

Beyond the borders of electricity

*The cross border effects of a German capacity market on
the Netherlands*

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Abstract

Within electricity markets, serious concerns exist whether a competitive electricity market will provide the necessary incentives for investment in generation. In Europe several countries are looking at the options of implementing a capacity mechanism. A capacity market provides a possible solution to this problem of generation adequacy but the effectiveness of different methods is disputable and one-to-one comparison is nearly impossible. With Germany deciding on the implementation of a capacity market, concerns arise regarding the cross border effects on the Dutch market. The main research question that stressed the problem is formulated as:

“To what extent does the implementation of a capacity market in Germany influence the performance of the Dutch electricity market?”

Answer to this research question can help policy makers in assessing policy decision in the electricity market including cross border effects. From literature, several performance indicators are derived. A combination including both system indicators as well as the policy goals reliable, sustainable and affordable are used.

The starting point for the modelling part of this research is the Power2Sim electricity market model. In order to be able to answer the research question, the Power2Sim model needs to be extended with two modules. An investment module and a capacity market module. The two modules are modelled in excel and a Visual Basic script is developed to create interaction between the three modules. The data used as input for the model consist of a wide range of reports and empirical data.

The results of the model show that the introduction of a capacity market in Germany has an effect on the performance of the Dutch electricity sector. The main finding is that a capacity market leads to higher investments in the country it is implemented. The cross border effects include improvements in expected loss of load hours, total consumer costs and CO₂ emission. These effects are enlarged with the expanding of the interconnection capacity between Germany and the Netherlands. CO₂ price sensitivity was taken into account as well resulting in some interesting observations regarding interaction between a capacity market and CO₂ prices.

Following the interpretation of the results, several recommendations have been proposed. The recommendations depend on the view of the policy makers. The three indicators reliability, affordability and sustainability include trade-off. Consequently, policy makers need to decide on which indicator to give preference. A general decision to be made for policy makers is whether they value an independent electricity sector more than the free rider benefits of being dependent on German capacity.

Every study is subjected to some kind of limitations. For this study, the limitations can be found in the number of scenarios that have been ran, the number of countries that have been analysed in detail and the basic way of evaluating investment.

Concluding, this study has led to several contributions. This study shows that the Power2Sim model can be extended to fit capacity mechanisms. This can be valuable for policy makers in the electricity market in evaluating decision considering the implementation or consequences of a neighbouring capacity mechanisms. Secondly this study has contributed to the validation of existing studies that measure the effect of a capacity market. It furthermore extended the existing research by adding specific cross border effects for the Netherlands under various conditions. At last the research provides directions for future research on the issues that either cannot be explained or could not be fit in the current model structure.

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1 Introduction

1.1 Introduction

Electricity can be seen as one of the most important components for facilitating today's economic activity. The limited storability of electricity makes the balancing of supply and demand a complex issue. Therefore, the availability of the necessary capacity to produce and to make use of this valuable resource is one of the key issues in current electricity markets debates. Over the last decades, serious concerns have been raised with respect to whether the current liberalized electricity market provides the necessary incentives for investment in generation capacity (Oren, 2000) (De Vries & Heijnen, 2008). The first indication of this deficiency appeared during the 2000 and 2001 electricity crisis in California as discussed by Turvey (2003) and these concerns were supported by shortages in New Zealand, Scandinavia and Italy in more recent years (De Vries L. , 2007). The magnitude of the societal cost of California's electricity crisis alone was estimated to be around 40 billion dollars, leaving no discussion about the costly and disruptive nature of these power shortages (Weare, 2003).

In theory, a competitive liberalised electricity market provides optimal incentives for investments in generation capacity (Joskow & Tirole, 2007). Policy makers in Europe held this view, taking no further actions in stimulating investment in peak capacity over the last decade. However, the theory assumes ideal market conditions in which prices will rise until the price is reached that consumers would rather be shut off from electricity than paying more. This price level is generally referred to as the value of lost load (VOLL). Furthermore, sufficient demand response is present under ideal conditions. Moreover, the theory is also neglecting the existence of strategic behaviour and market power as described by Newberry (2001). According to Finon (2008, p. 143) "insufficient attention was paid to the issue of investment in generation capacity during the period of designing the competitive electricity reforms", in order to prevent adequacy problems in the future.

In the scientific literature, there are several policy instruments, generally referred to as capacity mechanisms, which attempt to overcome the problem of generation adequacy and lack of investment incentives. Capacity mechanisms differ widely in their use and design and can be roughly distinguished into on the one hand, price based mechanisms like capacity payments and strategic reserves and on the other hand, volume based mechanisms like capacity requirement capacity subscriptions and reliability options. As the names indicate, price-based mechanisms steer the market by means of price regulation while quantity-based capacity mechanisms regulate by means of volume.

Currently, the implementation of capacity mechanisms in Europe is a major topic with several member states being on the edge of deciding upon implementing one. Germany is currently discussing the implementation of a capacity market. This, together with the UK, will be the first country that is directly physically connected to the Netherlands and given the importance of the electricity exchange between those

countries, the implementation of a capacity mechanism might have consequences for the Dutch electricity market as well.

1.2 Problem exploration

European trends

Over the last decade significant changes have struck the European electricity market. Currently, there is a tremendous focus on renewable energy. The 2020 European targets of 20% of the energy from renewable resources serve as an important driver for a fundamental change from a fossil oriented market to a renewables dominated market. Having a large share of renewables is a serious step in working towards a fully renewables sector in the future and towards not being dependent on fossil fuels anymore. However, there are some serious consequences for the performance of the electricity market as discussed by Elberg et al. (2013) and Meulman et al. (2012). First of all, a large share of renewables will decrease prices in general due to the fact that the marginal costs for wind and solar energy are close to zero. This means that some of the conventional units will be pushed out of the market. Since in electricity markets the price is determined by demand and supply, the expensive unit will not be “in the money” anymore and logically result in a lower electricity price. Secondly, intermittent renewables cause the electricity price to be more volatile. Since wind and solar are not always available, it is not a surprise that prices will rise and fall in times of no wind and high amounts of wind respectively. This volatility in prices raises distrust, or investment risk, with investors since they are not certain about their profit in the future and could lead to underinvestment (Meulman & Méray, 2012). Contradictive here is that this fluctuation caused by renewables needs to be filled up by fast start-up units, mostly gas power plants. This tension between the need for renewables on fossil plants within the same field makes the sector even more interesting but also gives rise to new adequacy and policy questions.

A second trend in Europe is an increased integration of electricity markets. This trend is generally referred to as the European target model of market coupling (ACER, 2014). This method basically focuses on North-West European price coupling. In order to succeed, flexible governance arrangements are required just as the shared information level needs to be achieved.

A third aspect is the low coal prices and low carbon emission prices. The emergence of shale gas in the US caused the export of coal to Europe to increase significantly. This in combination with a worldwide increase in the amount of coal on the market as well. Consequently this oversupply leads to lower coal prices, pushing the gas power plants out of the market due to competitive advantages. Furthermore the CO₂ emission prices do not provide any strong incentives, due to extremely low carbon prices, to invest in cleaner gas turbines compared to the relatively more pollutant coal fired power plants.

Combining this perfect storm of more renewables, increased market integration and low carbon and coal prices, against gas power plant resulted in several insights. These insights have to be taken into account when assessing the decision of

implementing a capacity market. It should be based upon 1) the effectiveness in a renewables dominated market and 2) it should be effective in co-existing with the EU target model.

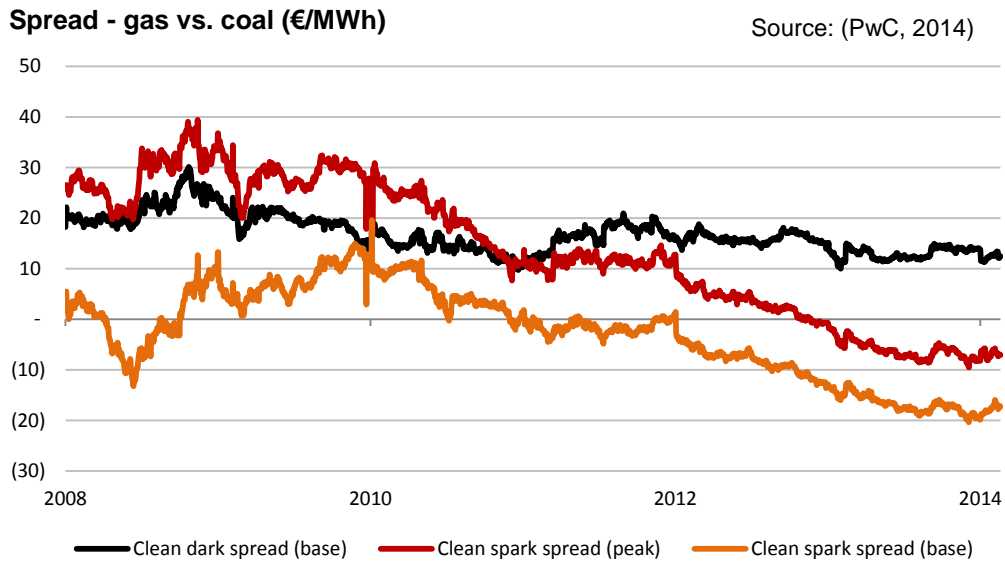


Figure 1.1 Spread

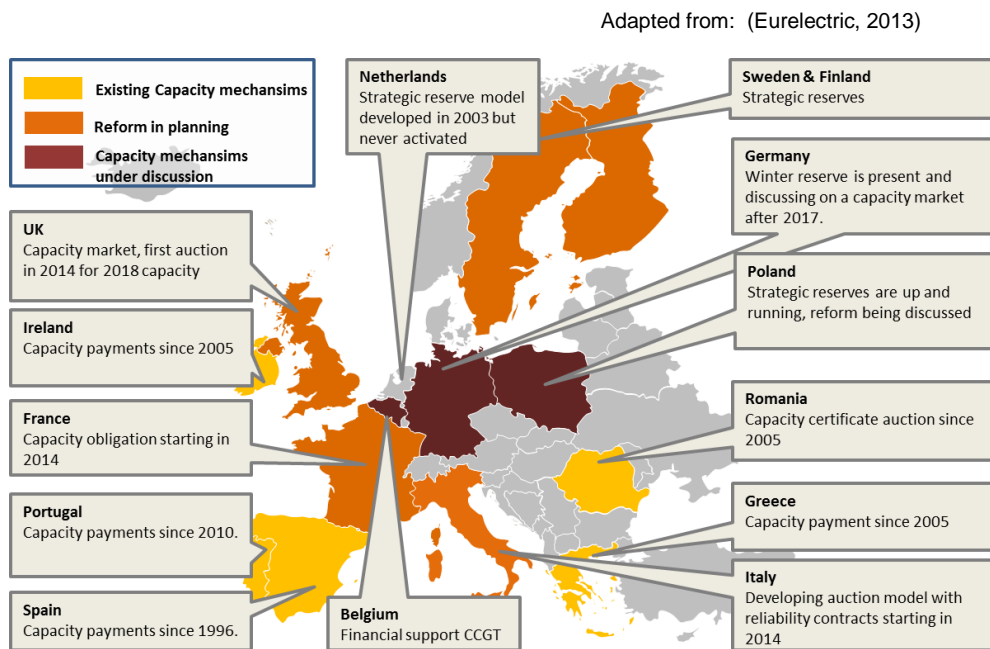


Figure 1.2 capacity mechanisms in Europe

Changing markets

Over the last couple of years, the attention and interest in capacity mechanisms to solve generation adequacy problems has increased significantly putting many countries into

thought of implementing such a mechanisms themselves. In Figure 1.2 an overview of different policy options in European countries is given. The figure shows that Germany's latest thoughts are about implementing a capacity mechanism in the form of a capacity market by 2017. However, the implementation is not the only available measure Germany could take. Several policy options come forward as a possible solution to a generation adequacy problem in Germany. These measures are: Strategic reserve, demand response and a capacity market. The purpose of this chapter is to show the different policy options Germany might have in solving the generation adequacy problem and to provide an argument for choosing one of these measures for further analysis.

