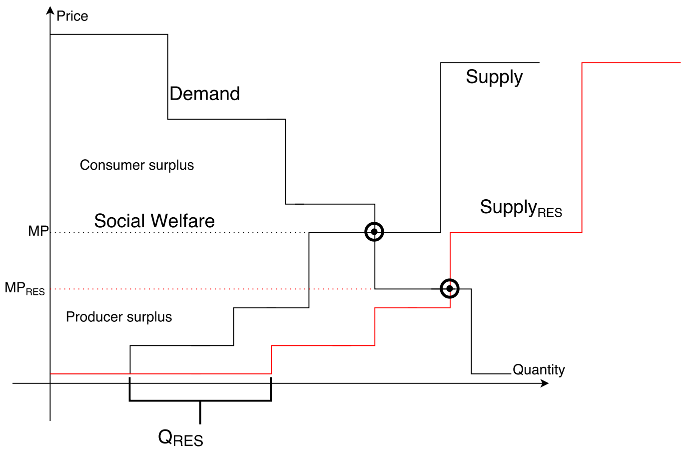

Figure 3.4. Price formation on the day ahead market - red line with additional renewable energy.

3.2.3 Market Zones and Interconnectivity

The electricity market is fundamentally different from most other markets in the sense that transmission and distribution is physically limited in cables. If power could flow freely without any limitations, which could be envisaged by a thick copper plate covering the entire earth, there would not be any limitations to the power flow, and no congestions would occur and a world wide electricity market with one price formation could be possible. This is of cause not feasible, and there will inevitably be limitations to the flow of electricity. [Energinet, 2017]

These limitation is reflected in the market by market coupling where the electricity market is divided into different price zones. Optimally, the formation of the zones would be based on where congestions happen, but there could be political influence in zonal formation in the electricity market. All the zones in the Nordpool area is seen in Figure 3.5, where it is noted that Denmark is split into two zones, DK1 west of Storebælt and DK2 east of Storebælt.

Figure 3.5. The bidding areas in the Nordpool spot market. [Nordpool, 2017]

The zones are key in determining the price in the electricity market. If no congestion occurs anywhere between the zones, they are treated as one big market and a uniform price for the whole market is set. This is very unlikely to happen since the interconnections between the zones are limited, and in practice different prices are often formed. The general rule of the zonal market is that electricity should flow from the low price to the high price zone, and thereby the most of the electricity will be produces in the most cost-effective manner. When trading in between zones and different prices occur, the TSOs in the respective zones collect congestion rent equal to the price difference multiplied by the transmitted electrical energy. [Energinet, 2017]

The European Union does as a part of the Energy Union have an interconnection target of 15% by 2030 [European Commission, 2015a]. This goal have been reached for a long time in Denmark, and in 2014, the interconnection capacity was calculated to 44%, which is expected to increase in the future as new cables will be implemented. [European Commission, 2015b]

The impact of interconnections to neighbouring zones is difficult to estimate. In order to get full insight, the entire neighbouring electricity market must be modelled when modelling the targeted market. For example, modelling the Danish market therefore requires information about e.g. the German market. This principle can be expanded, and it can be argued that the German model will be incomplete without including its neighbouring markets. The impact on the Danish market will decrease the further away the zones are. In the end, an exact model of the Danish market would require full insight in all the electricity markets in the region. In this project it is chosen not to include the interconnections to other markets.

3.2.4 Resource Adequacy

There are many concerns regarding resource adequacy in the energy only market. This is due to the fact that if generators bid with their short run marginal cost, they will only make contribution margin if there is a generator with a higher bid who gets cleared. Since it often changes who is the marginal generator from hour to hour, this will for most generators not be a significant problem. But for the generators at the higher end of the supply curve, there is a big chance that if they get cleared, they are either are or are close to being the marginal producer leaving only a small contribution margin. Therefore higher prices are needed if these producers should generate enough income to make their operation feasible on the long term. [Hogan, 2005]

In some markets the electricity prices are capped at certain levels, which introduces the missing money problem as displayed in Figure 3.6. Here it is seen that if the price is capped there is certain hours where the peak generators, A, will not receive high enough income to generate a significant contribution margin. [Hogan, 2005]

The approach to the missing money problem, is to remove price caps so that prices will increase to reflect scarcity. If there is not enough generation capacity to cover the demand, load shedding must take place in order to balance the system and the price will increase to the value of lost load, voll. The voll is a way of putting monetary measures on the access to electricity, and it is typically set quite high. It is estimated that the voll in

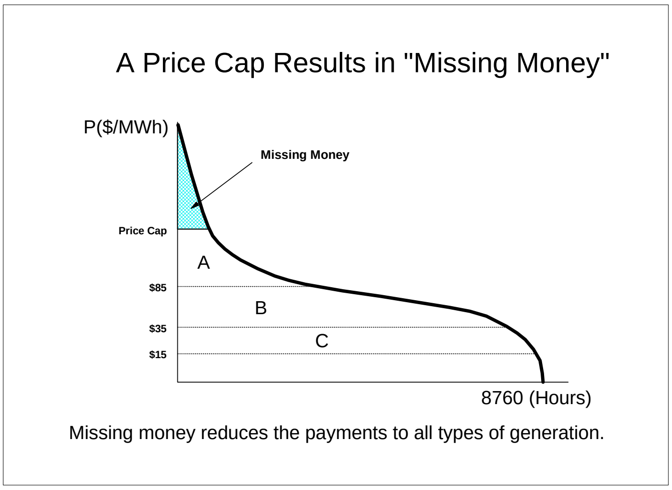

Figure 3.6. The missing money problem under price caps. [Hogan, 2005]

Denmark is between 2,933 €/MWh and 36,800 €/MWh [European Commission, 2016d]. At the Nordpool day ahead market the bidding limits are between -500 €/MWh to 3,000 €/MWh. [Energinet, 2017]

In the proposal for the European regulation "on the internal market for electricity" it is in article 9. 1. proposed that: *There shall be no maximum limit of the wholesale electricity price unless it is set at the value of lost load...* [European Commission, 2016c, p. 43].

Another way to tackle the missing money problem is to make it possible for consumers to put their own price on their willingness to pay for electricity individually. This approach might be able to flatten out the demand curve enough, so that the supply and demand curves will always be able to intersect. [Hogan, 2005]

On an European level, a lot is done as a part of the current development of the Energy Union to introduce a bigger extend of demand response and engaging consumers more on the electricity market. [European Commission, 2015a]

These somewhat theoretical issues of resource adequacy are very important to address because it is here that the price can vary extensively affecting the feasibility of generators. Removing price caps and accepting highly volatile prices and load shedding in order to address the missing money problem will most likely be a politically unpopular decision. On the other hand if consumers themselves value the access to electricity through demand response, it could be argued from a market point of view, that every need will be satisfied. This option might imply that low income households will have a lower willingness to pay, and thereby be left without electricity in more hours than the ones more willing to pay - what is described as energy poverty. [Hogan, 2005]

Both of these methods seems in contrast to the role that electricity has in modern society. Here electricity is a part of the societal infrastructure, and is needed to maintain peoples way of life. In the core of the energy only market design, is the argument market that decides the security of supply and through investments and operation in generation, it is decided how many hours the full demand will not be met, and load shedding will occur. In the Strategy Plan of 2014, Energinet, commits to ensuring a high level of security of supply [Energinet, 2015]. This might seem impossible when it is decided on the market if there is adequate capacity, but that depends on the definition of the therm security of supply. If security of supply is defined as access to the service that you are willing to pay for, then there will not be any conflict, because the consumers have stated their willingness through their bids.

A way of ensuring electricity could be to have a strategic reserve that could supply electricity in time of load shedding. This strategic reserve should not be allowed to participate in the market and thereby driving down prices to below the voll. [Hogan, 2005]

Another approach is to introduce capacity markets in order to make a payment for available capacity, so that it can be controlled that enough capacity is available in the system to cover expected demands. This approach is accepted by, but limited in the aforementioned proposal for regulations on the internal market for electricity by European Commission.

The model made in this project will be based on the current market design, and the reflections on the dynamics on this design will be discussed further in Chapter 7.

Model 4

The purpose of this chapter is to describe the developed model used to forecast the electricity prices. First it will be described how forecasts for the electricity prices are made in general describing first the method used by the DEA and the procedure build in to EnergyPLAN. Then the theory and calculations behind the constructed model will be presented which will use technical models of energy systems from EnergyPLAN as input for the calculation. Finally the model will be tested on a 2015 scenario in order to validate the calculations.

4.1 Methods in Ramses and EnergyPLAN

Since one of the aims of this project is to compare the prices calculated in this model to the ones developed by the DEA, it is interesting to investigate the approach used by the DEA. This will be based mostly on the newly developed basis forecast made in march 2017, [Energistyrelsen, 2017a], where the forecast of electricity prices is elaborated.

It should be noted that neither Ramses, nor EnergyPLAN are optimisation tools, but rather simulation tools for simulating energy systems.

4.1.1 Ramses

The models used by the DEA is developed in a program called Ramses which is a simulation tool for heat and electricity systems [Connolly et al., 2009]. Ramses is used for all baseline models of the Danish and Nordic energy system made by the DEA and have been used throughout the years since the 1990s [Connolly et al., 2009]. The model is based on Microsoft Excel and VBA codes and it makes calculations for electricity and heat on an hourly basis throughout a year based on technical input for demands and power plants. [Energistyrelsen, 2015b] The electricity prices in this model is calculated through estimates of the bid price of electricity production for each type of plant using equation 4.1. [Energistyrelsen, 2015a]

$$\begin{aligned} BidPrice = & \frac{P_{fuel}}{\eta} + \frac{P_{CO_2} \cdot E_{CO_2}}{\eta} + \frac{P_{SO_2} \cdot E_{SO_2}}{\eta} + \frac{P_{NO_x} \cdot E_{NO_x}}{\eta} \\ & + O\&M_{var} - P_{th} \cdot Q_{th} + Tax - Subsidy \end{aligned} \tag{4.1}$$

Where η is the electric efficiency of the plant, P is the price for fuel or tax, E is the net emission of gasses, and Q is the energy quantity.

With the assumptions for future efficiencies, prices and capacities for the Nordic system, Ramses uses this information for simulating the energy system and calculating electricity prices.

Since Ramses is developed for use by the DEA, and it is not public and requires training to use [Connolly et al., 2009][Energistyrelsen, 2015b], another tool must be used for modelling the electricity prices.

4.1.2 EnergyPLAN

Another tool for calculating electricity prices is EnergyPLAN. EnergyPLAN is developed at Aalborg University with the aim of simulating energy systems on an aggregated level throughout a year. This means that individual production and consumption patterns is aggregated into a less detailed model of the system. The reason for this is that the loss in detail is compensated by the speed of the model and the insecurity is inevitable anyway when simulating future energy systems. [Connolly et al., 2009] [energyplan.eu, 2017]

In EnergyPLAN the market electricity price is calculated by simulating trade and exchange on the international electricity market like Nordpool. This market analysis focuses only on minimising the short term cost for electricity consumers. [Lund, 2015] When interacting with neighbouring markets, EnergyPLAN uses the price in neighbouring markets as input for the model.

These neighbouring prices are determined using an hourly distribution of electricity prices. Here historical electricity prices are often used. These prices are then modified by multiplying with a *multiplication factor* and adding a number, an *addition factor*. In order to take into account the dynamics of trading with external electricity markets a price elasticity is set at a certain price.

This makes prices somewhat pre-determined since the assumptions of prices in neighbouring markets can have a huge impact on the price in the simulated energy system if interconnection capacity is high enough. Therefore, if EnergyPLAN is used to simulate future electricity prices, the results will be highly affected by assumptions of prices, and it is therefore very difficult to make an unbiased estimate of the future electricity prices in a technical energy system.