The German electricity market

The main problem Germany is currently facing is the profitability of gas peak plants. The increased amount of renewables have decreased power prices and at the same time increased the volatility. The peak plants are not profitable at current prices but without these peak units, no alternative backup for the intermittent renewables exists. The most recent example of the urgency of this problem is the \$4.5 billion depreciation last February by RWE of which \$2.9 billion was due to unprofitability of fossil fuel plants (Bloomberg, 2014). Supply could possibly fall short if several peak plants would close down their operations. Several utilities companies RWE, E.ON, Vattenfall and EnBW have already opted for the implementation of a capacity market due to the non-profitability of their power plants (Reuters, 2014). An additional aspect is the phasing out of the nuclear power plants in Germany. As nuclear power plants provide the electricity system with a stable base load, the need for conventional power plants as gas and coal increases and highlights the necessity of profitable fossil peak power units.

Strategic reserve - A strategic reserve can be seen as a particular amount of generation capacity that is activated during periods of scarcity. This means that it does not bid into the regular electricity market but is only used to increase the security of supply in the electricity market. One of the advantages of a strategic reserve is that it is rather easy to implement (De Vries, 2007). This means that no radical changes to the electricity market have to be made. The main difficulty with strategic reserves is the determination of the volume of the reserve and the corresponding price. Another downside would be that the implementation would indeed solve the adequacy problem, but will not solve the main problem of the current peak units to recover costs. Under a strategic reserve, electricity prices not necessarily rise resulting in current loss making peak unit continuing making losses and even decomposition of the plants is possible.

Currently, Germany already has some reserve capacity, also called winter reserve. However, this winter reserve serves a slightly different purpose than the strategic reserve meant for generation adequacy in the way that it is mainly used for balancing issues instead. A second difference is that a balancing reserve is coordinated entirely by the regulator while the capacity reserve will be a market based capacity tender procedure (Bundesministerium für Umwelt, 2013).

Demand response - The third option is demand response management. In this option, a transformation has to be made from a market in which supply has to follow demand to an opposed market in which the demand is adjusted for the availability of generation. In this study, it would be: “Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.” (Balijepalli & Murphy, 2011). In theory, a demand response approach would diminish the necessity of having a significant amount of backup capacity because of the flexibility of demand. Furthermore, a proper demand managing system could lower the costs of balancing (Faruqui & George, 2005) and could amount to significant decreases in peak electricity prices (IEA, 2003). Currently, national TSO’s, in both the Netherlands and Germany, are already managing demand by so called “load shedding” in which large industrial users can be turned off in order to maintain system balance in a period of supply shortage. Ideally, the demand response would not be limited to large industrial users but would be used for small consumers as well. In practice, this would mean that in order to communicate the appropriate market signals to the demand side, real-time monitoring, and intelligent services combining consumer preference and market signal have to be developed and implemented (Morales, Conejo, Madsen, Pinson, & Zugno, 2014). Recently, Germany decided not to roll out smart-metering of consumers contrary to the EU guidelines. The intelligence of smart meter devices is a necessity for making demand response at consumer level a success. This means that it is unlikely that Germany will focus on consumer demand response in the next couple of years.

Capacity market - Besides the strategic reserve, the implementation of capacity mechanisms is a second option for Germany to ensure generation adequacy in the future. A capacity market is a way for the electricity market regulator to ensure the availability of capacity in a market. It is based on volume regulation by determining the amount of capacity needed to ensure generation adequacy plus a certain reserve margin. Producers can subscribe by promising that they will deliver a certain capacity at a given time in return for a payment. Most of the times this process takes place by some sort of tendering procedure in which producers can bid for the obligation to produce. According to Calaminus (2014), Germany is currently discussing two different forms of capacity markets and is expected to start with the implementation of one of the two types in 2017.

Capacity market

The current discussion on the implementation of a capacity market in Germany also brings up the discussion why a capacity market would be the ideal solution. Other solutions like demand response and expansion of the current strategic reserve have been named as well. This thesis definition will continue from the viewpoint of implementing a capacity market.

As indicated by Iychettira (2013) several studies have been performed, analysing the performance of the electricity sector under various capacity markets. In general it can be concluded that a capacity market provides adequacy in the electricity sector. A field less explored is the cross border effects on countries neighbouring a market in which a capacity market is implemented. The increased physical coupling of markets in Europe brings up the discussion what will happen if that occurs. Currently the UK and France are implementing a capacity market, but there is little knowledge about price formation and the effect on the investment climate in neighbouring countries. In the following paragraph, the existing literature on cross border effects of capacity markets is discussed.

Cross border effects – state of art

The debate about capacity mechanisms is by all means not a new debate. Extensive (both quantitative and qualitative) research has been done on capacity mechanisms. With Germany deciding on the potential of a capacity market it might follow France and the UK in implementing such a mechanism (Calaminus, 2014). A field less known are the consequences for neighbouring countries. Therefore it is important to fully explore the current literature available. Over the last couple of years the interest for cross border effects related to capacity markets has increased. Several studies have either theoretically or quantitatively assessed possible consequences for border countries. In order to evaluate the state of art literature on these cross border effects, the division is made between qualitative studies and quantitative studies.

Qualitative studies An analysis from Vattenfall (2014) discusses the possible consequences of a German capacity market for the Netherlands. Their main insights are, firstly, that the implementation of such a capacity mechanism in Germany will have influence on the price level in other countries, but in a limited way. The second consequence is the investment climate in the surrounding countries. They claim that a difference in market climate will positively change the attractiveness of the “home” market and that investments are more likely to appear in the country with a capacity market. This way, surrounding countries could become dependent on the reserve capacity of Germany in times of peak demand.

Quantitative studies At this point still very little is known about the actual consequences of a German capacity market, especially on the quantitative side. Because quantification of the cross border effects is not yet fully explored, there is not a great amount of knowledge available regarding the price evolution and capacity evolution within the surrounding countries. It is furthermore hard because it depends on the assumption you make regarding the choice for a particular capacity mechanisms, the level of security determined by the regulator and the existence of other market support measures within the electricity market. Nevertheless, some studies exist discussing the consequences of capacity markets in a quantitative way. Iychettira et al. (2013) uses an agent based modelling approach to evaluate the availability of capacity in a market in

which a capacity market is implemented. They also look at the cross border effects of a capacity market. The conclusions related to the latter aspect are that the capacity market creates a surplus of capacity that eventually dampens investment in the neighbouring countries. Furthermore this could also lead to a higher chance of outages in the neighbouring country although this difference is indicated as marginal.

A second quantitative study on the cross border effects of capacity markets is an analysis by ECN (Özdemir, DeJoode, Koutstaal, & Hout, 2013). ECN makes use of the internal model COMPETES to simulate the electricity market. They use a forward capacity market to evaluate the general impact on the market and the border markets. From their results they conclude that investment in generation capacity is shifting towards Germany and that Germany will become a net exporter of electricity and that freeriding effects are noticeable in the countries neighbouring the country with a capacity market. As a final comment the impact on the existing users is evaluated. According to ECN, the capacity mechanisms will decrease super peak prices in neighbouring countries making them less profitable, and reduce the attractiveness of investment in peak capacity.

1.3 Problem Statement

For the purpose of this research, the above discussion is seen from the perspective of Dutch energy policy makers. From the above discussion on the possible implementation of a capacity market in Germany the following problem statement is derived.

It is unclear what the consequences of the implementation of a capacity market in Germany on the performance of the Dutch electricity market are and how ultimately negative consequences can be dealt with.

This problem statement is formulated for the perspective of Dutch policy makers. Assessing this problem gives Dutch policy makers a chance to anticipate on the consequences and to come up with counteraction in order to solve deficiencies.

1.4 Societal and scientific relevance

A grasp of the destructive nature of power shortages has been shown in the introduction. A better understanding of the effects reliability options have on the performance of the electricity market, and prevention of these shortages, will increase the effectiveness of policy making in the way that policymakers can test the cross border consequences of a capacity markets in Germany under various scenarios before actually attempting to counteract possible negative effects caused by such a capacity market.

The scientific relevance lies in the fact that this study enhances the current knowledge of electricity market modelling by adding cross border effects of a Germany capacity mechanism on the Dutch electricity market. Furthermore, this research can be used as

an endorsement in validating previous work. This is important given the limited research that has been done on the subject. At last, this research elaborates on existing literature on capacity markets and electricity market theory and will provide a basis for future research as well, thus continuing the cycle.

2 Research framework

The introduction discussed the current discussions in Europe regarding the use of capacity mechanisms to ensure generation adequacy. It made clear that there is limited literature available on the cross border effects of a capacity market. This chapter describes the framework that is used throughout the research project. Research questions will provide a basis for the research and are accompanied by research objectives and an explanation of the research method and data collection methods that are used.

2.1 Research objective

This research tries to provide knowledge, insight and information that can contribute towards helping policy makers anticipate and develop policies taking into account the cross border effects of Capacity markets. More specifically, it tries to contribute to solving the problem policy makers in liberalised energy-only markets, like West-Europe, have in ensuring the necessary power generation capacity by providing knowledge about the cross border consequences of capacity markets in an energy-only market.

Perspective and deliverable

The perspective in this research will be model using/building/adjusting. The basis here is provided by theoretical concepts of energy markets and capacity market designs. The deliverable is working model of a German Capacity market in an energy-only market connected to the Dutch electricity market, implemented in the Power2Sim model. This deliverable is accompanied by insights for Dutch policy markets regarding the cross border performance of a Capacity Market in a Western-European electricity market, including some policy recommendations.

2.2 Research questions

From the previous discussion and research objective stated above, the following main research question was formulated:

Main research question

To what extent does the implementation of a Capacity Market in Germany influence the performance of the Dutch electricity market?

Sub questions

- 1) What performance indicators can be derived from literature that is relevant for assessing the cross-border consequences of a capacity market?
- 2) How are the theoretical models of Capacity markets translated into implementable equations (conceptual model)?
- 3) How is the conceptual model implemented in the Power2Sim simulation model?
- 4) What are the consequences for the Dutch market given the performance indicators from (1)
- 5) What are the consequences for the Dutch market under specific scenarios?

- a. A renewables dominated market, both Germany and the Netherlands
 - b. Increased physical market coupling in terms of interconnector capacity
- 6) What recommendations for policy makers in the Dutch electricity sector can be given to improve the cross border effects of a German Capacity market on the performance of the Dutch electricity market?

2.3 Research Method

In the scientific literature found on electricity markets and specifically in modelling electricity markets, three methods are used most frequently. The methods are: system dynamics, agent based modelling and equilibrium models. All of these models have their strengths and weaknesses. For a more elaborate discussion on the three modelling paradigms please see Iychettira (2013).