4.2 Model Design

Due to the unavailability of Ramses and the unwanted characteristics of EnergyPLAN a model is developed as an alternative to the two. The foundation of the model must be that it must be able to clear the market on an hourly basis throughout a year being provided with technical characteristics of the electricity system. Because the input is technical characteristics, the model must itself be able to translate that into bids for each technology of electricity production before clearing the market.

It is chosen to use the software MATLAB for constructing the model. This is chosen due to its ability to calculate with big matrices making it ideal for the large dataset that an hourly model represents when simulating a whole year.

The model uses technical input from existing EnergyPLAN models of the Danish energy system. This is chosen since the aim of the project is to estimate the electricity prices and not develop the technical specifications of the energy system. Therefore the model will share the aggregated nature of a model developed in EnergyPLAN and not be specific down to the detailed level of every individual power plant. This introduces some uncertainty to the electricity prices, but this is assumed not to affect the overall level of the electricity prices.

4.2.1 Solving Strategy

As described in Section 3.2, the aim of the wholesale market is to promote the most cost-effective generation. This is done by aligning the bids from the power producing units in acceding order to form the supply curve. Thereafter the intersection with the demand curve is found. The electricity demand is often assumed to be inflexible. When clearing the electricity market and solving for the price, the aim is to maximise social welfare. This can be represented as the area between the demand and supply curve. This approach corresponds to minimising the area under the supply curve as illustrated in Figure 4.1.

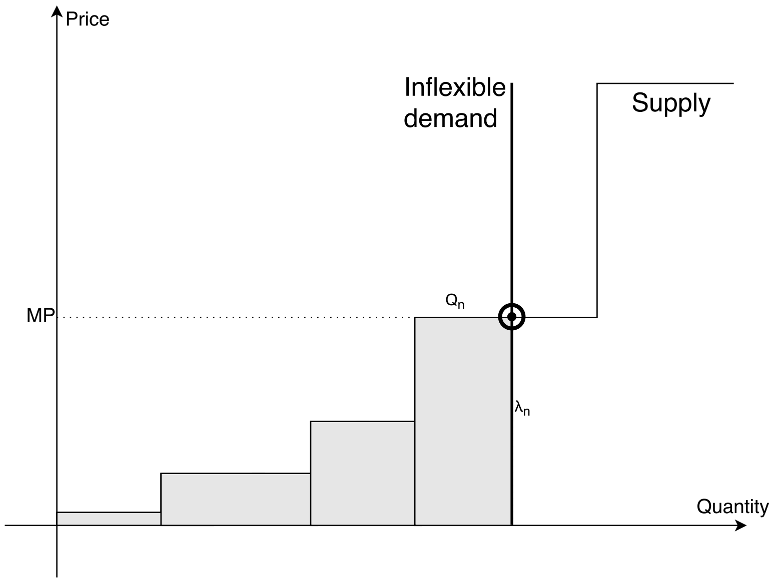

Figure 4.1. Strategy for clearing the electricity market in the model.

Where λ is the bidding price and Q is the offered quantity on the market. The minimisation of the grey are is done through linear programming in MATLAB as expressed in equation 4.2 where i is the indicator for each generator.

$$\min_{Q} \sum_{i=1}^{n} \lambda_i \cdot Q_i \tag{4.2}$$

When solving this linear program, all the generating units are gathered in vectors presenting the total generation. This makes it unnecessary to perform the sorting of price mentioned in relation to Figure 4.1, because the program will determine the optimum generation only on basis of the quantity and price offered.

The linear program is bound by an inequality constraint that limits the Q from exceeding the capacity of the technology, Q_{bid}, as presented in equation 4.3.

$$A \cdot Q \leq Q_{bid} \tag{4.3}$$

Here A is an unity matrix, Q is the generation of power on each type of technology, and Q_{bid} is the capacity of that technology.

Because the demand is considered inflexible, the desired demand must be fulfilled by all the generated electricity. This linear constraint can be expressed as seen in equation 4.4.

$$Demand = \sum_{i=1}^{n} Q_i \tag{4.4}$$

These three equations, 4.2, 4.3 and 4.4 are used in the linprog command solving the linear program which is executed for every hour throughout the year, and thereby clearing the electricity market. In order to do the market clearing, the model must be able to use input from EnergyPLAN to construct the bids for capacity and price for different technologies.

4.2.2 Model Inputs

The inputs for the model is the same technical data used as input for modelling systems in EnergyPLAN. From this file, capacities are read for different types of power generating capacities. This is for example the capacities for CHPs and condensing power plants as well as their efficiencies. Furthermore the type of fuel used by the power plants are read. This information is used to specify the technology type. For example when a CHP plant runs on coal, it is assumed to be a power plant with a coal fired boiler using a rankine cycle for electricity and heat production. When on the other hand a CHP runs on natural gas, it is assumed to be a gas turbine. This interpretation of the input and technology specification is important when calculating the bidding prices.

Besides of the input also used for the technical EnergyPLAN models, the model uses some of the output from a run of the EnergyPLAN model. This is for things like the electricity demand and the generation of electricity from renewable sources.

The electricity demand is in EnergyPLAN interpreted as a total annual demand, which is divided out onto a year using a distribution file for the demand. This spreads out the annual demand and gives hourly data which can be used in the model. Besides conventional electricity demand, e.g. the electricity used in households or industry, the model also takes into account any electricity which might be used in electric vehicles, heat pumps, electric boilers or the like. These demands are also gathered on an hourly basis and added to the conventional electricity demand, to give a total electricity demand which have to be covered in every hour. This might deviate from a real life scenario where these types of demand might become very dependent on the electricity price, where for example an electric vehicle could be set to charge at low electricity prices only. This effect of an elastic demand is not incorporated in the model, and the total demand is considered inelastic.

4.2.3 Bidding Prices

In order to use the technical inputs from the model to create bids in the market, the technical properties of the various power plants must be translated into a bidding prices. This price formation is done in a somewhat similar way as done by the DEA using equation 4.1 [Energistyrelsen, 2015a]. This equation is modified so that it fits the goal of the model and it can be seen in equation 4.5.

$$BidPrice = \frac{P_{fuel}}{\eta} + \frac{P_{CO_2} \cdot E_{CO_2}}{\eta} + \frac{P_{SO_2} \cdot E_{SO_2}}{\eta} + \frac{P_{NO_x} \cdot E_{NO_x}}{\eta} + O\&M_{var} - P_{th} \cdot Q_{th} \tag{4.5}$$

Compared to equation 4.1, the taxes and subsidies have been removed in equation 4.5. The taxes have been removed since commodities used solely for electricity production are not taxed [Skat, 2017]. Therefore the fuel taxes that are otherwise existing for various fuel types for energy purposes are not included in the mode. This might be an over simplification, since fuels used for heat can be taxed. This is not investigated, and it is out of the scope of this project. Furthermore the subsidies are removed as this is also the procedure in Energistyrelsen [2017a] where subsidies after 2018 and 2023 are excluded from their models.

All the prices P are determined using the DEA forecasts which is build upon data from the world energy outlook made by the international energy agency. Table 4.1 shows the fuel and emission prices used in the model and the assumptions behind them.

Fuel / Emisison	**Tax**
Coal	68.04 kr/MWh
Oil	376.38 kr/MWh
Natural Gas	131.76 kr/MWh
Biomass	189 kr/MWh
CO2	75.5 kr/ton
Sulphur	23.3 kr/kg
NOx	5.1 kr/kg

Table 4.1. Fuel prices and assumptions are based on [Energistyrelsen, 2017b] and emission prices are from [PricewaterhouseCoopers, 2016].

For the oil, the price is assumed to be the average between fuel and gas oil. For the biomass it is assumed that the total biomass consumption consists of 37% wood chips 37,% pills and 24% straw, which is the average distribution of use in the years 2010 through 2015 [Energinet, 2016a].

The information obtained from EnergyPLAN is the generation capacities, together with the fuel distribution of electricity produced via this type of unit as in Figures 4.2 and 4.3. This must be translated into actual power plants in order to make estimates on the emission levels, E, and the variable O&M costs which both are variables that are found in the technology catalogues, [Energistyrelsen, 2012b] and [Energistyrelsen, 2016].

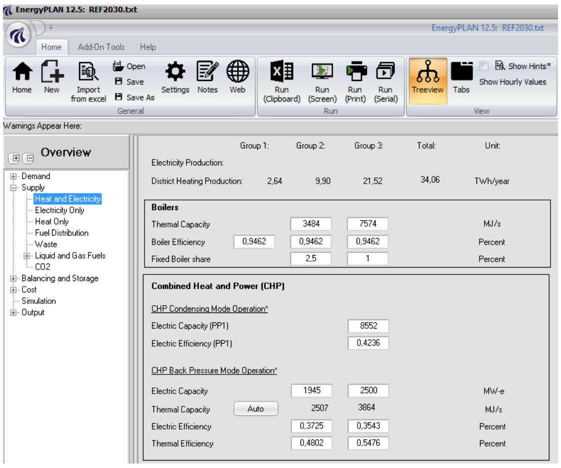

Figure 4.2. Controllable generation units.

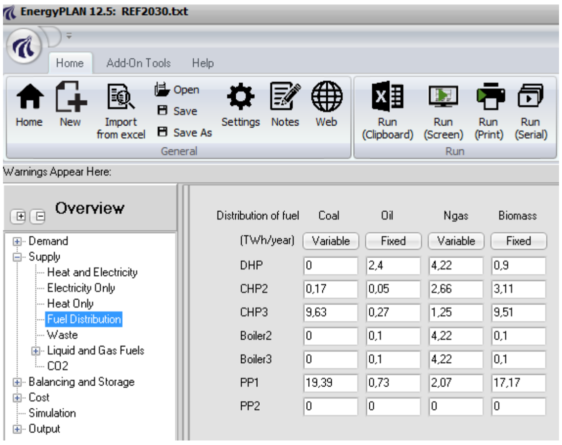

Figure 4.3. Fuel distribution.

The capacities indicated in Figure 4.2 are distributed on basis on the fuel distribution indicated in Figure 4.3 in order to determine the capacity of each technology. This is used to find a suitable comparison in the technology catalogue for information of the O&M.

It is assumed that all the coal fired power plants, no mater if they are CHPs or condensing power plants are fired with pulverised fuel in a boiler driving a ranking cycle. A similar assumption is made about the biomass fuelled power plants. The natural gas fired power plants are assumed to be gas turbines and the ones running on oil are assumed to be engines. Since no oil engines were present in the technology catalogue, the values for a natural gas fired engine is used.

It is estimated that the largest uncertainty in the assumptions is for the oil fired power plants, modelled as engines. In real life oil is used for start up in power plants, and it is uncertain if the oil used for that purpose or in their own power plant when extracting data from EnergyPLAN. The effects of the uncertainty in the use of oil is estimated not to have a large impact, since the oil consumption is very small compared to the other fuels.

The emission data, E, used in equation 4.5, for the power plants are derived form the technology catalogue based on the assumption of generation technology, and can be seen in Table 4.2.

	NOx	**CO_2-content**	**Sulphur**
Coal	0.126 kg/MWh	342 kg/MWh	0.029 kg/MWh
Oil	0.216 kg/MWh	266 kg/MWh	-
Natural Gas	0.036 kg/MWh	205 kg/MWh	-
Biomass	0.292 kg/MWh	-	-

Table 4.2. Emissions from the power plants [Energistyrelsen, 2012b] and [Energistyrelsen, 2016]. Sulfur value is after 97% desulphurisation.

For the CHP plants that also produce heat the income from heat generation must be taken into account. Heat prices for the suppliers to district heating networks are not publicly available. It is in this project assumed that the income from heat sales corresponds to the price of the energy content of the fuel. E.g. for smaller power plants it it takes 2.68 MWh of fuel to produce 1 MWh of electricity and 1.29 MWh of heat meaning that the CHP will generate income from the 1.29 MWh of heat and thereby reducing the bidding price. This is modelled by reducing the bid price for electricity with the price of 1.29 MWh of fuel.

In real life there are more costs associated to the generation of heat like the cost of heat exchangers and pumps to drive the cooling and taxes associated to heat production. This is not included in this project as it is assumed that these costs will be forwarded to the heat consumers, and not the electricity prices.

4.2.4 Output

When the model have imported the input as described in section 4.2.2 and set the prices and the quantities for the bids as described in section 4.2.3 it solves the electricity market for every hour throughout the year as described in section 4.2.1.

An example of the calculated bids for electricity produced by a condensing power plant is presented in Figures 4.4 through 4.7.

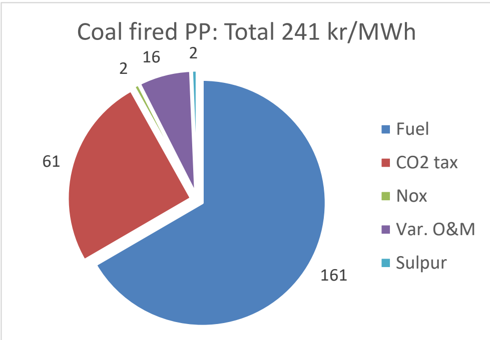

Figure 4.4. Bid price formation for a coal fired power plant.

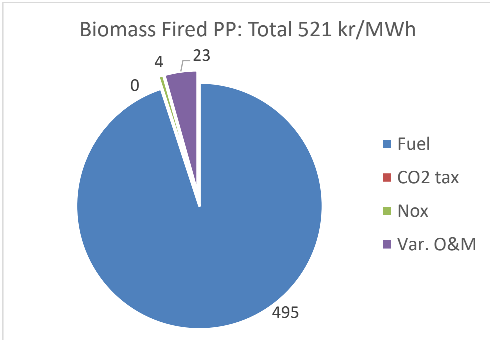

Figure 4.5. Bid price formation for a biomass fired power plant.

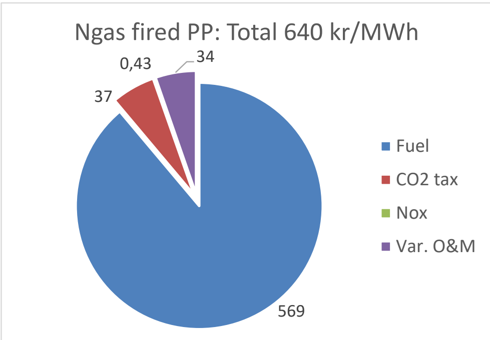

Figure 4.6. Bid price formation for a gas fired power plant.

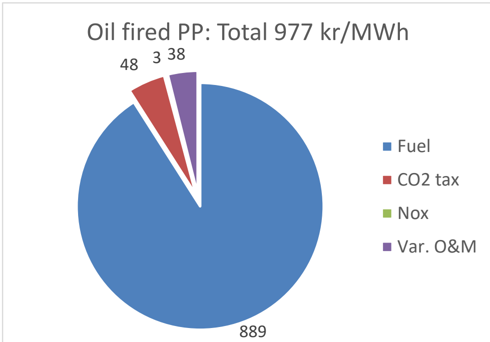

Figure 4.7. Bid price formation for an oil fired power plant.

Similarly to the bid formation the bids are formed for CHP plants. The bids for renewable generators are set to 0. The value of lost load is modelled as a generator with the bid of 22,380 kr/MWh which corresponds to the Nordpool maximum of 3,000 €/MWh. The voll will only be scheduled if there is not enough capacity from the power plants, and any generation, can be interpreted as necessary load shedding.

In order to present the output in a more visual way, an hour of the 2030 reference scenario is found as the example for the the model calculations and can be seen in Figure 4.8.

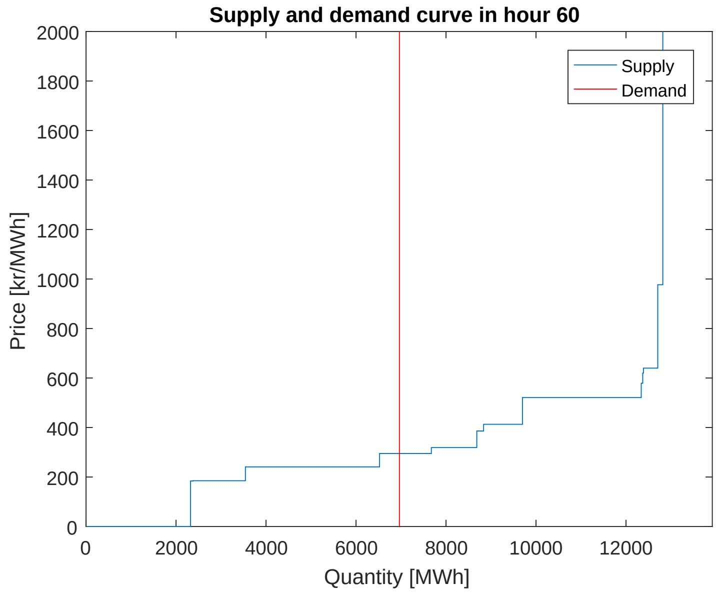

Figure 4.8. Example of market clearing and the supply and demand curve in hour 60 in the 2030 reference system.

In this hour the demand was 6,964 MWh and the price is cleared at 294 kr/MWh, corresponding to the price of the large biomass CHP plant, which is the marginal producer in this hour. A complete list of the producing technologies, capacities and prices can be seen in Table 4.3.

Generator	**Capacity [MW]**	**Bidprice [kr/MWh]**
Onshore wind	2350	0
Offshore wind	1239	0
PV	0	0
Wave	0	0
CSHP (waste)	543	0
Small CHP - Coal	55	184
Large CHP - Coal	1164	185
Large PP - Coal	2981	241
Large CHP - Biomass	1151	295
Small CHP - Biomass	1010	319
Large CHP - N.Gas	151	387
Small CHP - N.Gas	864	413
Large PP - Biomass	2640	521
Large CHP - Oil	33	579
Small CHP - Oil	16	620
Large PP - N.Gas	318	640
Large PP - Oil	112	977
VOLL	-	22,380

Table 4.3. List of all modelled generators, capacities and bids in the 2030 scenario.

The generator, CSHP, is used to describe the waste incinerations. They are assumed to bid in with 0 kr/MWh since one of their main objectives is remove waste. This might deviate from real bids from waste incineration facilities. Furthermore it can be seen that all the capacities from the oil fired plants are very low compared to the other technologies. This indicates that the oil might not be used as primary fuel in dedicated oil fired power plants, but instead used in the start-up process of the coal or biomass fired power plants. This is not included in the model where it is assumed that the generators running on oil are actually oil generators, which might cause some uncertainties.

When repeating this procedure throughout every hour of the year, the production from the renewable sources vary which translate the supply curve right or left depending on the renewable production. This is the merit order effect which was presented in Chapter 1 on page 4 in Figure 1.4. Besides the varying renewable production, the demand changes throughout the year creating a new interception between the supply and demand curve for every hour.

The electricity prices and the cleared generation on each type of plant is after solving throughout the hour saved in an excel file for later analysis.

4.3 Validation

After the model was constructed, a test run of a 2015 system was made in order to evaluate the validity of the model output.

With the models developed in the IDA climate plan there were also an EnergyPLAN model the reference system in 2015 [Mathiesen et al., 2009b]. This 2015 model forms the basis of the validation of the model since the modelled results of 2015 can be compared to the real electricity prices which formed in the year.

The input for the model was modified to the input files for the 2015 reference system and the output price was an average of 178.3 kr/MWh compared to 175.4 kr/MWh in 2015. This data from the model run is presented in Table 4.3.

	Historical prices	**Modelled Price**
2014	233.0 kr/MWh	
2015	175.4 kr/MWh	178.3 kr/MWh
2016	181.4 kr/MWh	

Table 4.4. Historical prices and modelled price around 2015.

It is seen that the modelled price in 2015 deviates with 1.7% compared to the actual prices in 2015. This result does not make it clear that the model is valid. The prices in the yeas before and after 2015 were higher than in 2015. It is unlikely that major changes have occurred in the energy system in these years and it it seen that the modelled price for 2015 is significantly lower than the prices in 2014, but near the prices in 2016.

The validity of the model is investigated further through the duration curve of the prices as seen in Figure 4.9.

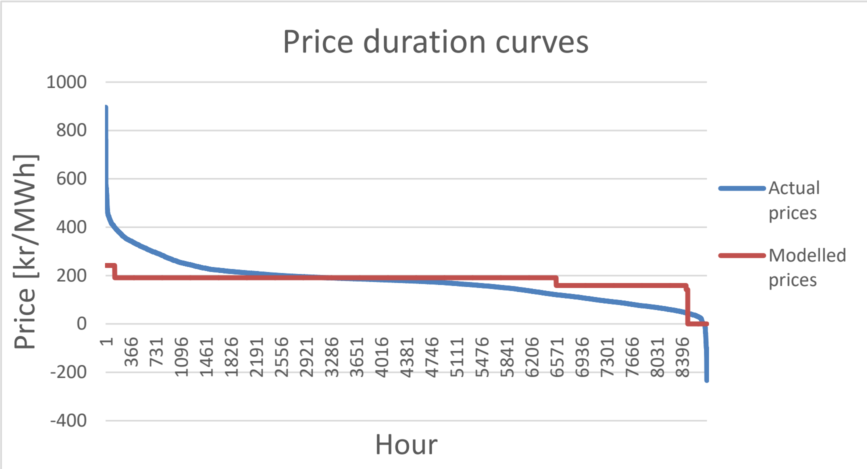

Figure 4.9. Duration curves for the electricity prices in 2015 and the modelled 2015 prices.

From the duration curve of the prices it is seen that the prices in general tend to be in the same range. Due to the slightly different characteristics for different plants, it can be assumed that the real life electricity system have a more smooth supply curve than the one modelled. This makes the prices distribution more smooth as seen in Figure 4.9. Another factor that effects the prices is the trade with other markets through interconnectors which is not included in the model.

The price of electricity produced by the marginal generator is very important, since this is the one setting the price for the system. In most cases there is one or few generators which is the marginal generator in most of the time, and the distribution in Figure 4.9 is a good example of this. Therefore the price formation of this generator is very important in order to model the electricity system. This is affected by factors like the fuel prices, the CO_2-quota prices, the efficiency and the operation costs.

The modelled system might vary from the actual 2015 energy system. First of all the capacities of different technologies might be different in the model compared to the real life energy system. Another uncertainty is the fluctuating variables, like the demand and the electricity from wind generation. 2015 did have exceptionally high wind generation which might have caused the prices to decrease to the level of the model [Ingeniøren, 2016].

In general it is can be seen that the modelled prices are within the same range as the ones from the electricity system.

Results 5

The purpose of this chapter is to present the results of the model developed in Chapter 4 for the 2030 reference scenario. This includes the electricity prices and the scheduled production from the various generators. From these results, it will be analysed which generating technologies are financially feasible, and thereby the incentives send through the electricity market for the development of the energy system.

5.1 Electricity Prices

The modelled system is the reference system for 2030 proposed by DEA and modelled in EnergyPLAN as a part of the development of IDAs climate plan 2050, [Mathiesen et al., 2009b], and are downloaded from the EnergyPLAN webpage, [Mathiesen et al., 2009a]. This is set as the input for the developed model and the electricity prices are calculated throughout the year of 2030 which can be seen in Figure 5.1.