The choice of modelling tool for use in this master thesis is the software package Power2Sim. Power2Sim is an electricity market model which simulates the European power market using a fundamental model. The base model consists of three main parts. First there is the load model which outputs hourly electricity prices based on real market data. Secondly there is an import-export model which simulates the cross-border flows of electricity in Europe. At last there is a CO₂ model that calculates the CO₂ prices for the entire market.

The reason that Power2Sim is an effective tool for the purpose of this thesis is as follows. The objective of this research is to evaluate the performance of the Dutch electricity sector. Within electricity markets, the electricity price is the basis for numerous decisions like investment decisions, decomposition of plants and cross border trade. Being able to accurately calculate future electricity prices is therefore preferable. For this purpose, the Power2Sim is highly appropriate since it outputs hourly electricity prices.

Secondly, the Power2Sim package is very detailed. Developing a model from scratch would take an enormous amount of time. Time which can be spend more effectively in actually provide valuable outputs and advices. This, in combination with the model being quite flexible in the sense that it is manageable to add extra modules to the model, makes it an attractive tool for use for the purpose of this study. Thirdly, the Power2Sim tool has been developed by German experts who have an extensive knowledge about electricity markets in Europe which increases the reliability of the outcomes that will be provided. At last, providing validation of the cross border effects of capacity mechanisms is valuable. Therefore, it is important to compare the results of different tools and modelling paradigms. The Power2Sim tool has never been used for this purpose, while it has the potential to do so, and could thus function a validation purpose for the existing ABM and equilibrium models.

Validation

For the validation of the model several methods are used. Firstly there will be made use of expert validation. The model has been made by electricity market experts and the capacity market to be implemented will be discussed among

several different expert parties. Furthermore, the outcomes of previous research could be inserted into the Power2Sim model. This can be done as a separate scenario and will act as a validation of the results. Besides that, there is a great deal of data available on historic electricity price and historic trade volumes between countries. These will be used for historic validation.

2.4 Research approach

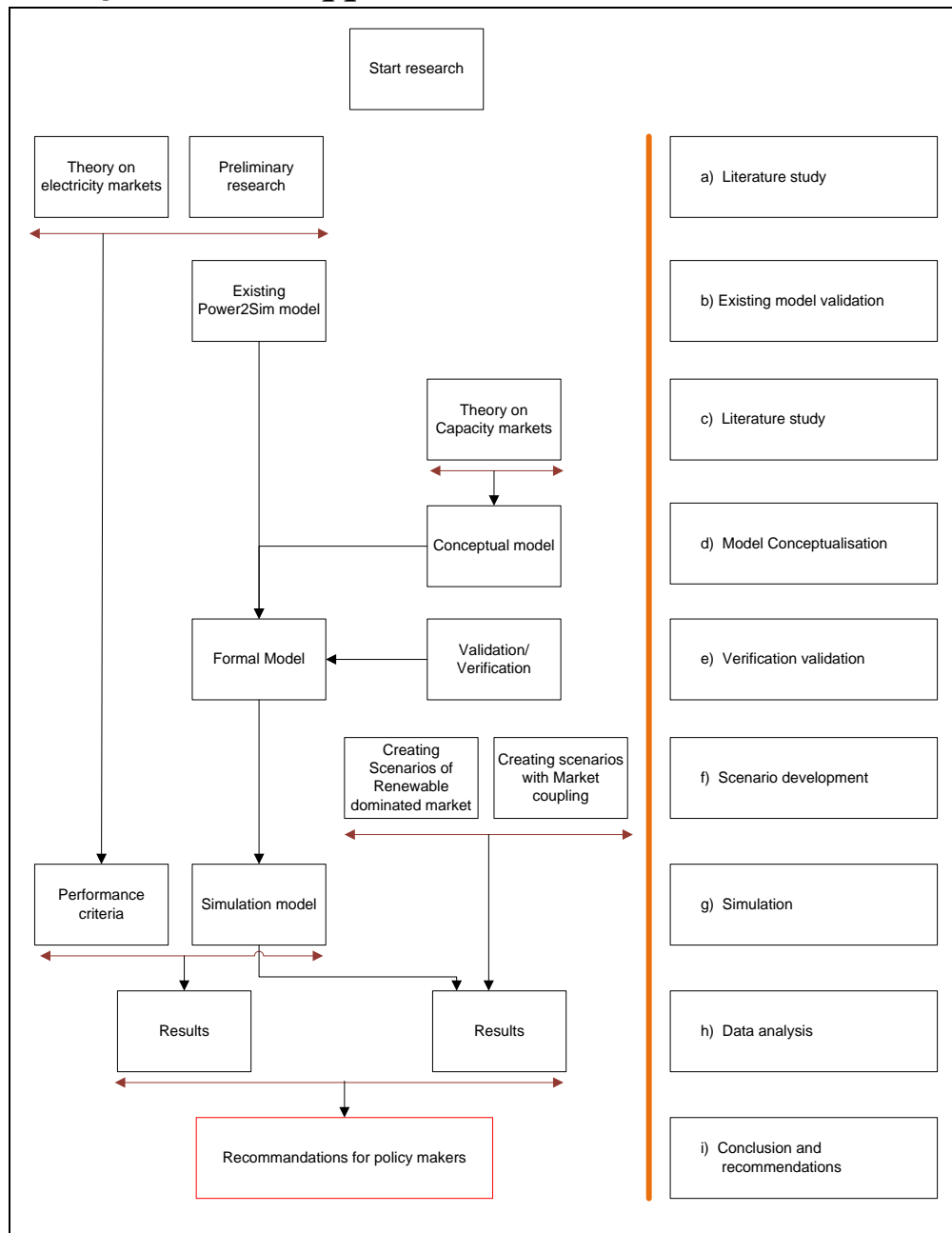


Figure 2.1 Research framework

This framework is formulated as follows:

(a) A literature study regarding theory on electricity markets and on previous research results in a set of performance indicators. (b) Introduces and validates the existing model which is going to be used for further research (c) uses theory on capacity markets to provide the basis for the conceptual model created in (d). This conceptual model transferred to an actual formal model and verified in (e). (f) Used current knowledge about renewable energy electricity markets and knowledge about the effects of different regimes on electricity markets to build scenarios. The simulation model is confronted with the scenarios and the performance indicators in (g) resulting in several outputs that are analysed in (h)

which are the basis for the recommendations to policy maker or in other words the research objective in (i).

Data Gathering and processing

Table 2.1 Data requirements

Research step	Data requirements	Data analysis tool/source
a)	Scientific Articles	Scopus/Google Scholar
b)		
c)	Scientific Articles	Scopus/Google Scholar
d)	Dummy Data	-
e)	Real life data from PwC and Energy Brainpool	
f)	Scenario Data	Interview/literature
g)	-	-
h)	Model output data	Excel/R-studio
i)	-	-

3 Electricity market theory

In order to fully understand the current debates about capacity markets, it is recommended to firstly catch a grasp of the fundamentals of electricity markets, and energy only-markets in particular. This chapter elaborates on energy-only markets, their implication and possible solutions provided by literature. The goal of this chapter is to identify performance indicators based on electricity market literature. The last part of this chapter explores the performance indicators from literature that can be used to evaluate the performance of a capacity market in Germany and the cross border impact of a capacity market in Germany.

3.1 Energy-only markets

An energy only market is an electricity market which does not differentiate between capacity and price, making the market entirely based on the electricity price and the marginal costs of production. In theory this should lead to optimal electricity market that always clears and provides the necessary incentives for producers to invest in new generation capacity. However, in reality there are quite some problems occurring in these energy only markets.

The missing money problem In energy-only markets, investment in capacity is solely dependent on electricity prices being high enough to recover costs. In theory, during periods of scarcity, price peaks will emerge that are high enough to recover the costs of peak capacity. Often these periods of scarcity only exist during a limited amount of hours, making high peak prices necessary for the peak capacity units to recover costs. In many markets, the regulators have put a cap on peak prices. This cap reflects the price level in which consumers rather be closed off from electricity instead of paying a higher price, this price is also referred to as the value of lost load (VOLL). In the literature, estimations of the VOLL differ widely in their assumptions and values providing a lot of freedom for application in an electricity market (Cramton & Lien, 2000). However, in some cases peak capacity is in need of higher price than the price cap given the limited number of operational hours making it impossible to recover the fixed costs. The difference between the necessary price to recover costs and the price cap put up by the regulator can be referred to as the missing money problem. To illustrate this example, Figure 3.1 shows a load duration curve with and without price cap.

Inelastic demand Imagine that demand in electricity was perfectly and instantaneously elastic. This would imply that the market always clears, making the market absolutely reliable. Sadly enough this does not reflect the current characteristics of the electricity market. The elasticity of demand reflects the consumers' willingness to pay for more or less supply in the very short run by balancing supply and demand (Joskow P. , 2006). The article states that the limited amount of real time demand response is the cause for the spot market to be extremely inelastic. This not only means that prices will go up significantly in periods of scarcity but it also means that the

possibility of a blackout is present due to the non-responsiveness of consumers. In the orange line situation (Figure 3.2), a blackout occurs. This means that the supply cannot meet the demand and the demand is insufficiently elastic to withhold demand and clear the market. Recent developments in this area are discussed by Joskow et al. (2012). Although there is more attention for elastic demand, progress on this side is still marginal. Consumers do not have powerful incentives to lower demand during periods of stress in the system. This means that today's market can still be seen as the orange line.

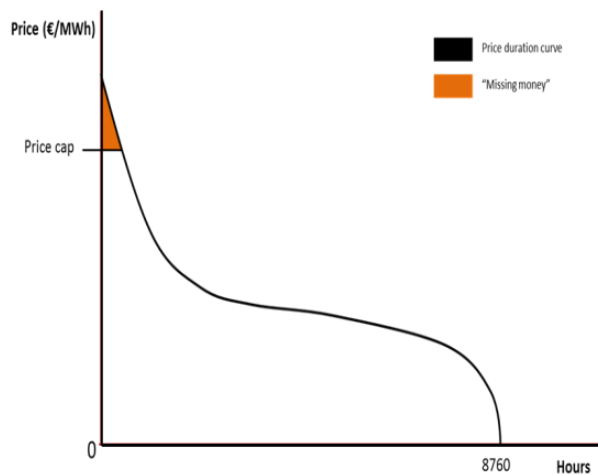


Figure 3.1 missing money problem

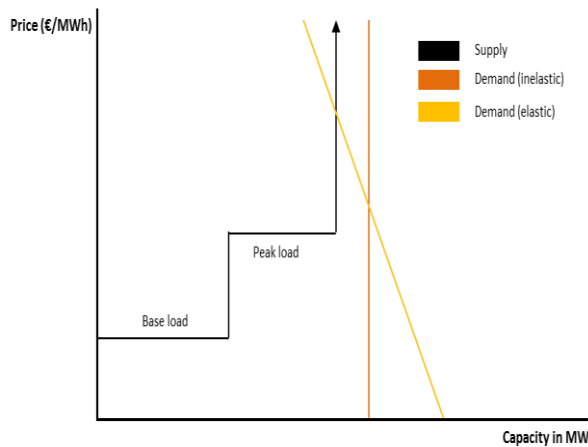


Figure 3.2 demand supply

Investment cycles As explained, producers determine their investment on future demand and electricity prices. However, due to the volatility of the prices, producers tend to only invest when they are certain that they will earn enough to recover costs in the future. According to Ford (Ford, 1999), the risk averse behavior in combination with an inadequate lengthy time horizon is the main cause for this delay in investment. Generally it takes several years before new production capacity is in operation leading to a delay in investment. This delay might cause investors to overreact building too

much capacity once the period of scarcity arises. This cycle of over and under capacity is called investment cycle.

Market Power In general, price peak appear in periods of shortages. However, due to strategic behaviour of electricity producers, electricity price could be manipulated resulting in peak prices appearing outside periods of scarcity as well. Producers can do so by withholding capacity that they put available in the energy only market. This will cause a shift of the merit order, resulting in possibly significantly higher electricity prices. However market power is hard to measure due to the in-distinguishability of strategic behavior and actual scarcity. This way, investors are not sure whether the witnessed peak prices are a true investment signal or a signal caused by strategic behaviour, increasing uncertainty in the market. According to Borenstein et al. (2000) these artificial price signal might not only damage the electricity sector in terms of inefficient investments, but they might also have an impact on electricity intensive industries who might switch off to less efficient electricity substitutes in case higher prices maintain in the market.

Reliability as a public good

In case a producer is not producing, the corresponding revenues are zero. However, the fact that this producer is available in the market, although not actively, still provides reliability to the market (Jaffe & Felder, 1996). In case of a sudden demand rise or sudden failure of active power plants in the system, the system might put a call on this particular plant therefore assuring reliability for the consumers in the system. This way, the energy-only market does not take this reliability factor into account making it likely that underinvestment will occur. (Joskow & Tirole, 2004) Since we can assume that power plant failure is somewhat random, the presence of generation capacity that is not in the merit order, but might be in the merit order in case of a plant failure can thus be considered a public good.

Price volatility

The volatility of electricity prices has a somewhat ambiguous role in the energy only market. On the one hand, prices peaks allow producers to recover their fixed costs (Stoft, 2002), but on the other hand, volatility increases the investment risk while producers are looking for ways to diminish risks and uncertainties as much as possible. The sector already has high investment risks due to long construction times and high capital costs. Estimation of future revenue in a highly volatile market therefore increases risk. In order to regulate the maximum price of electricity, many countries introduced a price-cap. Due to inelastic demand, prices might go to infinity. This price-cap would ideally be set equal to the VOLL, but literature show that there is a wide variation in estimations of this VOLL, ranging from €2400/MWh to €20.000/MWh. Setting the price-cap too low might have a positive effect on the volatility of the market, but might increase the missing money problem as addressed previously. On the other hand, setting it too high might lead to higher volatility than necessary and leads to windfall profits for electricity producing companies.

3.2 Capacity mechanisms

The previous paragraph provided insights in the reasons why generation adequacy is not optimal in nowadays energy only markets. This paragraph sheds light on the solutions literature provides in addressing this adequacy problem. Within the available literature on capacity mechanisms a rough distinction can be made between price based incentives and quantity based incentives. The latter mainly focusses on providing the actual volume incentives in the electricity market whereas the former focusses on measures with a direct effect on the electricity price. In this case, higher prices cause the right investment incentives for producers. Since every country has a different structure, the outcomes may differ per country making a general assessment of less value. Therefore, the main focus in this paragraph is on the theoretical concepts and empirical observations.

Capacity payments were among the first capacity mechanisms as a solution for the generation inadequacy problem and were introduced by Vazquez et al. (2002). Basically, it is a subsidy given to the electricity producer for every MW of capacity available. Over the years, capacity payments were introduced in Columbia, Spain and Argentina. However, the successfulness of these measures is disputed. As Pfeifenberer et al. (2009) discusses, the difficulty with capacity payments is in the determination of the payment. For optimal functioning the payments need to be in accordance with the actual market providing the appropriate investment signals.

Strategic reserve, often also called Mothball reserve, is another price based mechanism. For this mechanism described in an article by Stoft (2002), the system operator secures a number of power plants to be used in case of supply scarcity in the market. This way, the system operator ensures that there is enough available generation capacity because it can always fall back on its own reserves. This approach is however criticised by Finon et al. (2000) for disturbing the regular electricity market in the way that it takes away part of the incentives for generator to invest in especially peak generation units. Over the years, strategic reserves or similar concepts have been introduced in Sweden, France and New Zealand.

Capacity requirements are in contradiction to the first two mechanisms, a concept based in volume rather than a direct price measure. The clearest example of an implementation is the PJM electricity market in the United States as described by PJM Interconnection, L.L.C (2003). This price-based capacity mechanism obligates load-serving entities to require a number of capacity credits equal to their own peak demand plus an additional reserve margin.

Reliability options are a fairly new approach for capacity mechanism. The idea was presented by Vazquez et al. (2002) and is based on common financial options. They suggest that the system operator purchases call-options from electricity producers which give the system operator the opportunity to pay the options' strike price in case the electricity price exceeds this price. Looking at the mechanism this way, it can be

seen as a price cap as well (Vries, 2007). Since the system operator purchases a volume of options equal to the desired generation level, generation adequacy can be reached. For a more detailed discussion see Vazquez et al. (2002). An alternative closely related to reliability contracts named bilateral reliability contracts has been suggested by Vries et al. (2004). The alternatives differ in the sense that the latter requires the load-serving entities to buy options instead of the system operator as is the case in general reliability options.

Capacity subscription is another capacity mechanism based on quantity measure and was suggested by Doorman (2003). This mechanism differs from the other capacity mechanisms in its essence. Capacity subscriptions essentially obligate every consumer to subscribe on a certain level of capacity. This level chosen is the maximum capacity they are allowed to consume during peak hours. Of course, this “reliability mechanism” is only exercised by the regulator in case the available capacity not able to fulfil market requirements.

Capacity market

A capacity market aims at providing investment incentives for producers to invest in generation capacity. A capacity market can be seen as a market wide capacity mechanism. This means that the inner structure of the market will be adjusted to ensure generation adequacy. The idea is that there will be a separate market for capacity and for energy with generator being paid a certain payment in order to provide the system with reliability due to sufficient investment.

Various countries in the world have implemented a variety of different a capacity market. Roughly the distinction can be made between forward capacity markets and central capacity markets. A strong disadvantage of a central capacity market is that the complexity of the electricity market in general increases. In general, the more complex, the higher the risk of regulatory deficiencies (Pfeifenberger, Spees, & Schumacher, 2009). The idea of capacity markets is definitely not new. Several countries in different continents have already implemented such a mechanism. All with their own design and differences in performance. Below, an overview of different types of capacity markets currently implemented is provided.

PJM From all capacity markets, the PJM capacity market is probably the best known. The capacity market is also known as the Reliability Pricing Model (RPM). The RPM contains of a sequence of auctions for the delivery of power in the future. The RPM has a three year in advance forward market, meaning that producers commit to delivery three year in advance. This contains the major part of capacity and this first auction is known as the Base Residual Auction (BRA) (PJM, 2014).

NYISO In the NYISO capacity market, a demand curve is specified. In this case, all suppliers will be paid according to the aggregate available capacity. The NYIOS demand curve is created administratively. The demand curve consists of three parts. The first part consists of a horizontal line indicating a shortage above 8%, a horizontal line used as price cap, and a linear section connecting the two horizontal lines. The idea of the horizontal sections is as follows: above a certain capacity, any additional capacity

has 0 added value for reliability and on the other extreme, once the system is under sufficient stress, energy prices alone will give the right incentives for investment in new generation capacity.

Brazil The Brazilian system can be defined as a forward capacity market. Each of the electricity distributors have to determine their own energy demand. These demands are added up forming the base for the energy auction. Afterwards, the producers that won the auction are involved in bilateral contracts between themselves and the electricity distributors. From the first auction in 2004, several auctions are held each year. Every auction differing in duration from 5 till 30 years.

3.3 Performance indicators

In order to fully compare the different capacity mechanisms we make use of the literature available to determine the performance indicators for the capacity mechanisms. Several comparative studies have been found in literature determining how to evaluate the effectiveness of capacity mechanisms in an energy only market. The articles by de (De Vries L. , 2007), (Oren, 2005), (Cramton & Stoft, The convergence of market designs for adequate generating capacity., 2006) and (Joskow P. , 2006) were used to identify the performance indicators. The results can be found in Table 3.1.

Considering the cross border effects of the capacity market some indicators are more important than others. On the long term the focus will be on the investment climate in the Netherlands compared to the German situation. On the short term, the effects on trade, prices, volatility and reserve margin would be interesting to look at.

Table 3.1 Overview of performance indicators per author

De Vries (2004)	Oren (2005)	Cramton and Stoft (2006)	Joskow (2006)
- Investment incentive	- Investment incentivize	- Investment incentive	- Investment incentive
- Available during peak hours	- Stable income for producer	- Replace the “missing money” problem	- Availability during peak hours
- Stable prices	- Institutional feasibility	- Possibility of hedging to reduce producer/consumer risk	- Decrease volatility
- Handle regional shortage	- Incentivise performance	- Both short and long term effectiveness	- Prevent market power
- Supply-side efficiency	- Facilitate risk sharing between consumers and producers	- Targeting capacity quantity	- Possibilities for new entrants
- Effective in open market	- Provide incentives on the consumer side	- Stable capacity price	- Reflect transmission
- Feasibility (physical and institutional)			- Congestion and reliability

The central research question “*To what extent does the implementation of a Capacity Market in Germany influence the performance of the Dutch electricity market*” focusses on the performance of the Dutch electricity market. It is therefore important to be clear what performance indicators are relevant and adequate in answering the main

research question. The focus will be mostly on the outcomes of the system rather than administrative and logistical difficulties. Besides measuring the effectiveness, it is also interesting to look at the results from the perspective of the system as a whole. When it comes to electricity, the Dutch government has three main public goals that need to be pursued. These three goals are: Reliable, affordable and clean. In order to get a good insight in the impact of a capacity market in Germany these goals need to be taken into account as performance indicators.

Reliable

Reliability is defined as the availability of energy in both the long and short term. This means that the electricity sector has to provide electricity taking into account future demand and availability of resources as well as the extent to which electricity is actually delivered to the consumer. A third issue is the extent to which we are able to resist an energy crisis, but this is beyond the scope of this study and will not be taken into account. The following two performance indicators correspond with the issue of reliability.

- LOLE, loss of load expectation
- Reserve margin

Affordable

Affordability is defined as an economic efficient supply of electricity. This includes both efficiency, low marginal cost, as purchasing power on the consumer side. In addition to the electricity price and volatility, the following performance indicator is used:

- Total consumer costs

Sustainable

Sustainability is defined as being able to produce electricity according to the highest environmental standards possible. Sustainability consists of many aspects including all kinds of different greenhouse gasses and soil and water pollution. The latter one is impossible to extract from the model. Regarding greenhouse gasses, the most 'popular' greenhouse gas is chosen. The following indicator is used to determine the sustainability of the electricity sector:

- Total CO₂ emission of the electricity sector

Figure 3.3 summarizes the performance indicators that are going to be used in this research.