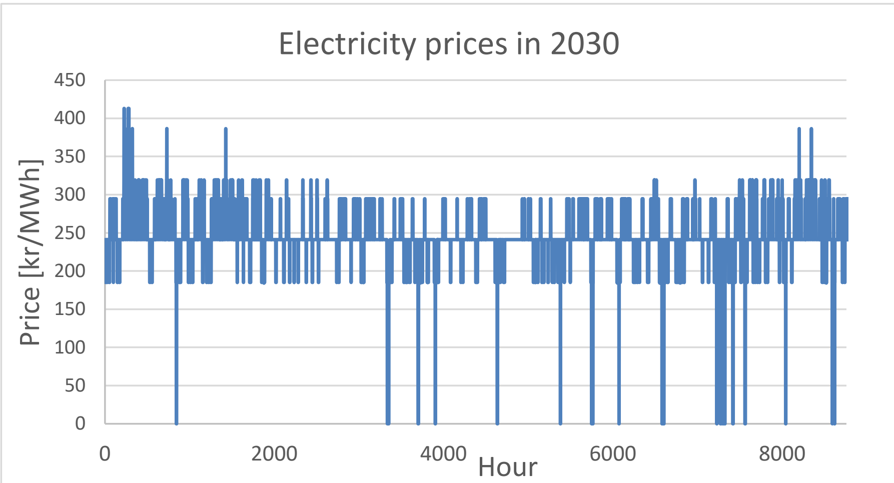

Figure 5.1. Modelled electricity prices throughout 2030.

From Figure 5.1 it is seen that in much of the time the prices is around 240 kr/MWh, but that it varies throughout the year. This indicates that it is often the coal fired power plants that is the marginal producer, with their bid price of 241 kr/MWh. This price is very close to the average price of 249 kr/MWh, meaning that the coal fired power plants must be setting the price in most hours.

The minimum price is 0 kr/MWh, a price that occurs in 96 hours throughout the year. In practice, this means that all the demand is covered by the renewable sources that bid in with 0 kr/MWh. The maximum price, 412 kr/MWh is the price of the small natural gas fired chp plants which is the marginal producer in 10 hours throughout the modelled year.

The different prices is better illustrated when sorted, as seen in Figure 5.2 where the electricity prices are plotted together with their corresponding demands. The demand is plotted as a running average over 30 points in order to get better visual understanding of the correlation.

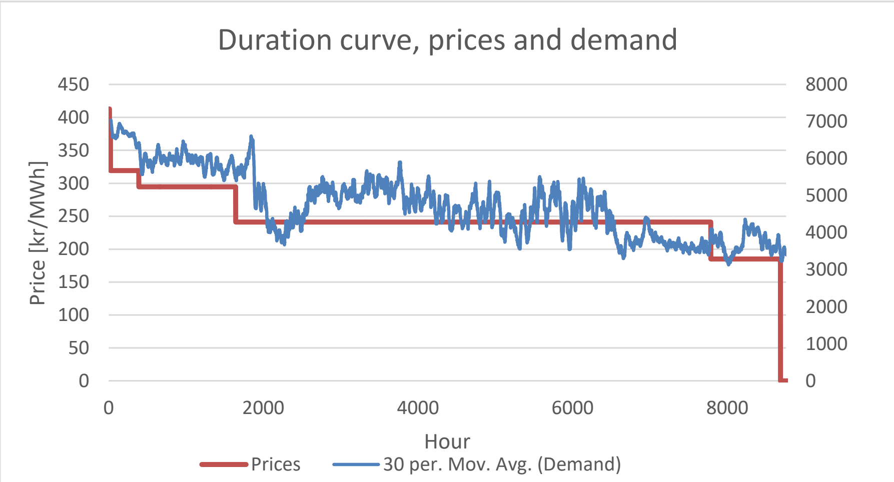

Figure 5.2. Modelled prices sorted and plotted with corresponding demands.

From the Figure it is seen that there is some correlation between the electricity prices and the demand. This effect is a consequence of the market structure and is to some extend as expected. The deviation between the pattern of the demand and the prices is caused by the intermediate generation of renewable electricity from the onshore and offshore wind turbines.

The correlation between demand and prices can be investigated more isolated, where the prices can be plotted as a function of the residual demand, which is defined as the electricity demand minus renewable electricity production. [Wagner, 2012]

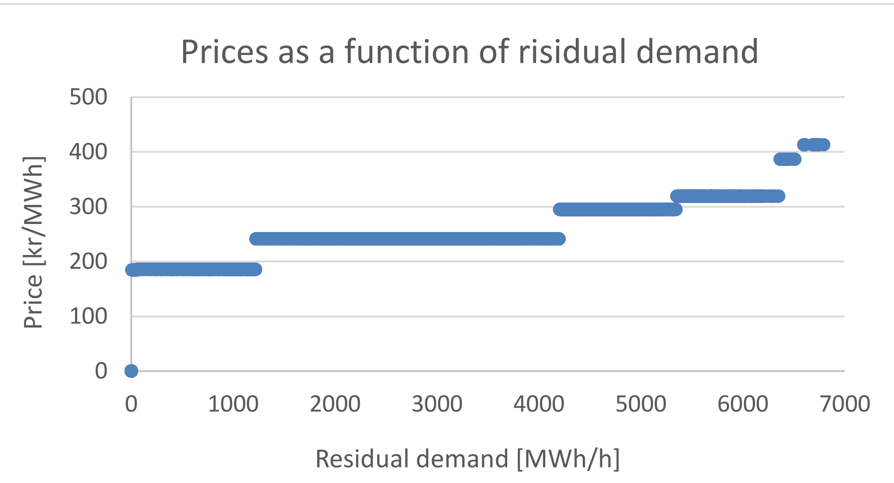

Figure 5.3. Modelled prices as a function of residual demand.

It is seen that when plotting the prices as a function of the residual demand, a step like function occurs which mimics the pattern of the demand curve presented in Figure 4.8 in Page 24.

The effect of the fluctuating wind power production can also be seen when analysing the prices as a function of the wind power penetration as done in Figure 5.4.

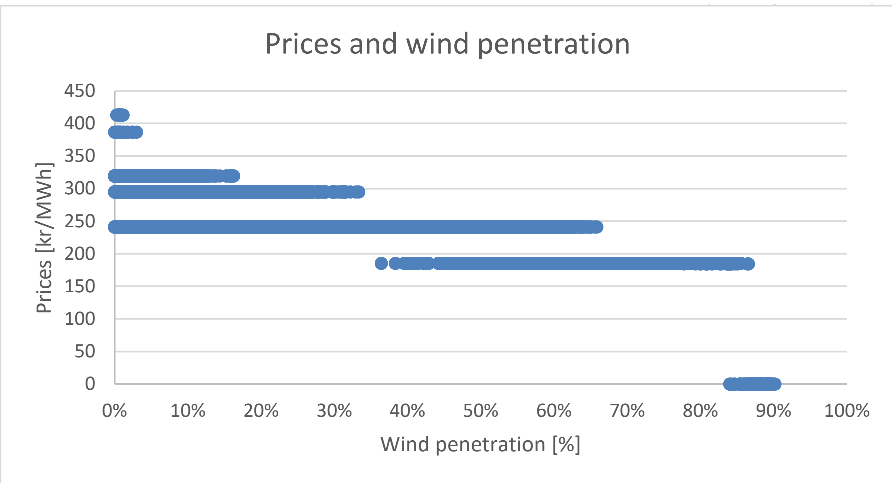

Figure 5.4. Modelled prices as a function of wind power penetration.

As seen in Figure 5.4 as wind penetration increases, there is a trend to decreasing prices. The prices go to 0 kr/MWh at penetrations around 85% which is due to the fact that the CSHP plants also is modelled with a bid price of 0 kr/MWh pushing down the prices at lower penetrations.

From Figure 5.4 it is also seen that it is difficult to evaluate exactly what effect the wind generation have on the electricity prices. The penetration does not give a clear picture of the isolated effect, since there is variations in demand. Another approach could have been to remove the wind generation and investigate the prices, but this would also be a misleading analysis, since the system is developed to include some wind generation, and the capacity margin might be too tight in such an analysis.

5.2 Feasibility of Generators

In order to investigate the feasibility of the generating plants, some financial analysis must be made. Therefore the annual generation and average income is analysed and this is used to establish an income per installed MW per year. Together with data for the expenses for power production the feasibility for the generators is evaluated.

5.2.1 Income for Generators

As stated above, the average modelled electricity price in 2030 is 249 kr/MWh, but this does not correspond to the income generated by various generators. The Annual electricity sales and the average income per MWh is seen in Table 5.1.

Generator	**Annual electricity sales [GWh]**	**Average income [kr/MWh]**
Onshore wind	6,572	227
Offshore wind	4,920	232
CSHP (waste)	4,678	245
Small CHP - Coal	479	247
Large CHP - Coal	9,678	250
Large PP - Coal	14,149	262
Large CHP - Biomass	1,082	307
Small CHP - Biomass	158	331
Large CHP - N.Gas	3	402
Small CHP - N.Gas	18	413

Table 5.1. List of scheduled generators, their annual sales and average income.

Here it is seen that all generators, except the small natural gas fired CHP plants generate an incomme higher than their bid prices, which can be seen in Table 4.3 on Page 24. This is due to the fact that for all generators, except the small natural gas fired CHP plants, there will be hours with generators setting a higher price.

Furthermore it is seen that the difference from bid price to average income is largest for the wind turbines and the CSHP plants who all bid in with 0 kr/MWh. The larger the difference, the larger is the profit margin and therefore it is more likely that the technology is feasible. The difference from the CHSP to the wind turbines are due to their different generation pattern. Furthermore the pattern for onshore and offshore wind vary slightly, and since there is a much larger onshore wind capacity, it is more likely that the prices are pushed down in hours with large onshore generation compared to offshore generation.

The average electricity price paid to the CSHP, of 245 kr/MWh, is very close to the annual average of 249 kr/MWh which is due to the flat production characteristics. The average income is slightly lower due to production curtailment in the hours where wind and CSHP covers all the demand and the price is 0 kr/MWh.

5.2.2 Feasibility of Generation Capacity

In order to evaluate the feasibility, both income and expenses must be known. The income is determined in Table 5.1 and the expenses can be calculated using data, specific for the technology which can be found in the technology catalogues, Energistyrelsen [2012b] and Energistyrelsen [2016].

The expenses are calculated as a combination of multiple variables as seen in equation 5.1.

$$Expeses = Variable\ costs + Fixed\ costs + Pay\ down \tag{5.1}$$

Where the Variable costs is the bid price multiplied by the annual generation per MW. This covers all variable costs like the fuel cost, the $O\&M_{var}$ and emission taxes as described in equation 4.5 on page 21. The fixed costs are described in the technology catalogues for every technology. For the pay down are calculated as an an annuity loan with the technical lifetime of the generator as the number of rates in which the loan is paid down. The interest rate is set to 4%, which is the standard given in Energinet [2014] when making socio economical analysis. The investment cost is determined by the technology catalogues.

The total revenue, total expenses and profit can be seen in Table 5.2.

Generator	**Annual revenue [kr/MW/year]**	**Annual expenses [kr/MW/year]**	**Profit [kr/MW/year]**
Onshore wind	635,529	606,865	28,664
Offshore wind	919,895	1,496,282	-576,387
CSHP (waste)	2,143,981	4,125,927	-1,981,946
Small CHP - Coal	2,142,254	2,564,510	-422,256
Large CHP - Coal	2,073,058	2,745,288	-672,229
Large PP - Coal	1,243,769	2,352,513	-1,108,744
Large CHP - Biomass	288,430	1,484,988	-1,196,557
Small CHP - Biomass	51,853	1,989,432	-1,937,578
Large CHP - N.Gas	6,705	785,818	-779,113
Small CHP - N.Gas	849	473,241	-472,392

Table 5.2. Revenues, expenses and profit.