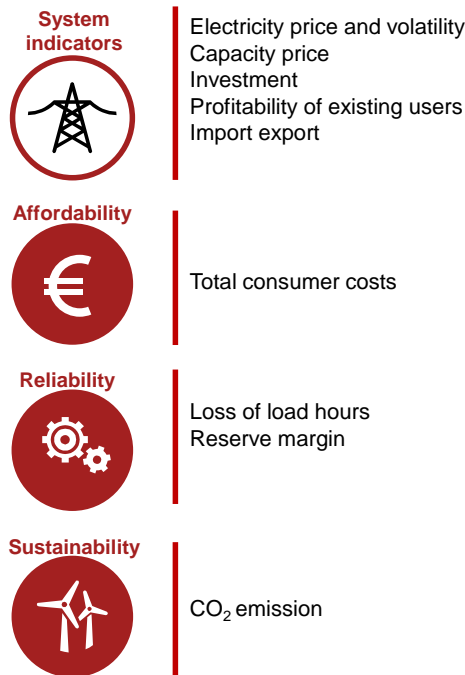


Figure 3.3 Summary performance indicators

3.4 Conclusion

The aim of this chapter is to provide insight in the problems associated with energy-only markets, the mechanisms suggested in the scientific literature to tackle these problems and the current considerations for capacity remuneration mechanisms in Germany. From the above discussion, it is unlikely that Germany will be able to focus on consumer demand response in the short term, although it seems like a promising option. This lack of demand response is a failure in the current electricity market. An ideal market would have such a demand response but until this is feasible, other measures need to be taken. A strategic reserve or a capacity market could possibly fulfil this transition role and therefore, demand response is not included in the further analysis of this thesis. Furthermore, several performance indicators have been identified in the literature of which a selection is made. These performance indicators will be used to evaluate the consequences of a German implementation of a capacity market.

4 The Power2Sim electricity market model

This chapter describes the model environment in which this research takes place. The chapter consists of two major parts, the model description itself and the modeling methodology regarding implementation of a capacity market in the model. It provides a short description of the Power2Sim model and its scope and some of the major assumptions that it includes. The limitations of the model will be discussed, as well as the relevance for this methodological approach. The second part elaborates on the strengths and weaknesses of using Power2Sim for this particular research and provides a methodology on combining the Power2Sim model with an investment model and a capacity market module.

4.1 Power2Sim model

The model that is going to be used for the purpose of this thesis is the Power2Sim model. A capacity market is going to be built in this existing model. The purpose is to provide an overview of the dynamics of the existing Power2Sim model. Power2Sim is developed by German experts in electricity markets aiming to adequately estimate future electricity prices.

Power2Sim is a fundamental model based on merit order principles of European energy only markets. This means that the model is based on least cost optimization, also called economic dispatch. It outputs hourly electricity prices as well as predictions for future CO₂ prices and electricity trade. The power2Sim model is based on 29 nodes or price zones including EU27 plus Swiss and Norway. Countries neighboring this geographical region, like Russia, are included as external input. This chapter discusses the existing model components of the Power2Sim model and it furthermore describes in what way, a capacity market would be implemented in the current model structure. Figure 4.1, an impression of the model interface is given.

The following paragraphs describe the basic model features in a comprehensive way but in a limiting way to the mathematics behind it. For a more technically detailed descriptions please see appendix A.

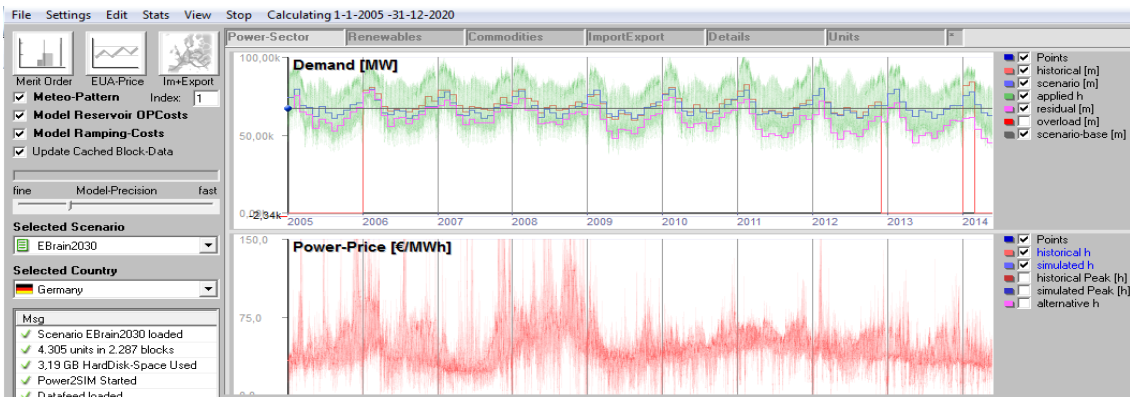


Figure 4.1 Power2Sim model interface

4.1.1 Basic model features

Power price

The power price is calculated hourly by matching supply and demand while minimizing the costs of generation. This is referred as to the minimal costs economic dispatch. The minimal costs are calculated by creating a merit-order, in other words, a sorted list of all the available generation units including their marginal cost of production. The intersection between the merit-order and the demand at a particular hour is the electricity price for that particular hour. This means that the marginal costs of production have a large influence on the electricity price. The Following formula is used to determine marginal costs (MC) of a power plant.

$$MC = \frac{\text{Operating expenses} + ((\text{fuel costs} + \text{transport costs}) + CO2 \text{ price} * CO2 \text{ emission factor})}{\text{efficiency}}$$

Please note that the MC will be different for every single power plant in the system since each plant has its own efficiency, operating expenses and fuel costs differ per technology.

Demand

The electricity demand is calculated for each country separately. The sensitivity of the demand profile is estimated by linear regressing of historical demand data. This is done taking into account:

- National and regional holidays
- Temperature sensitivity
- Working days/non-working days

Until the last day of available historic data, the demand is equal to the historic value. After this data the demand values are estimated.

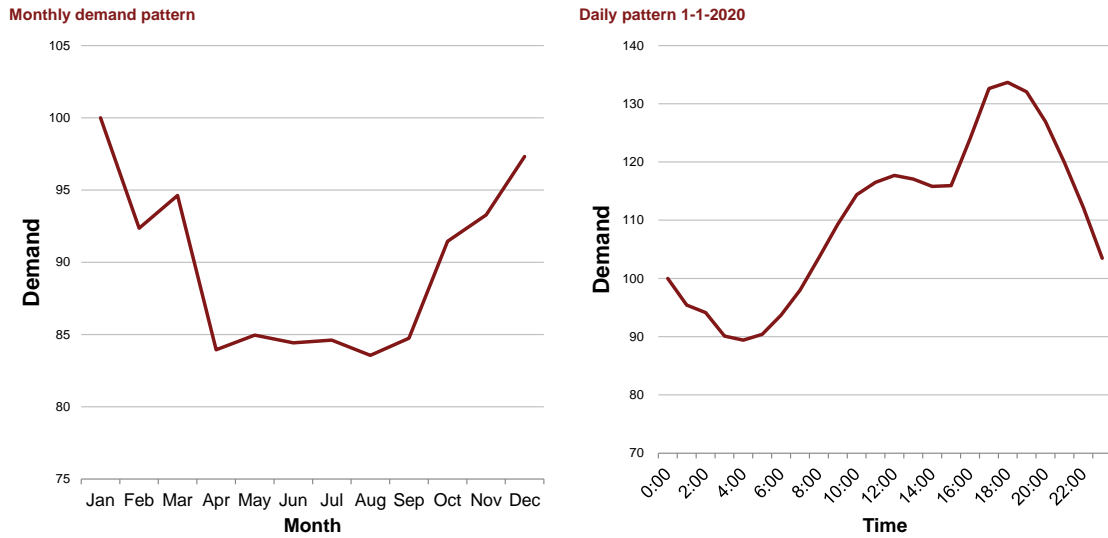


Figure 4.2 Monthly and Daily demand pattern 2020

Intermittent resources

- Wind power**
 Wind power is highly sensitive to fluctuation in the weather conditions. Therefore it is hard to adequately make future forecasts. This is modeled by creating so called 'wind loops'. These are recorded wind patterns translated to future wind patterns. For instance the January 2015 scenario is derived from the historic wind pattern of January 2010. For every node, if available, detailed historic data is loaded into the model. Due to the fact that historic data is the basis for calculating a wind pattern instead of an artificially created wind pattern, geographic differences in the availability of wind are included. Although Power2Sim recalculates wind patterns for future months, it basis it calculations for all countries based on the same hour. This prevents for instance that wind data at a particular hour differs significantly between two geographically almost identical locations. For example when comparing the Netherlands and Germany. Power2Sim is able to translate this data into

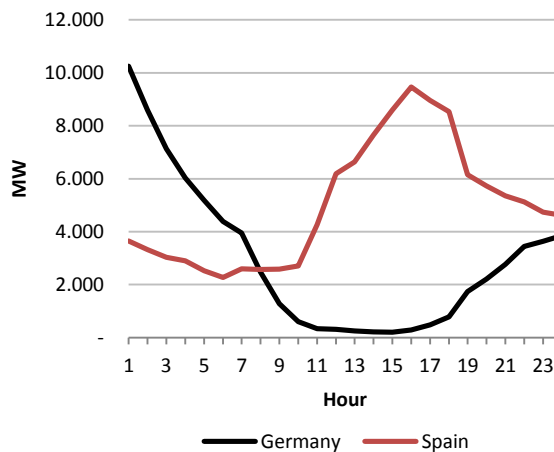


Figure 4.3 Wind patterns Germany and Spain on April 3rd 2020

different wind patterns of which 10 have been pre-programmed into the model. Installed wind capacity itself is modeled as an external input since it is highly policy driven.

- *Solar power*
Solar power forecasts are made by using country specific monthly profiles. The same principles are used as for the calculation of wind patterns. For the installed capacity the same as for wind power is applied.
- *Hydro power*
With hydropower, the distinction is made between running water plants, Pump storage plants and storage plants. The former two are treated as residual load while the latter is treated as a conventional plant.

Conventional technologies

Besides renewable resources, the Power2Sim has several conventional technologies. These technologies are (Energy Brainpool , 2013):

- Nuclear
- Lignite
- Oil
- Biomass
- Hard-coal
- Gas
- Reservoir
- Other

Appendix C contains a list of all the power plants in Germany and the Netherlands that have been used for the analysis.

Congestion

The entire system is simulated single merit order model, constrained by the capacity of interconnectors between different countries. The model contains 29 nodes. An overview of the countries and interconnectors is provided in Figure 4.4.



Figure 4.4 Geographical coverage of the Power2Sim model

This single merit order constrained by interconnector capacity results in allocation in- and export quantities. Firstly the two countries with the highest difference between importing costs and exporting costs transfer the amount of available capacity. This

process is repeated until the intrinsic costs of all countries are balanced or no more capacity is available between two countries or demand or power plant do not allow further in- and export. The process that is used is called re-dispatching. This means that one country is forced to ramp-up production and the other country to ramp-down production. This results in converging (or equal) electricity prices in the two countries. This procedure is illustrated in Figure 4.5. Assume there are two countries, A and B. In case of no re-dispatching, or simulation of isolated countries, the prices P_A and P_B are outcomes of market A and B (left figure). As you can see there is a price difference between the countries. In the right figure, you can see that price $P_{A,B}$ would be the price of the combined markets. k illustrates the export from B to A since B is the low price region. The automatically means that country B needs to ramp-up production and country A needs to ramp down production until the prices are equal. However, transmission between two countries is often limited by interconnector capacity. If the interconnector capacity is smaller than k , the prices will converge, but equal prices are not reached. On the other hand, if the interconnection is larger than k , the prices will be equal and some of the interconnection will remain unused.

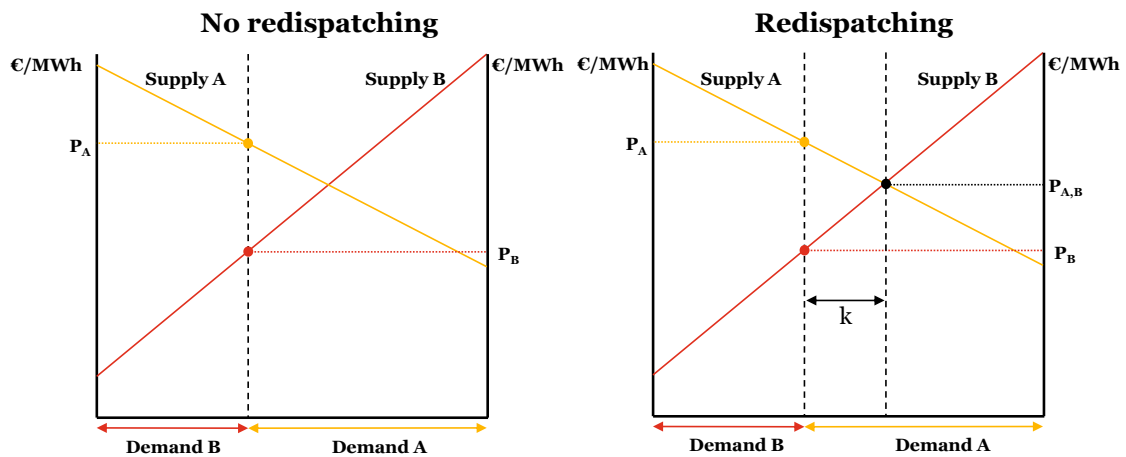


Figure 4.5 Re-dispatching and no re-dispatching

A complete overview of the Power2Sim model is provided in Figure 4.6.

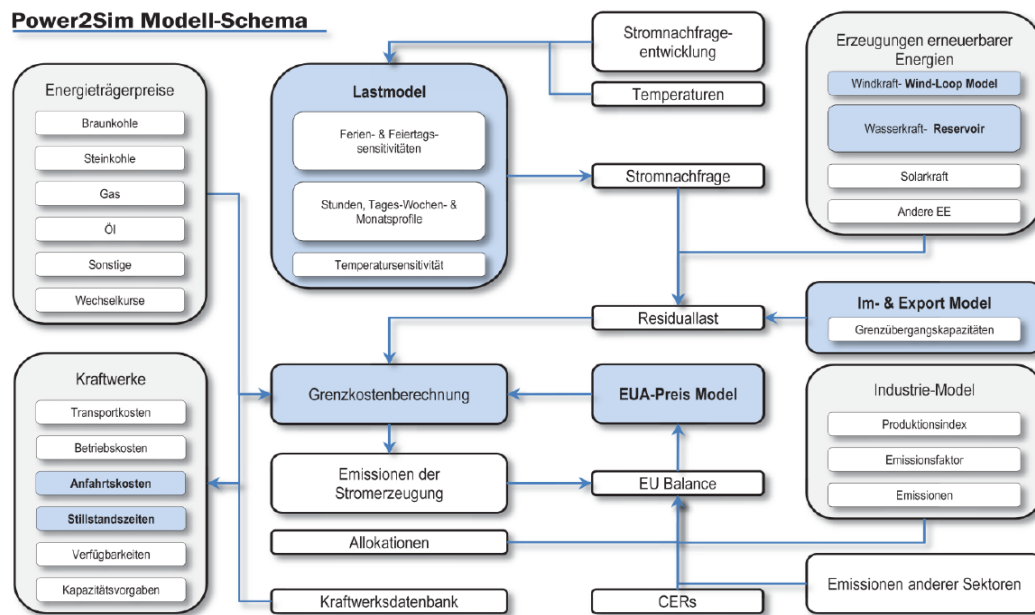


Figure 4.6 Power2Sim model

4.2 Model criticism

Although the model includes a great amount of detail and interesting features, there is also room for improvement. A couple of these are presented below.

One of the major points of critique is the way that new power plants are modeled. Power plants are categorized in the categories gas, coal, lignite and oil for conventional power plants. Existing power plants are imported from the power plant data base with detailed data on plant specifications. This means that two gas plants can have a completely different efficiency resulting in different marginal costs for these two plants. New power plants are added to the model according to features that have been pre-defined in the model. Consequently, it is not possible to add gas plants with different marginal costs. This means that a choice has to be made beforehand whether new plants should be peak or base gas plants. This is not realistic and needs to be improved in order to make the model more realistic. The same argumentation holds for coal and lignite plants in which a wide range of different technologies is available.

The availability of power plants is not fixed, which is a good way to simulate unavailability of power plants. However, the availability pattern is the same for all power plants of a particular technology.

CHP (combined heat power) is implemented in the system as a percentage of the available amount of conventional plants. This means that the increase in CHP is purely dependent on an increase in conventional capacity. In the real world, some plants are dedicated CHP plants, producing electricity on the side. It would be better to distinguish between CHP and regular electricity plants to increase modelling accuracy.

A final point of critique is the use of a deterministic model for non-deterministic processes. There is no randomness involved in the model. It could therefore be the case that the wind patterns in the system are outliers. This is partly solved by using several

different pre-calculated wind patterns but it is not possible to do a Monte Carlo analysis on 1000+ runs to determine the robustness of the system.

4.3 The null hypothesis and the relevance of Power2Sim

Section 2.3 on the methodology already discussed the choice for the modeling paradigm, but it is also important to check the relevance of Power2Sim for this particular study. Before starting the analysis and develop a conceptual model it is important to think about why this approach is used to tackle the capacity market issue. This paragraph therefore presents the null hypothesis of the electricity market without intervention. It also presents the relevance of the Power2Sim regarding this study by looking at the overlap between what we do not know yet, and what the model is capable of.

The null hypothesis

As explained in chapter 1, energy only market should in theory provide generation adequacy in the market but experience has proven that this is often not the case. This results in the following hypothesis.

An energy only market does not provide the right incentives for investment in generation capacity investment to ensure generation adequacy in the electricity market and this effect will become stronger in the future.

This non-optimal functioning of the electricity market is likely to be negatively affected by a renewables dominated market in the future. With gas peak plants having difficulties to recover costs, earlier explained as the missing money problem in section 3.1 the functioning of the electricity market is under pressure. According to literature, renewables tend to decrease wholesale prices which again negatively affect the peak plants. The expectations for the future are, especially since Germany has a huge focus on renewables, that the business case for peak plants is threatened to a far greater extent than it now already is. According to literature a capacity market is a possible solution for the failing energy only market, and signs are there that Germany is actually going to implement one. This makes this issue topical and relevant.

There are three main reason for this problem to be replicated in a simulation model. Firstly, there haven't been implemented any capacity markets in countries neighboring the Netherlands yet¹ so no empirical data is available. Secondly, modeling provides us with the ability to test multiple designs and scenarios Thirdly, modeling the problem can prepare policy makers for the consequences before the actual implementation and provides them with insight on how to limit eventual negative effects.

The relevance of the Power2Sim model

In chapter 2, the main research question is formulated with the purpose of finding an answer to the extent to which a capacity market affects The Dutch electricity market. In

¹ The UK obviously has implemented a capacity market, but since there have been no auctions yet, there is no data available regarding the consequences.

section 3.1 several performance indicators have been proposed to measure this effect. The figure below shows the relations between these performance indicators. From the figure it can be concluded that the electricity price is the main driver for the calculation of the performance indicators. It has a feedback loop with investment which create a portfolio which again results in a particular reserve margin, loss load hours and CO₂ emission.

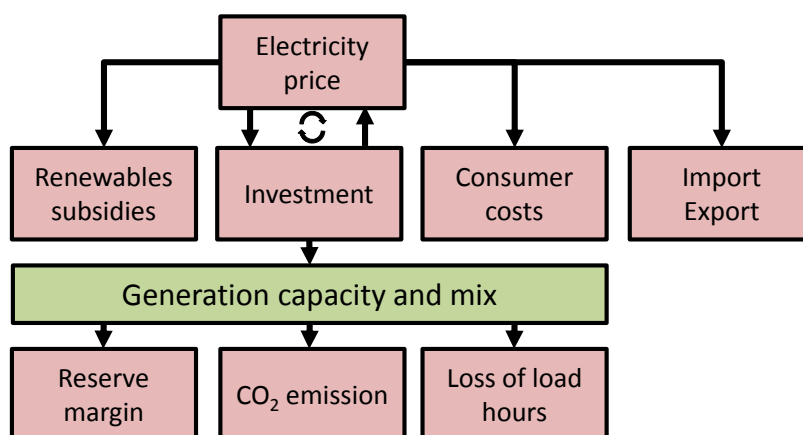


Figure 4.7 Relation between performance indicators

With electricity prices being the main driver behind this study, it is important that the model is capable of calculating detailed electricity prices given a certain state of the system. The main advantage of using Power2Sim is that it is capable of calculating electricity prices at an hourly basis as well as the intercontinental flows of electricity. Although Power2Sim has some limitations that have been discussed in the previous paragraph, the choice is made to use the model as a basis for the analysis.

4.4 Capacity market and Power2Sim

In the current Power2Sim model, no capacity mechanisms are incorporated. It is important to be clear and precise on how a capacity market is actually incorporated in the current Power2Sim model. A capacity market is used to ensure enough investment in generation capacity. This suggests a close interaction between investment and a capacity market. A reliable investment algorithm is preferred when implementing a capacity market in the model.

This instantly shows one of the major limitations of the current Power2Sim model, the lack of an endogenous investment algorithm. In Power2Sim, investments are introduced through external scenarios. For renewable resources like sun- and wind power this is not really a problem since investment in these technology are mainly policy driven. The same goes for investment, or decomposition, in nuclear power plants. However, investment plays an important role in evaluation capacity market performance and this makes it important to add an investment module to the model.

The coming paragraph will elaborate on ways to avoid these limitation and provides a methodology on incorporating investment and a capacity market in the model.

4.5 Modelling methodology

In order to be able to give relevant conclusions regarding capacity markets, it is hugely important that the model provides the adequate output, matching with the performance indicators as described in section 3.3, for answering the research questions. From the above paragraph, it can be concluded that two modules need to be added to the Power2Sim model:

- I. Investment module
- II. Capacity market module

A module of a capacity market as well as a module for investment can be modeled in various ways, as well as the choice for a certain type of capacity market. Therefore it is important to precisely describe the approach taken for this study to prevent confusion in later stages of the research. Based on the limitations identified in the previous paragraph, a modeling methodology is provided to show how to deal with these particular limitations.

4.5.1 Modelling investment

One of the features of the Power2Sim model is that investment is exogenous, as an input. The model calculates the outputs given a certain investment pattern. The main lack of this feature is that the base model cannot evaluate investment behaviour let alone incorporate multiple power companies. However, adapting the model into incorporating endogenous investment would be an option in making this possible. The downside of incorporating a complete investment algorithm in the model would be time constraints as well as difficulties with risk perception, forecasts and financial constraints of individual power companies.