The revenue is simply the total annual revenue divided down to the produced MWh per MW during the year. It is seen that the onshore wind turbines are the only feasible generation technology. The offshore wind turbines generate a higher revenue than the onshore wind turbines due to higher capacity factors. And compared to the wind turbines, the CSHP generates a higher revenue due to the continuous generation. For the more expensive generators, the revenue per MW decreases due to the decrease in sold energy during the year.

From the analysis it is seen that only the onshore wind turbines generates a profit throughout the modelled year. This revenue of 28,668 kr is quite small compared to the revenue and annual expenses of operating the wind turbines, and at an interest rate of 4.6% the onshore wind turbines go from being profitable, to unprofitable. With this small a margin it leaves little security to the investors and the incentive created is small. On the other hand, if one was to invest in the electricity system, the analysis indicates, that onshore wind turbines is the only feasible technology.

It should be noted that this analysis is done on an average basis on each of the technologies. The generators have more scheduled hours on their "first" MW of generation capacity than they do on the "last" which affects the feasibility of the investments. For example, the large biomass fired CHP plans only have 389 hours of full load but more than 1600 scheduled hours throughout the year. It is unlikely that there will one large biomass fired CHP plant with the capacity of 1,150 MW, but more likely there will be more smaller ones. This makes the marginally cheapest one the one scheduled the most, in 1600 hours, more feasible than the marginally more expensive one scheduled for only 389 hours throughout the year.

Scenario Analysis 6

The purpose of this scenario analysis is to evaluate the expected range in which the electricity prices can develop if some of the assumed forecasts for prices does not hold true. This is done by running the model with a low price and high price scenario defined by the DEA, Energistyrelsen [2017b]. Furthermore the IDA 2030 scenario with 2.2 times the renewable capacity will be modelled under the same conditions as the reference system in in order to evaluate the impact of an increased renewable capacity.

6.1 Low and High Price Scenarios

A low and high price scenario is modelled based on the expectations for the development of fuel and CO_2 prices described by the DEA in their basis forecast, Energistyrelsen [2017b]. Here the low and high price scenarios will be used to show a range in which it can be expected that the prices can develop.

The low and high price scenarios are not a flat scaler of the inputs of e.g. 20% but represent the expected ranges for future international fuel and CO_2 prices.

When modelling these scenarios, all the price fluctuations of the various fuels are combined into one scenario, meaning that the low price scenario includes the low price for all types of fuel and vice versa. This makes the scenarios somewhat extreme, but gives an indication of the deviation range of the modelled results. It should be noted that changes in the emission taxes for NOx and sulphur are not taken into account in this scenario analysis.

The new bid prices and deviations for the low and high price scenario can be seen in Table 6.1.

Generator	**Low [kr/MWh]**	**Dev. [%]**	**Modelled [kr/MWh]**	**High [kr/MWh]**	**Dev. [%]**
Onshore wind	0	0 %	0	0	0 %
Offshore wind	0	0 %	0	0	0 %
CSHP (waste)	0	0 %	0	0	0 %
Small CHP - Coal	127	-31 %	184	365	98 %
Large CHP - Coal	127	-31 %	185	374	102 %
Large PP - Coal	171	-29 %	241	411	71 %
Large CHP - Biomass	268	-9 %	295	323	10 %
Small CHP - Biomass	290	-9 %	319	350	10 %
Large CHP - N.Gas	225	-42 %	386	515	33 %
Small CHP - N.Gas	240	-42 %	413	539	31 %

Table 6.1. List of bid prices for the low and high scenario compared to the modelled system.

From Table 6.1 it is seen that in the low price scenario the bids are 9 to 42 % lower than the modelled scenario, and for the high prices the bids are 10 to 102% higher. It is seen that the deviations are in the same range for the plants fuelled by the same fuel, which links to the inputs being changed is the fuel and CO_2 prices.

Furthermore it is seen that the smallest deviations are linked to the biomass fired plants. This is due to the fact that these plants do not pay for CO_2 emissions and are thereby not affected by the variations in CO_2 prices as the other plants are. The CO_2 price seems critical for the bidding price and it can be seen that the deviations on the high price scenario are larger for the coal fired power plant than for the natural gas fired power plants, which can in part be difference in CO_2 emissions, where the emission linked to coal is 1,67 times the emission linked to natural gas.

As a consequence of these different impacts on the bid prices for the generators, their place in the supply curve have also shifted. For the low price scenario, the natural gas fired CHPs have become cheaper than the biomass fired ones, and for the high price scenario the biomass fired CHPs have the lowest bid, except the renewable generators.

When running the model with the low and the high price scenarios, the duration curves for the prices are as seen in Figure 6.1.

Figure 6.1. Price distribution for the low and high price scenario and the modelled prices.

The difference in bid prices for the various generators is visible from Figure 6.1, where the low, modelled and high price scenarios have different patterns in where the breaks for the different prices occur. The resulting prices for the scenarios are presented in Table 6.2.

	Low [kr/MWh]	**Dev.**	**Modelled [kr/MWh]**	**High [kr/MWh]**	**Dev.**
Minimum	0	- %	0	0	-%
Average	184	-26 %	249	380	53 %
Maximum	290	-29 %	413	539	31 %

Table 6.2. Minimum, average and maximum prices and deviations for the different scenarios.

As seen in Table 6.2, the average prices in the low price scenario is 26 % lower than in the modelled scenario and 53 % higher in the high price scenario. The effects of renewable generation is similar in all of the scenarios, since the same distribution for demand and renewable generation is used in all scenarios. The only difference is in the controllable generation units.

When evaluating the feasibility of various generators in the low and high price scenario, it is seen that in the low price scenario, no technologies generates a profit. For the high price scenario, only the onshore wind turbines can generate a profit, just like with the modelled scenario. In this case the profit have increased to 385,000 kr/MW compared to the 29,000 in the modelled scenario, an increase of approximately a factor 13. This decreases the risk of the investment as a larger profit is ensured.

Even though the onshore wind turbines is the only feasible investment, the deficit have decreased dramatically for many of the generators in the high price scenario. For example the deficit of the offshore wind turbines are in the high price scenario around -66,000 kr/MW compared to -576,000 in the reference scenario. Also the internal rate of return have increased to approximately 3.5 % which indicates that the deficit is small compared to the modelled scenario where the internal rate of return for the offshore wind turbine generators were negative.

6.2 The IDA 2030 Model

As a part of the IDA climate plan, [Mathiesen et al., 2009b], an alternative energy system was developed with the objective of showing that in 2050 the Danish energy system could be based on 100% renewable energy. As a part of this work, a stepping stone of the 2030 energy system was provided and modelled in EenrgyPLAN. Therefore this energy system serves as a good example of how the electricity prices could develop if additional measures are taken to develop a renewable energy system. Since the energy system is fundamentally different, capacities and bid prices for the IDA 2030 scenario is presented in Table 6.3.

From Table 6.3 it is seen that compared to the reference, the IDA 2030 scenario introduces 2.2 times the renewable capacity. Besides that, the controllable capacity from power plants and CHPs have decreased from 10.497 in the reference model to 9.523 in the IDA 2030 scenario. In general it is seen that most producers have a lower bidprice than in the reference model which is in part due to the higher efficiencies of power plants assumed in the IDA 2030 scenario. Compared to the reference scenario, the coal fired power plants bid in with the lowest costs, and they have a very large capacity compared to other fuels. Most noticeable is the increase in capacity for the renewable energy source and the introduction of PV and wave energy.

Generator	Capacity [MW]	Bidprice [kr/MWh]
Onshore wind	4,454	0
Offshore wind	2,600	0
PV	683	0
Wave	400	0
CSHP (waste)	484	0
Large CHP - Coal	1,981	160
Small CHP - Coal	55	161
Large PP - Coal	4,246	206
Large CHP - Biomass	206	281
Small CHP - Biomass	1,010	291
Large CHP - N.Gas	257	362
Small CHP - N.Gas	864	373
Large PP - Biomass	219	443
Large CHP - Oil	56	542
Large PP - N.Gas	453	545
Small CHP - Oil	16	560
Large PP - Oil	160	829
VOLL	-	22,380

Table 6.3. List of all modelled generators, capacities and bids in the IDA 2030 scenario.

Another major change in the IDA 2030 scenario compared to the reference system is on the demand side. Here the conventional electricity demand is decreased to 20.6 TWh annually compared to 40.6 in the reference system. Besides the drastic decrease in the demand, parts of other sectors have been electrified like some of the heat sector through heat pumps or electric boilers and much of private road transport is modelled as electric vehicles with smart charge, meaning that they aim to charge when renewable production is high. Furthermore some of the demand have become flexible, giving some demand response so that electricity is used when prices are low. This flexible demand is not included in the model as prise sensitive, but an hourly distribution is obtained from the EnergyPLAN output file.

The modelled price distribution throughout the year for the IDA 2030 scenario with low, expected and high prices can be seen in Figure 6.2.

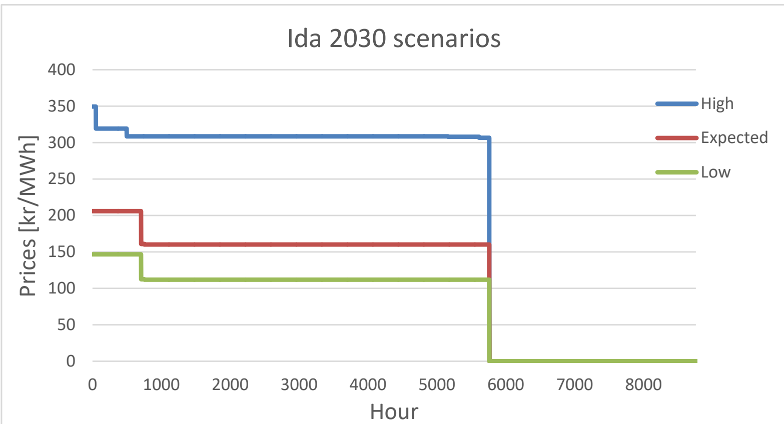

Figure 6.2. Price distribution for low, expected and high prices in the IDA 2030 scenario.

In the IDA scenarios, the prices are significantly lower than in the reference system. This is due to the 3,000 hours where the renewables covers all of the electricity demand and the prices is 0 kr/MWh. This number is lowered by the fact that the flexible demand and the electric vehicle demand increases consumption when there is large amounts of renewables in the system. If both of those were constant, the number of hours with prices at 0 kr/MWh would increase to around 3,600.

Furthermore the shape of the curve and its breaks in the high price IDA 2030 scenario in Figure 6.2 is different from the expected and low price scenario. This indicates that also in the IDA 2030 scenario, the saved CO_2 emission taxes makes the biomass fuelled CHP plants cheaper than the coal fired condensing power plant.

The minimum, average and maximum prices from the modelled IDA 2030 scenarios can be seen in Table 6.4

	Low [kr/MWh]	**Dev.**	**Expected [kr/MWh]**	**High [kr/MWh]**	**Dev.**
Minimum	0	- %	0	0	-%
Average	79	-29 %	112	210	88 %
Maximum	147	-56 %	206	349	69 %

Table 6.4. Minimum, average and maximum prices and deviations for the IDA 2030 scenario with low, expected and high prices.

The average prices per MWh is 112 kr/MWh with the expected prices, and 79 kr/MWh and 210 kr/MWh in the low and high price scenario respectively. Overall the IDA 2030 scenarios generate significantly lower prices compared to the reference system, and in all scenarios, the average prices are less than half of the prices in the reference system.

In none of the IDA 2030 scenarios, is it profitable for any generator to sell electricity to the market.

6.3 Findings From the Scenario Analysis

One of the main findings is that the renewable capacity has a significant impact on the future electricity prices. From the price levels seen today, the future electricity prices will stay in within the same range in the future with around 249 kr/MWh in the reference scenario compared to the range 400 - 500 kr/MWh that the DEA forecasts as seen in Figure 1.5 on page 5. The low price scenario was infact very close to the prices seen today which is also reflected in that all fuel and emission prices for the low price case is similar to the ones used in the model validation for 2015.

The electricity price is decreases in both low, expected and high price scenarios when modelling the IDA 2030 scenario. This is due to the higher penetration of renewables, which pushes down the price. This effect is very profound and the prices are less than half of what is seen in the reference system. If the demand response from the flexible demand and the electric vehicles were not implemented, this effect would have been more profound. This indicates that in a renewable energy system with an electricity market structured like todays markets, the electricity prices are bound to decrease. This highly effects the feasibility of all producers in the system, and the market does not create incentives for new investments in generation.

From the scenario analysis of the low, expected and high price scenarios it is seen that the CO_2 prices have a large impact on the bidprice of the generators. From the reference scenario, it is seen that the supply curve changed at the high price compared to the expected price scenario which due to the increase in CO_2 prices. From the expected to the high price scenario there is an increase in CO_2 prices from 76 kr/ton to 257 kr/ton, an increase of a factor 3.4 . This have a large effect on the bid price for the coal fired generators, since large amounts of CO_2 emissions are linked to the burning of coal. The effect is less profound for the natural gas fired plants, since they have a smaller emission for the same energy content.

From most of the analysis, investing in electricity generation, is not a feasible with the current market design. At the expected price scenario for the reference system, the onshore wind turbines generated some profit. And in the high prices scenario, this profit increased, but the onshore wind turbines were still the only feasible technology. If many investors were to seek the profit in onshore wind generation, the capacity would increase which in turn would increase the merit order effect. This would decrease the electricity prices, especially in hours with high wind generation, and thereby decrease revenues making all onshore wind generation infeasible. This cannibalistic effect from the renewables become especially profound in the IDA 2030 scenarios, where there is a much larger renewable capacity and the prices drop to unforeseen low levels. This cannibalistic nature of renewable generation under current market conditions can be concluded, not only from market theory, but also from the scenario analyses.

Market Dynamics 7

The purpose of this chapter is to discuss both the implication of the results from the model and how it will impact the energy system. The market dynamics presented in Chapter 3 and applied with the construction of the model in Chapter 4 will be discussed and put into relation the the results of the analysis seen in Chapter 5 and the scenarios presented in Chapter 6.

The discussion of the market dynamics will be grouped intro different areas where a specific niche of the market dynamics will be covered individually. The market dynamics are complex and intertangled but in order to maintain focus, this approach is chosen.

It should be noted that the aim of this project is to model the prices of a technical energy system under the current market design and investigate its dynamics. The origin of this inherited system is out of the scope of the project and it can be assumed to be developed as a consequence of political measures like the feed in tariffs that is known today.

The aim of the discussions is not necessarily to uncover specific results from the market design, but to a larger extend to focus on the market dynamics, dilemmas and tradeoffs that occurs with the current market design.

7.1 Interconnectivity

In this project, the interconnectors to neighbouring countries have not been modelled. This was a deliberate choice in order to isolate and investigate the market dynamics, but also because the effects might be assumed to be of small importance in the future.

If the interconnections with the neighbouring markets were to be modelled, excessive information on the energy systems of these markets were required. This would be a difficult task, since there is large uncertainties on the development of the energy system in countries and it might not be possible to find detailed plans for all neighbouring markets for the year 2030.

The impact of the interconnectivity would be rather small if the neighbouring markets developed their energy system in the same way as the Danish. If all neighbouring markets had a totally similar energy system and demand pattern, the modelled prices in the Danish system would be the same as in the model, independently of the magnitude of interconnection. In the modelled scenario, there is no interconnection, and therefore the energy system is modelled as an isolated island. If there were to be infinite interconnection capacity between the markets and the energy systems were similar the prices would also be the same as it would just be a scaling of the modelled system.

In real life the energy systems would not be identical in neighbouring markets since different natural resources are available in different geographical locations. Denmark is ideal for a large degree of wind capacity since it is relatively flat and surrounded by ocean where average wind speeds are high. The possibility for an energy system based on large amounts of wind is the same for the near neighbours, making wind generation an interesting technology to analyse further.

The variations in generation patterns of wind turbines in different markets could have a large impact on the prices in different energy systems if the interconnections are modelled. When studying the correlation between wind power generation there is a strong correlation dependent on the distance between generators, as seen in Figure 7.1.

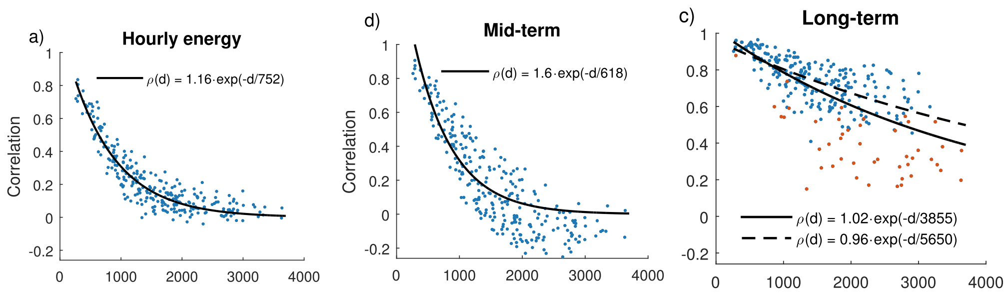

Figure 7.1. Correlation of wind generation as a function of distance, measured in km,$\frac{1}{2}$ on hourly basis, mid and long term [Olauson and Bergkvist, 2016].

From Figure 7.1 it is seen that there is a strong correlation between wind generation, especially at short distances between the sites like 200 to 400 km. In other words, the closer together the wind turbines are, the more similar is their power output. Therefore to harvest the full potential for interconnectors, they must connect to markets far away. Figure 7.2 displays circles with 200, 400, 600, 800 and 1,000 km radii from Denmark. Here it is seen that almost all neighbouring markets are within a 400 km radius from Fredericia, Denmark. Therefore the impact of variations in wind generations might not be large enough to have a significant impact on the use for interconnections in high or low wind hours, because wind generation will have similar patterns.

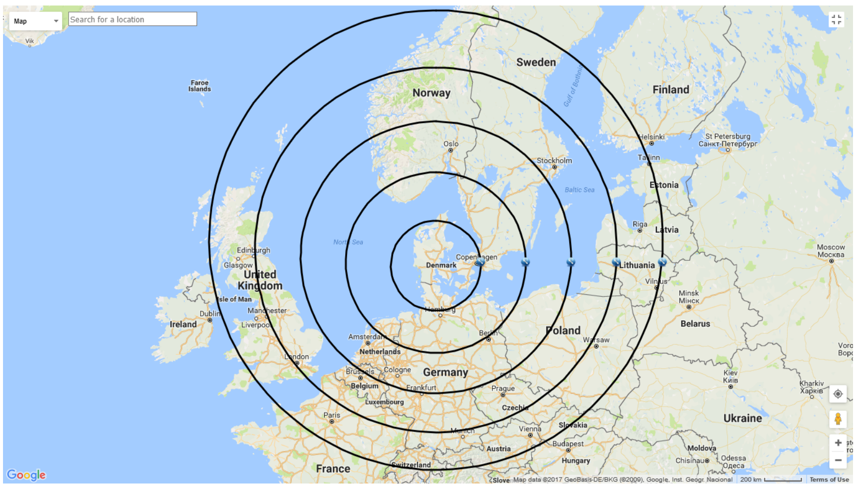

Figure 7.2. A map of Denmark with circles with 200, 400, 600, 800 and 1,000 km radii [FreeMapTools, 2017].

In other words, if the generation patterns from renewable sources like wind and PV are similar to our close neighbouring market and the demand patterns are somewhat similar, the effect of interconnectors will only be significant if the rest of the energy system is fundamentally different in these countries. In the long run, the goal for most countries is to have an energy system which is primarily based on renewables which makes it important to evaluate the actual needs for the interconnectors.

If the argument is to connect with a high price zone, it must to some extend be based on the assumption that that zone will either have a fundamentally different energy sytem or that the expansion of renewables in this country will fail. A failed expansion of renewables would mean that the merit order effect will not drive down prices in this zone itself, and by connecting to it it could generate income in the Danish system.

7.2 Resource adequacy

Resource adequacy and attracting investment is key for developing the energy system to be reliable and ensure security of supply.

In the energy only market design, it is a core assumption that the market will favour cost effective energy production and only produce the amount of energy that reflects a need. Therefore, if a technology is feasible, it should enter the market, and the ones not feasible should exit the market. Even today, onshore wind is considered the cheapest way of producing electricity, but anyway, we do not see heavy investments into this technology [Mathiesen, 2017]. If the feasibility on the market is not driving enough investments today, then is it a fair assumption that it will drive investments in the future with the current design?

As seen in the modelled scenarios for 2030, it is only the onshore wind turbines which are feasible investments. Due to the merit order effect, heavy investments into onshore wind turbines would drive down prices like seen in the IDA 2030 scenario. This effect of feedback of the market is visualised in Figure 7.3.

Figure 7.3 shows the feedback mechanism of the electricity market if it is assumed that it is a perfect market without barriers for entry and exit. Here it is seen that in markets with low prices, generators will pull out due to lacking profits. This will decrease the capacity margins making the prices increase and more volatile. The higher prices will in turn create room for feasible investments and new generators will invest due to an expected profit. This increase in new capacity will increase the capacity margin driving down prices. The magnitude of the feedback mechanisms depend on various factors.

If there is a big development in technology, then new and more cost effective technologies can replace old and ineffective technologies by outperforming them on the market. This typically requires a certain maturity of the new technology and it might be difficult to mature a technology enough to get it to a competitive state where it can enter on a large enough scale to replace old technologies. This would decrease the impact on the feedback mechanism as new investments are not made if they are not matured enough to break market barriers.

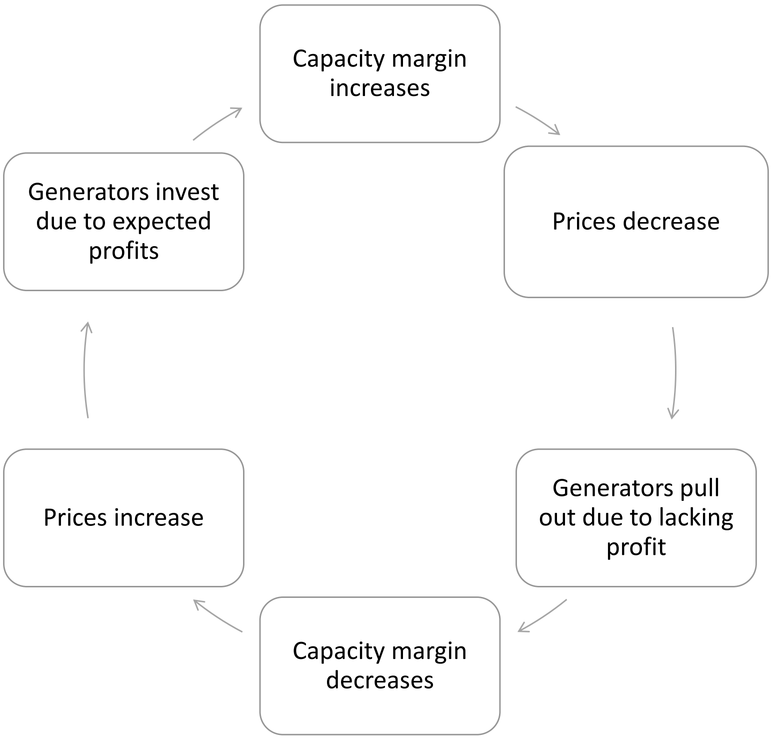

Figure 7.3. The feedback mechanism ensuring resource adequacy in the energy only market.