A solution would be to assume optimal investment in the market and add capacity in a top down manner. This way it is possible to add capacity to the model as long as it is profitable. In order to do so, the assumption is made that in the long term, the electricity market is in equilibrium. This means that now a long term investment is profitable if the sum of short term profits equal the capital costs of investment (Borenstein & Holland, 2005). In other words, it is assumed that the economic profit under perfect competition is at least equal to zero while minimising the costs of production. This means that a new entry will add capacity until the profitability is 0. The optimal investment level can be calculated by making use of the electricity theories of Stoft (2002). This way, the least costs portfolio can be found taking into account the profitability of plants. The economic profit can be calculated by the model by looking at future electricity prices once a certain capacity is added to the system at a certain time. Iteratively, the capacity added can be increased until the optimal point is reached. This procedure can be repeated each year.

4.5.2 Modelling a capacity market

There is a wide variety in capacity markets designs available. Every design has its own specific features as described in paragraph above. The current German discussion on

capacity market has not been concluded on yet. Therefore, it is difficult to make a prediction on what direction they will go.

The goal of the model is to:

- I. Evaluate cross border effects of a German capacity market in the Netherlands
- II. Contribute to policy making in the electricity sector

Modelling, a German capacity market as detailed as possible is preferred if looking at internal market performance but is not a goal itself in this research. Since modelling is a time consuming effort, it is questionable whether this is necessary when particularly interested in cross border effects. In combination with the uncertainty regarding the exact design Germany is looking at makes an argument that alternatives might be preferred. Figure 4.7 presents the modelling methodology.

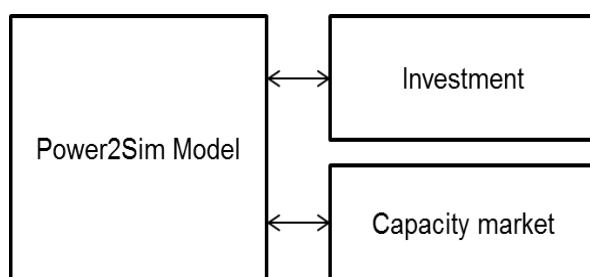


Figure 4.8 Overview modelling methodology

Corresponding capacity market clearing will be modelled in a separate excel module. The assumption could be made that a prediction will be done of future revenues and that that way missing money can be calculated, given the optimal investment as discussed in the previous paragraph about the investment methodology. Producers can bid their missing money in this way in the capacity market auction. A detailed discussion about the functioning and implementation of a capacity market is worked out in Chapter 4.

In order to validate the results of the modelling process, three studies will be used namely from the ECN (Özdemir, DeJoode, Koutstaal, & Hout, 2013), Iychettira (2013) and (SWECO, 2014). Figure 3.4 provides a visual representation of the modelling approach.

4.6 Conclusion

Although Power2Sim is a powerful tool in prediction future electricity prices and trade, it has some major limitations as well. In order to evaluate the cross border effects of a German capacity market on the Netherlands, two modules need to be added to the model:

- I. Investment module
- II. Capacity market module

Currently the model does not include a capacity market in Germany. Besides that, investments are not made endogenously. Implementing these two models will enable the Power2Sim model to evaluate the performance of the Dutch electricity sector. Chapter 5 will show a detailed conceptualization of the two models to be built.

5 Conceptualization

In the third chapter, a methodology was introduced to be able to model a capacity market in Germany. The methodology consists of two parts. Firstly, a base model will be determined to be able to evaluate a capacity market situation to a non-capacity market situation. Secondly, the capacity market situation will be conceptualized. The goal of this chapter is to use the methodology as a starting position from which the two modules will be developed and result in a conceptual model. This conceptual model will then be translated to a workable model in chapter six.

5.1 Translating the methodology in a conceptual framework

In order to determine the optimal electricity market, several concepts need to be introduced. These concepts are optimal investment, optimal technology mix, renewable scenarios and a capacity market in Germany. The latter one has been elaborated on in section 3.2 and renewable scenarios explain the development of renewables over the coming years. Optimal investment level and optimal technology mix are concepts introduced by Stoft (2002) and are used to evaluate a perfect market in equilibrium. Further introduction and exact definitions are provided in the paragraph below.

Figure 5.1 provides an overview on how the methodology is translated in a conceptual model. The boxes in black show the base case investment scenario without capacity market. The box in red shows the capacity market Germany, which is the basic scenario plus the capacity market in Germany. In both cases the same output performance indicators are used as being derived from literature in section 3.3.

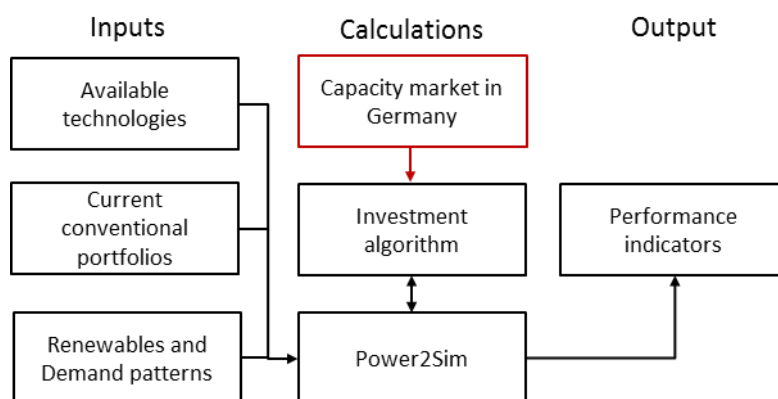


Figure 5.1 Conceptual framework

5.2 The base-model

The goal of this study is to evaluate the consequences of a capacity market in Germany on the performance of the Dutch electricity sector. Section 4 already showed that in order to do this, the existing model needs to be complemented with an investment algorithm and with a capacity market module.

The base model is the Power2Sim model including an investment algorithm to introduce new capacity in the market in 2020. The alternative hypothesis will be a model in which the capacity market module is included as well. This model will be altered in order to answer the sub-questions of this research. The null-model is based on technologies that are readily available in the market and investments are made according to profit-maximization. The market outcomes will be based on macro-economic theory of supply and demand, using a cost minimizing efficient dispatch approach. The idea of the null model is to adequately simulate investment in the Netherlands and Germany given today's conditions. It nullifies the existence of a capacity market to see what the market outcomes would be in its absence.

5.2.1 Simulating a non-optimal market

The main reason for a capacity market to be implemented is to ensure generation adequacy. From literature (Joskow & Tirole, 2007), it is concluded that an energy only market should provide optimal incentives for investments in generation capacity. This implies that a capacity market is not needed in case of optimal investments. Therefore, simulation a market under optimal conditions would result in the conclusion that a capacity market is not needed because the underlying problem does not exist. In the next two paragraphs, the optimal investment as explained by Stoft (2002) is elaborated on. First on the theoretic principles and second on a way to make the market non-optimal.

Optimal investment level

According to Stoft (2002), optimal investment in an energy only market is reached when the long term marginal costs of production of the most expensive plant in the system are equal to the marginal costs of a power cut. In literature, the marginal costs of a power cut are addressed as the value of lost load (VOLL). In this study, the VOLL was assumed to be €10.000/MWh, averaging the range² of estimates in literature (Cramton & Lien, 2000). The following formula is used to calculate the long term marginal costs of production.

$$MC_{long} = \frac{AI}{R} \quad 3 \quad (5)$$

Where:

MC_{long} = Long term marginal costs

² Crampton et al.(2000) performed a literature research on VOLL estimations. Outcomes ranges between €2400/MWh and €20000/MWh. The choice for €10000/MWh was made because it has appeared more often in literature and Stoft(2002) used €10.000/MWh as well as the price allowed during periods of scarcity.

³ Ideally, also variable costs like fuel and CO₂ should be added to these MC but since these cost are relatively small to the fixed cost, these variable cost will be ignored.

R = Running hours
AI = Annual investment

To illustrate this example, assume that the investment costs of the most expensive peak plant in the system are €750.000/MW. Following (2), the corresponding annual investments are €795.559/MWy. Following the VOLL to be estimated at €10.000/MWh this would mean that the peak plant has to run for €795.559/€10.000 is 7,9 hours per year. Therefore, the optimal level of investment is considered to be a situation in which the most expensive peak plant is running 7,9 hours. Translating this to the model would mean that capacity is added until the long term marginal costs equal the VOLL. This can also be done by simulating the demand of a reference year and output hourly demand levels which can be sorted by demand level. The demand level of the 8th hour would in this case be the optimal level of investment.

Optimal technology mix

The optimal technology mix can be seen as the least cost generation portfolio in an electricity market. Stoft (2002) describes the optimal portfolio as a tradeoff between generators based on their fixed and variable costs. Since the fixed costs and variable costs of different power generation technologies differs, it is logically there must be a preferred technology given the number of running hours (variable costs) a year. A coal plant for example has relatively high fixed costs compared to a gas powered plant. On the other hand, a gas plant has higher fuel costs. The upper graph in Figure 5.2 shows the total costs development of gas and coal plant by varying the capacity factor (running hours per year). In this example, it can be derived that a capacity factor of 0,3 is the tipping point between the choice for technology, meaning that gas plants will cover 30% highest demand and coal the lower 70% of the demand. This is illustrated by the lower graph in Figure 5.2.

Source: (Stoft, 2002)

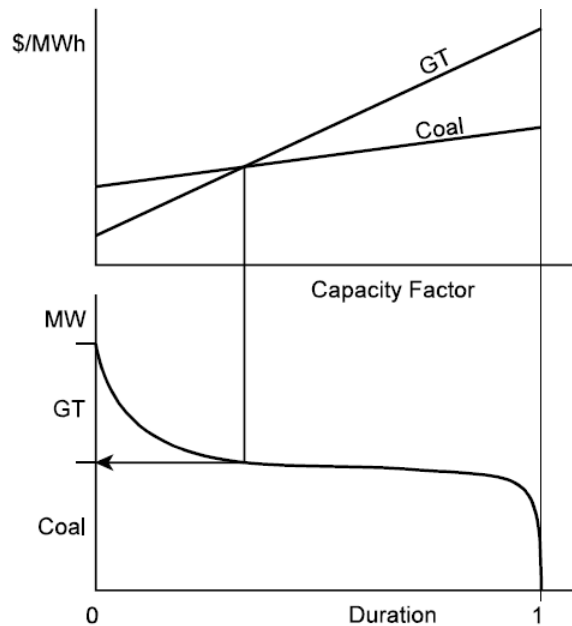


Figure 5.2 Optimal technology mix (Stoft, 2002)

When using this methodology, one must assume that that (1) generators are adequately described by FC and VC and (2) that demand is completely inelastic since a circular dependency between price, technology and load curve might provide inadequate outcomes. For the actual simulations, the number of technologies is of course larger than the two technology example.

Since intermittent renewables like solar and wind are considered to be “must run” plants the demand curve is specified as: $Load = Total\ load - "must\ run"\ renewables$

Adding market failure

In every investment that is evaluated some sort of risk is involved. The way that investors value this risk is called the risk preference of an investors. In the literature, the distinction is made between risk-averse, risk neutral and risk loving risk preferences (Chen, 2007) . In an optimal electricity market, investments are evaluated in an economically optimal, profit maximizing way. In this optimal market, investors are risk neutral meaning that they base their decisions on expected value only, meaning that they are indifferent about certain and uncertain return as long as the expected return is equal. In this research the assumption is made that investors in the electricity market have a risk averse risk preference. As a result, the following argument is used to adjust the discount rate of electricity producers in the investment model. According to De Vries and Neuhoff (2004), producers may be risk averse meaning that they prefer certain investments over risky investments. Considering a North-West European electricity market, prices can be very volatile which affects the profitability of power plants. However, the effect is not the same for different generation technology. A coal power plant will for instance continue producing for a while once the electricity price falls below the marginal costs of production. A gas power plant is able to shut down operations almost instantly. Gas plans are thus more flexible and in case the power-

price falls below marginal costs of production. In case the power-price falls below marginal costs of production permanently, the capital costs of a coal power plant are higher than those of a gas power plant making it cheaper for a gas plant to exit the market. Therefore gas plants might require a smaller risk premium. This risk premium on capital will influence investments in favor of less capital intensive investment alternatives. In the reverse way, adjusting the discount rate, either higher (capital intensive) or lower (less capital intensive) will provide more realistic model outcomes.