The construction time of technologies also affects the magnitude of the feedback. If the construction time of new technologies is very long, then the capacity margin might tighten even more before the first feasible generators are made. This could send the signal to less feasible generators that there is a market for them driving investments in inefficient technologies. By the time the most effective generation is implemented the prices will be affected which might make the half-finished inefficient generator infeasible, before even entering the market.

It is very difficult to predict how the market will respond using the feedback mechanism described above. For a step input in a typical system, the response could look like seen in Figure 7.4.

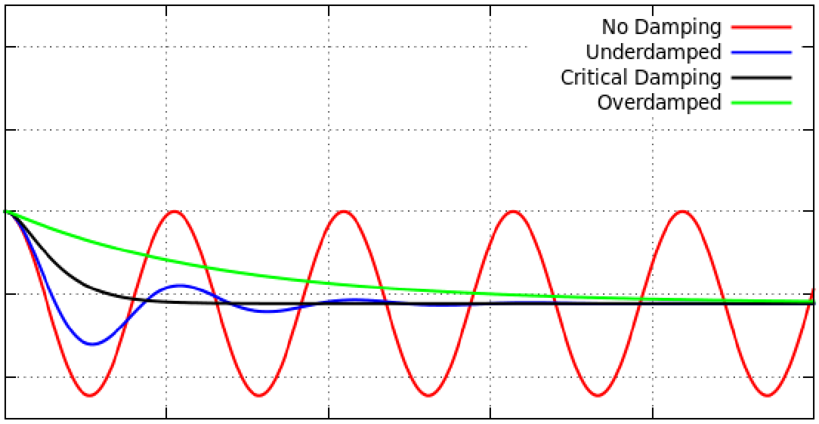

Figure 7.4. Different response patterns to a step input [Greer, 2014].

As seen in the case with no dampening, the red line in Figure 7.4, it could be possible for the system to oscillate between high price and low price via the feedback explained in Figure 7.3. On the other hand, if the system was dampened. e.g. by only a few investors being willing to enter the electricity market a steady market situation could be achieved with low or no overshoot. This is assuming that it is only economic returns that drive investments and that the future market will have constant characteristic. If the market is changing quick through, e.g. introduction of demand response, it is difficult to predict how the development of the energy system will react when the market is varying in time.

It is difficult to predict investors willingness enter the electricity market, but it can be assumed that most investors are seeking opportunities which ensures a secure long term return on the investment. Therefore risk averse investors might be hesitant in investing in the electricity market due to a possibility of price volatility.

The dynamics of this feedback and the willingness to accept price volatility needs to be taken into account when determining if the current market model is the best one for achieving the societal goals.

7.3 Demand Response

The effect of demand response is difficult to predict. Demand response can be defined as electricity consumption that is dependent on the electricity price. To an extend, with explicit monetisation of electricity for consumers, all demand will be responsive to prices if they are high enough.

Demand response is especially interesting where large amounts of energy can respond, which makes power to heat, gas or fuels interesting technologies. Few of these technologies are mature at the current state, and in order to be viable in the market they will only engage at low prices.

Technologies like heat pumps or electric boilers in combination with heat storages is very interesting from this point of view. Both are mature technologies, which could be viable in the market and use renewable electricity when the price signals a surplus.

The effect on the market price is very dependent on the strategy of the power to heat generators. If the aim is to replace heat generation from e.g. a gas boiler, it would make sense to bid in with a price corresponding to, or just below this price. This would cause an increase in the electricity prices since there would be less hours with a price of 0 kr/MWh. On the other hand, if the aim is to provide the cheapest heat to heat consumers and a sufficient heat storage is present, it would make sense to bid in with the short run marginal cost of the heat. This would be close to 0 kr/MWh as heat pumps and electric boilers can be operated automatically. In this case the effect on the electricity price would be insignificant because the heat generation would only run if the prices were 0 kr/MWh.

The electricity generators would hope that flexible demand through demand response would bid in with a price close to their current bid, but in order to maximise profits, the flexible demands might bid in at 0 and thereby driving down prices.

The impact of demand response needs to be discussed, as it might not drive up prices in the electricity system. In the IDA 2030 model, even after the flexible demand, heat pumps, electric boilers and smart charge of electric cars, there were an renewable overproduction of 3.5 TWh, corresponding to more than 17% of the conventional electricity demand. This is of cause very high because interconnections are not modelled, but it underlines that there will be plenty of energy priced at 0 kr/MWh for demand response to absorb.

7.4 Security of Supply

In the Proposal for a new Directive on common rules for the internal market in electricity, the European Commission states that:

> *A so-called 'energy-only market' option would see European markets being sufficiently improved and interconnected that it provides the necessary price signals to spur investments in new resources and in the right places. In such a scenario, no capacity mechanisms would be required any longer. [European Commission, 2016b, p. 15]*

This underlines that the aim of the European common electricity market is an energy only market design currently used in the Nordpool area, and that the market should provide the price signals for future investments. This is underlined in the aim to "*improve price signals to dive investment in areas where it is needed the most, reflecting grid constraints and demand centres*" [European Commission, 2016b, p. 4].

This effectively means that tight capacity margins should be reflected through scarcity prices. The ultimate signal for electricity scarcity is to load shed and set the price at the value of lost load. This spurs a discussion on the security of supply and how it is defined.

Traditionally security of supply is measured in the number minutes that the consumers have been without access to electricity [Det Økologiske Råd, 2014]. Therefore, signalling scarcity through load shedding would affect the security of supply.

Energinet does in their lookout of the future market designs state that "*Energinet works toward increasing the maximum bid price from 3,000 € per MWh to a level that to a larger extend reflects the consumers real value of electricity. [Energinet, 2016b, p. 7]*". Thereby consumers would have to explicitly monetise their value of electricity in any given hour. As consumers have different preferences, some would set their willingness to pay low, meaning that they would be without power in high price hours.

Concerns about energy poverty and our standard of living with accessibility to services raises the question of scarcity pricing and security of supply:

Is load shedding through explicit monetisation of access to electricity affecting security of supply and is such a system in the best will of society as a whole?

7.5 Market Power

Even though perfect markets assume no exercise of market power, this is an opportunity in the real world, and generators will evaluate the risk versus the profits from exercising market power.

Illegal forms of market power would be to form cartels. These cartels could agree on bidding prices or artificially limiting capacity through planned maintenance in high demand periods as seen in the Californian Electricity Crisis in 2000 and 2001 where Enron manipulated the energy market [Brenenson, 2002]. This was possible due to their dominant position on the market.

There is no, to the author, known rules on what should determine the bid price. The assumption of generators bidding with their short run marginal cost can therefore be discussed. The assumption seems reasonable since bidding with short run marginal costs, under full competition, will be the most efficient way of ensuring to be schedules when a profit margin can be made. The assumption of full competition is a theoretical one and in real life there is no perfect market.

Some generators might speculate in placing a bid higher than their short run marginal cost, and thereby include a small profit margin in their bid. This might decrease the number of schedules hours but will ensure a higher revenue per MWh of electricity. In a market where an actor is fully informed about other competitors, it could seem like a good strategy to bid in with a price just below the next producer in the supply curve. If done correctly, the generator would not miss any hours of being scheduled, and in hours where the generator is the marginal one, the price would be higher, leaving a higher overall profit to the generator.

In the modelled electricity system, this approach would be very easy to implement since the ownership of the different generators is not taken into account. If there is many owners of the capacity they might compete internally, but this is not taken into consideration in the model, where it is assumed that the generators bid in with their short run marginal costs. In the reference scenario, this strategy would drive up average prices from 249 kr/MWh to 358 kr/MWh which is an increase of 44%. This would have a significant impact on the price and would be a good bidding strategy to maximise profits for all market players, even though it will go against the aim of the market, which is maximising societal welfare.

In real life this strategy will be difficult to implement since the ownership of the energy system is diverse. Further more the supply curve is more smooth due to different plants of the same technology having slightly different running costs and the interconnection to neighbouring markets. If a generation company were large enough and had enough technical expertise, it might be possible to identify hours where the generator could be the marginal producer before market scheduling. This, combined with knowledge of competitors could be used to adjust bids in these hours, and thereby maximising profits. Even small adjustments can have a large impacts when accumulated over time.

The exercising of market power might be difficult to prevent and might seem like speculations that could not take place in a real system but if the possible gains are large enough it might take place. There exists Danish cases of market power, e.g. with DONG being sued for exercising market power in 2005 to 2006 [Nielsen, 2016].

7.6 Political Aspects

Energy policy is a very complex political area and it affects many other aspects than just proving energy. Some of the other interests are climate, security of supply and financial aspects.

The climate aspect seem more and more urgent, as greenhouse gas emissions continue to rise [U.S. Environmental Protection Agency, 2017]. With the aim from the Paris agreement of keeping the temperature increase well below 2°C, the political aim of curbing greenhouse gas is starting to gain ground. In order to achieve these goals, the energy system needs to change significantly. This change is not presented in the reference scenario, but the IDA 2030 scenario represents a system where focus is on curbing greenhouse gas emissions. In this scenario, the average electricity price was the lowest of all systems, which makes it highly unlikely that the market alone will drive the green transition. In the model the cost of emissions are included. The aim of these taxes is to send a market signal promoting greener alternatives. This impact is seen in the scenario analysis, where the biomass plants becomes cheaper than the coal fired plants in the high price scenario where the CO_2 increases from 76 to 257 kr/ton.

Security of supply have become an increasingly important geopolitical area in resent years with Russia as the main provider of energy to the EU with approximately 29% of coal, 30% of crude oil, and 38% of natural gas in 2014 [eurostat, 2016]. Internally, the European countries also seems to be more reliant on neighbouring countries and the European Commission have interconnection targets for the European electricity market [European Commission, 2014]. This might affect the geopolitical security of supply for the individual countries, but strengthen the European situation. Furthermore, the most obvious way to become energy independent, is to produce energy oneself, and for this purpose, renewable energy is ideal.

The financial aspect, and providing energy in the most cost efficient manner is another key goal. Here the aim is that e.g. the electricity market should be able to do this. Another facet of this aspect is job creation and employment. On this aspect, renewable energy technology will typically employ more people domestically than abroad [Mathiesen et al., 2009b]. On top of this, it might foster specialised production that could be exported, both aspects that are desirable from a socio economical point of view.

This raises the question:

How are these complex energy political aspects affected by the energy only market?

The aim of the energy only market is solely to provide electricity that is the most cost effective in the short term. But in order to function properly, and to ensure resource adequacy, the market must stand alone independent from political interference like building new capacity or capping prices [Hogan, 2005]. Thereby, the current market design isolates the cost effectiveness of the production from the other energy political aspects. This places the politicians in a dilemma. In order for the market to function as intended, they must not interfere, thereby loosing control over emissions, security of supply, and job creation. If on the other hand, there is interference in the market, the feedback mechanism ensuring resource adequacy will not function as intended. The energy only market then effectively creates barriers for the politicians to interfere in the development of the energy system.

7.7 Why this Market Design

After the discussion of the market dynamics a question arises:

What is the reason behind this electricity market design?

The main motivation behind the energy only market is cost effective electricity production, which is a noble goal, but there are tradeoffs as discussed above. One of the biggest tradeoffs is that in order for the market to function properly, there should be no political interference. This should especially hold true with increasing electricity prices, but other energy political aspects might make this difficult, e.g. public pressure over increasing prices [Hogan, 2005]. The fact that the energy only market creates barriers between the market and the politicians might be a driver for some actors, for either financial or political reasons.

The DEA mentions in their forecasts, that *"the forecasts are not to be interpreted as prognosis. [Energistyrelsen, 2017a, p. 2]"* but rather the forecasts are frozen policy scenarios. This precaution does not seem to be communicated on many other public channels. An example of this is the recommendations for the future energy policy by Energikommissionen where it is stated that *"Currently, the electricity prices are low, but they are expected to increase until 2030" [Energikommissionen, 2017, p. 34].* A continuation of this argument follows, that with decreasing costs for renewables, the subsidies should be cut and all technologies should compete in the market and the market should drive new investments. Based on the findings from this report, that scenario seems unlikely.

This example underlines that it is important to communicate the precautions and intended use of an analysis before the information enters a political arena, where interests, policy and ideology can filter information and define its use in arguments.

This apparent confidence that the electricity prices will increase and that the market will send the correct signals for investments seem in contradiction with the other political goals, when taking the market dynamics into account. What causes this consensus is unknown.

7.8 A Future Electricity Market

It is difficult to predict how the future electricity market will be in the long run, and it can be questioned if a liberalised for profit market will lay the best path to achieve societies goals. Before the liberalisation, the market actors operates from non-profit companies owned by municipalities or in co-operatives. In such a system, long term planning might be easier, since decision making is centralised and the price signal could be based on long term signals such as the levelised cost of energy in stead of the short run marginal cost. With the trend of market liberalisation of public companies on both Danish and European level, this seems unlikely and modifying the current market design would be a more attainable task.

Under the current market conditions it seems unlikely that all energy political aspects can be realised without interfering in the market. Therefore the markets needs to be designed so that they can be an active tool in realising the political and societal goals [Mathiesen, 2017]. This makes it interesting to investigate which characteristics a future market design could have.

7.8.1 Auction Based Competition

Having a pooled energy market, like the day ahead market, fosters competition between generators. This feature would also be desirable in a future market. An alternative to this would be long term contracts for energy which does not necessarily endorse cost effective production and is typically an non-transparent product. A pooled market makes it easy to match generation and consumption for all market players and if a generator is unavailable, there there are others to take its place.

7.8.2 Short and Long Term Signals

The prices in this market should reflect both short term and long term costs. By reflecting the short term efficiency most cost effective generator is scheduled, but as seen in the analysis of this project this is not sufficient to attract investments. Therefore a future market should also reflect long run costs in order to ensure that the development of the energy system is realised. This could be signalled in many ways. One would be to establish a capacity market on top of the energy only market. In this market capacity payments would be allocated from an auction where generators can make bids for the availability of generation capacity. In this market, generators could signal their long term costs and the capacity auctioned could be designed with the aim of security of supply. The tradeoff from this will be that established capacity will bid in with low prices, and there will be a payment to e.g. existing coal fired power plants which might clash with climate political goals.

7.8.3 Environmental Signals

If the Paris agreement is to be realised the environmental impact of the generators must also be reflected in such a way that green technologies are preferred over black technologies. The current ETS is one way of doing it. Another approach could be a CO_2 tax. The main difference between these two is that in the ETS system, the total number of allowances is politically determined and the prices unknown, and for a CO_2 tax, the price is politically determined, but the emissions unknown.

All the above factors must be taken into account when designing a future electricity market. In order to make the correct market design, the energy political aspects must he prioritised clearly so that a market can serve as a tool with the aim of fulfilling the societal goal.

Discussion 8

The purpose of this chapter is to discuss the methodology used in this project. The results of the reference system and other scenarios and the dynamics of the model have been investigated in Chapters 5, 6 and 7. The aim of this discussion is to elaborate on the consequences of some of the more fundamental methodologies and assumptions in this project.

8.1 Methodology

The choice of using a technical system as input for the price model has the largest impact on the results. The developed EnergyPLAN models for both the reference system and the IDA 2030 scenario are made some years back. Therefore they might be misleading compared to the present visions for how an energy system could look like in 2030. Such a correction would be relatively simple, as the model is developed in such a way that a new input in form of a different energy system is easy to implement. On the other hand the two technical systems have fundamental differences in their combination of technologies and are fit for the purpose of displaying the market dynamics that occurs when implementing more renewables.

One of the assumptions that have the biggest impact on the results are the technical EnergyPLAN models. This is so because EnergyPLAN is a very aggregated tool for simulating large energy systems with sectoral integration between electricity, heat, fuels and transport. This assumption makes the supply curve have a more step like shape than a real life scenario, since there will be variations within technologies and their performance. This assumption is assumed to have an impact on the prices, but not a large impact on the level of the average prices in the system, since the variations from technology to technology have a larger difference that internally in a technology niche.

The prices used in the model is the forecasts made by DEA, and for the technologies in the feasibility analysis, prices from the technology catalogue is used. This might affect the results of the model. The effects of fuel and emission prices are studied through the scenario analysis, but their individual contribution is not investigated. For the financial data like the investment costs it is difficult to predict what future price might be. The impact of these prices on the feasibility of the generators have not been investigated.

8.2 Core assumption

This project seem of somewhat self-fulfilling nature. The core assumption is that a technical energy system is used to forecast electricity prices under the current market design. It is found that the forecasted prices are not high enough to financially support the installed capacity in the energy system, which then forms the basis of the critics of the current market design.

The underlying assumption in this argument is that the simulated energy system will be inherited. This is assumed without taking into account, that in order for the system to be financially viable under the current market design, it must be the market that develops the system through the feedback explained in Figure 7.3 and 7.4 on page 42. Therefore this project might seem redundant and not adding value to the debate of the future energy market.

The aim of this project is not to make the most accurate prognosis of the price development, but rather to investigate the market dynamics if the current energy market is applied to a future energy system. If former energy policies are continues, there will be interference with the market, and market powers will not dominate the development of the energy system. It is the dynamics and consequences of such a scenario that is investigated in this project.

Another approach could be to actually do the market economic iterations through the feedback displayed in Figure 7.3. This would imply removing all, infeasible generation from the market until the capacity margin tightens sufficiently. Then when prices increase generation should be introduced in the technologies that generates profit. It is unknown how the development of such an energy system would look like, but it is estimated that a steady state could be achieved. If one were not to do these iterations manually it could be modelled through a too like e.g. Balmorel [Connolly et al., 2009].

9 Conclusion

As the climate is changing, mitigating greenhouse gas emissions has become a focal point in policy. The energy sector is one of the largest emitters of greenhouse gasses, and the electricity market is a key political tool for regulating the energy system and the electricity sector. With the current market design, the merit order effect drives down prices when renewable energy is introduced, yet an increase in electricity prices is forecasted by the Danish Energy Agency.

This makes it interesting to investigate how the electricity prices are expected to develop under the current market conditions and how the market dynamics create incentives for the development of the energy system.

In order to answer this, a model have been set up in MATLAB which used the technical characteristics from an EnergyPLAN model to calculate the hourly electricity prices throughout a year. The model aims to simulate the fundamental characteristics of the current market design and give the resulting prices. When operated with a technical EnergyPLAN model for a 2015 system, the average electricity price deviates with approximately 2% compared to the actual 2015 prices. This does not validate the results from the model, due to differences like the lack of modelling interconnections, but indicates that the modelled prices are within the same range as the ones from the electricity system.

When modelling the prices for the 2030 reference scenario developed by the DEA, the average electricity prices are 249 kr/MWh. The model is also used on the IDA 2030 scenario with 2.2 times the renewable capacity than the reference scenario. In this scenario, the average prices are decreasing to 112 kr/MWh, 55% lower than in the reference scenario. In both scenarios the average prices are significantly lower than the range of 400 to 500 kr/MWh forecasted by the DEA. As a result of these low prices, the only feasible generation technology to operate was the onshore wind turbines, and the market design would not be able to sustain the technical energy systems.

The results of the modelled energy systems indicates that the current market design will drive down prices with the introduction of renewables as prices in the IDA scenario is significantly lower than in both the reference scenario and the forecasted prices.

In order to understand the consequences of maintaining the current energy-only market design, despite its effect of pushing down prices to an infeasible level with increased renewables, the market dynamics are discussed.

The impact on the price from interconnectors have not been modelled, but might not be enough to affect the feasibility of the system since, in essence, interconnectors are making that market larger, not altering the fundamentals of the market design. If neighbouring systems have similar characteristics as the Danish with similar distribution of the demand and generation from wind turbines the prices would be in a similar range as the ones modelled without interconnectors.

Demand response might push down average prices in a scenario with high levels of renewable energy, if the strategy is to bid only in hours with surplus of renewable energy. This would move consumption to hours with prices of 0 kr/MWh and avoid consumption in high price hours driving down average prices.

If all consumers monetise their value of access to electricity, the demand would be responsive to price fluctuations. Most likely there would be no hours with load shedding, because prices could increase to levels higher than some consumers willingness to pay and thereby reducing demand. This would not affect the security of supply, since prices reflect willingness to pay, but might lead to concerns about energy poverty and not be in the interest of society since access to electricity is fundamental for modern way of life.

Energy policy is a complex area that e.g. involves aspects like climate, domestic job creation, security of supply and a cost effective, competitive economy. With the energy only market design, the market should be independent of interference in order for the market feedback to be functional. This might create a barrier for direct political interference, which could oppose reaching some of the energy political goals if the market could not accommodate these by itself.

These findings suggests that the market design might need modifications to better accommodate reaching all energy political goals. These modifications could include a better way of sending both short and long term price signals as well as a signal for the environmental consequences of electricity production. Designing such a self supporting electricity market, is a complex task if all energy political goals should be taken into account.

With the various energy political goals in mind, it it essential to have a clear understanding of how, the market will develop the energy system, with the market as the only driver, if the current energy only market design should be maintained.

Further Studies 10

Besides analysing the future of the electricity system, this project have gained ground to a lot of new questions and interesting areas for further studies.

This project does not take the interconnection between electricity markets into account. It would be interesting to investigate the same scenarios, but with inter connectors to neighbouring markets so that their effect could be investigated. This would prove difficult, since the uncertainty of the energy system would not be limited to the Danish, but be even bigger, and the input for the model, which is the technical EnergyPLAN model, might not have been developed for these systems.

Another interesting continuation of this project would be to use the market feedback of which technologies is feasible and use these as the only tool for developing the energy system. This would imply installing more capacity of the feasible technologies and cutting back on the infeasible ones. This might give an indication of in which direction the market would pull the energy system without any interference. If excessive modelling resources were available, this could even be added on to the developed model.

Besides the 2030 scenarios modelled in this project, it would be interesting to analyse the response of a 100% renewable energy system. The uncertainties linked to this will be very large since technological progress and bidding strategies are difficult to evaluate. Nevertheless this could give an indication of a trend of the electricity prices, their level and volatility and if it seems feasible that the current market design can sustain such a system.

Since the price levels for the forecasts made by DEA and the modelled prices deviate so much, it would be interesting to get a better understanding of their approach. This could be obtained either through modelling in Ramses or through interviews with DEA officials. Such an investigation could uncover the main differences in assumption and methodologies that have led to this deviation, and thereby gain an even clearer insight in the dynamics of the electricity market.

Another approach of this project could have been to investigate the consequences of other market designs and thereby evaluate their performance compared to the current one. This would require extensive modelling, but could be a valuable tool in decision making processes.

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