The discount rate estimates for different technologies will be chosen on the basis of literature. A report by Oxera (2011) analyzed the discount rates for low carbon technologies including CCGT as a reference. This way an estimation can be done regarding coal and lignite power plants. From the analysis, an average discount rate of 11% and 7,5% for respectively nuclear and CCGT plants is determined. Next a linear interpolation is made based on the overnight cost of a particular technology. The overnight costs are extracted from a report by the Energy Information Administration (EIA, 2013). This resulted in a discount rate of 8,5% and 8,8% for coal and lignite power plants.

A second reason for market failure is the intervention of a regulator in periods of scarcity. Prices will not rise to the VOLL, which they would in an optimal market, therefore limiting the revenue stream for a producer. This type of market failure can be easily implemented in the model by adding a price cap in the market. This implies that the price during scarcity, which would normally be equal to the VOLL, is now only allowed to go as high as a regulatory determined price cap. For the German spot market, a €3000/MWh price cap exists (Epexspot, 2014). Since this value is about one third of the estimated VOLL, this will stimulate non-optimal market outcomes. The influence of adding a price cap and different discount rates to the model is visualized in Figure 5.3 Investment under different discount rates and price cap. It is clear that the results follow the expectations provided in the latter two paragraphs. The next paragraphs will elaborate on the conceptual investment algorithms.

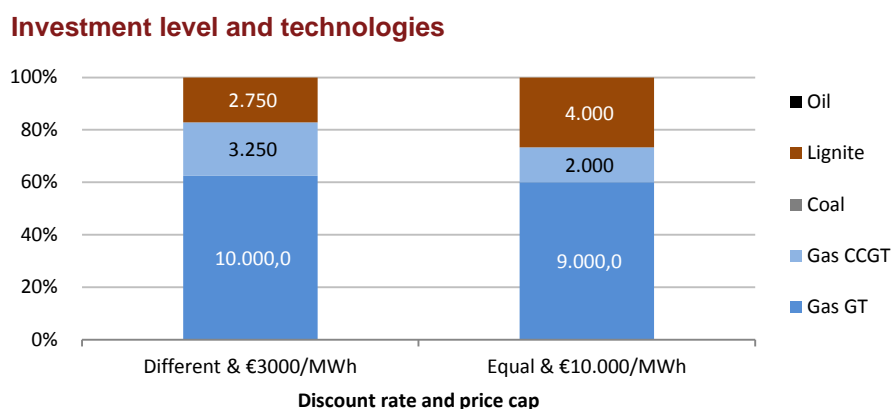


Figure 5.3 Investment under different discount rates and price cap

5.2.2 Investment without capacity market

The Power2sim model does not make use of endogenous investment algorithms. This means that the model does not add capacity to the market automatically based on a set of investment rules. In the base model, investments are included scenario wise making the investment exogenous.

Stoft (2002) in his book “power system economics” describes the fundamentals behind power markets which are used as a starting point for development of the basic investment scenario. In the long term, power plants are evaluated by their cost and profit. As long as the revenues surpass the costs, investment is attractive. According to Stoft, *investment costs* (IC) are not spent in once, but spread over years as an annual *fixed cost* (FC). However, there are also *variable costs* involved (VC) depending on the number of hours that a plant will be in use, which differs per technology. Combining these costs provide the basis for the so called annual revenue requirement. The formula for the *Annual Revenue Requirement* (ARR) is thus:

$$ARR = FC + R * VC \quad (1)$$

Where:

ARR = Annual revenue requirement

FC = Fixed costs

VC = Variable costs (fuel, transport, operational costs)

R = Running hours per year

Where *capacity factor* is the capacity factor or the percentage running hours compared to full load. The fixed costs are typically measured in €/KWy of capacity. However, most of the time the investment cost are known in €/KW as if it would be a lump sum investment. The following formula is used for conversion:

$$FC = \frac{r * IC}{1 - \frac{1}{(1+r)^T}} \quad (2)$$

Where:

r = Discount rate

IC = Investment costs

T = Power plant lifetime

Opposed to the revenue requirements are the revenues itself. For the purpose of this study it is assumed that power plant sell their capacity at at least the marginal costs of production, mostly the cost of fuel. This means that a plant will only run in case the electricity price is higher than the marginal costs of production. This also implies that for every hour that a power plant does run, it receives revenue equal to the difference between the marginal costs of production and the electricity price, this can also be called scarcity rent.

$$Profit = P_e - MC \text{ if } P_e \geq MC$$

$$Profit = 0 \text{ if } P_e \leq MC \quad (3)$$

Where:

P_e = Electricity price

MC = Marginal costs

In order to match these two equations into a measurable equation, (3) needs to be converted into an annual profit (AP) giving:

$$AP = \sum_0^R Profit \quad (4)$$

Where:

AP = Annual generated revenue

R = Total number of running hours

In order to determine whether an investment is profitable, the ARR and AGR need to be compared. In general, an investor would invest in a certain technology as long as the AP is larger than the ARR , investment will be done.

The methodology used to determine the AP is similar to (De Vries, Chappin, & Richstein, 2013). A time t is taken which represents t years from now. For this study this is chosen to be 10 years. So for instance, if the time 0 would be 2010, the reference scenario for investment would be 2020. The reference scenario is calculated by the model by simulating electricity prices by taking into account the growth of demand, renewable scenarios and the decomposition of existing fossil fueled power plants. The resulting calculated prices for the year 2020 will now be the basis of the investment algorithm. Since the Power2Sim model is lacking an automated optimization module for this particular method, the investments are done manually in an iterative manner. For the reference scenario in 2020, the electricity prices are updated after each investment block. Future price forecasts are made by adding capacity to the maker and simulating the market afterwards. The resulting price indicates whether there is still an opportunity for investment. After adding capacity, the electricity price in 2020 is recalculated. This procedure is continued until there is no profitable investment opportunity in the 2020 market.

To clarify the procedure, the following example is used:

Assume a country in which only gas plants are producing. Furthermore assume that the gas plant has investment costs of 350€/kW and a plant lifetime of 20 years and a discount rate of 0,1. Converting this to an annual FC by using equation (2) gives an annual FC of €41.11/kWy. So as long as the revenues from the wholesale market surpass the annual fixed costs, investment will be made. Table 5.1 summarizes this procedure.

Table 5.1 Investment in new capacity example

Iteration	Investment	Annual FC	Revenues	Decision
1	+500MW	€41.11	€65,00	Next investment
2	+500MW	€41.11	€40,00	Stop

Modeling renewables and nuclear plants

Renewables are included as scenarios in this base case. Since renewables are mainly policy driven, it is hard to develop a reliable investment algorithm. Therefore scenarios were taken from previous research by the Deutsche Energie-Agentur GmbH (2012) as model input. Regarding nuclear plants, the German government has a clear policy. Over the next 8 years, the existing nuclear plants will be phased out. After 2022, no more nuclear production is available to the market. This is therefore included in the scenario. Table 5.2 shows the renewable and nuclear development over time.

Table 5.2 Renewable and nuclear installed capacity development in Germany

Energy Source [MW]	2005	2006	2007	2008	2009	2010	2015	2020	2030	2040	2050
Wind	18,4	20,6	22,1	23,8	25,7	27,2	35,0	41,9	59,7	71,5	76,0
Hydro	4,1	4,1	4,1	3,5	4,0	5,3	5,2	5,1	5,2	5,2	5,2
Solar	2,1	2,9	4,2	6,1	10,6	16,5	35,9	42,0	60,0	70,0	75,0
Nuclear	20,5	20,5	20,5	20,5	20,5	20,3	12,1	8,1	0,0	0,0	0,0

5.3 Capacity market model

In the previous paragraph, the basic investment scenario has been explained which basically forms the basis for the capacity market scenario. The main difference between the two scenarios is that in the capacity market scenario, an additional market for capacity is introduced which aims at providing a reserve margin to ensure sufficient generation adequacy.

A regulator in the system determines a reserve margin for the system. For this study a reserve margin is used equal to 15%. Of course, the height of the optimal reserve margin is dependent on the fuel mix, geographic location etc. of a market making it hard to set a fixed value for a reserve margin in the German market. The following formula is used to determine the required level of capacity. It shows that the required level is depending on the highest estimated peak for a reference year multiplied by a certain reserve margin R . Figure 5.4 Load duration curve with reserve margin shows a general load duration curve in which a reserve margin is included.

$$C^* = (1 + R^*) * D_{peak}$$

Where:

C^* = Minimum installed capacity level

R^* = Required reserve margin

D_{peak} = Peak demand for a particular year

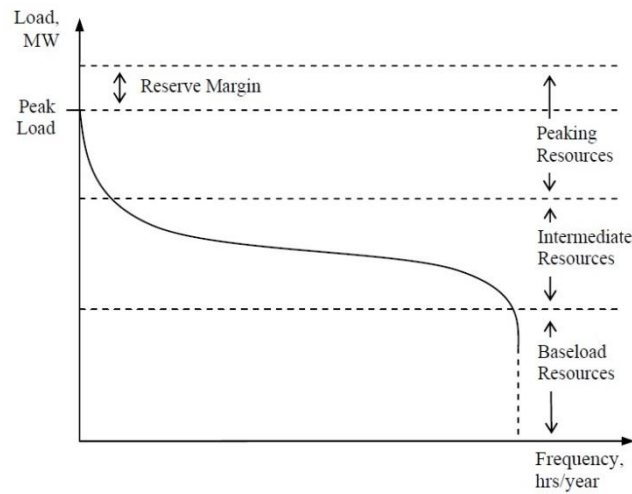


Figure 5.4 Load duration curve with reserve margin

Demand curve

Within literature, as described there are various ways of designing a demand curve for the capacity market. However, the purpose of this study is not to model a capacity market as adequately as possible, but to show the general effects of a capacity market in Germany. Therefore, the choice was given to a vertical demand curve at the required capacity level.

Capacity bids

A capacity market aims at providing an extra incentive for generation in generation capacity in case the current level of generation capacity is below a certain threshold level determined by the regulator. Conceptually, a capacity market provides extra reliability to the market. It therefore aims at making sure that plants at least stay online. In case a plant is not running, it is still making costs like maintenance, salaries etc. to keep it standby. These cost, also called fixed operational and maintenance (fixed O&M) costs, can be defined as the cost that do not vary with the plants operational hours and electric output (EIA, 2013). The revenue that is obtained in the electricity market together with the fixed O&M form the basis for the capacity bid. A capacity bid is only greater than zero if the fixed O&M costs exceed the revenues from the electricity market. In that case, the bid is equal to the difference between the fixed O&M costs and the revenues from the electricity market. Else, the capacity bid is equal to 0.

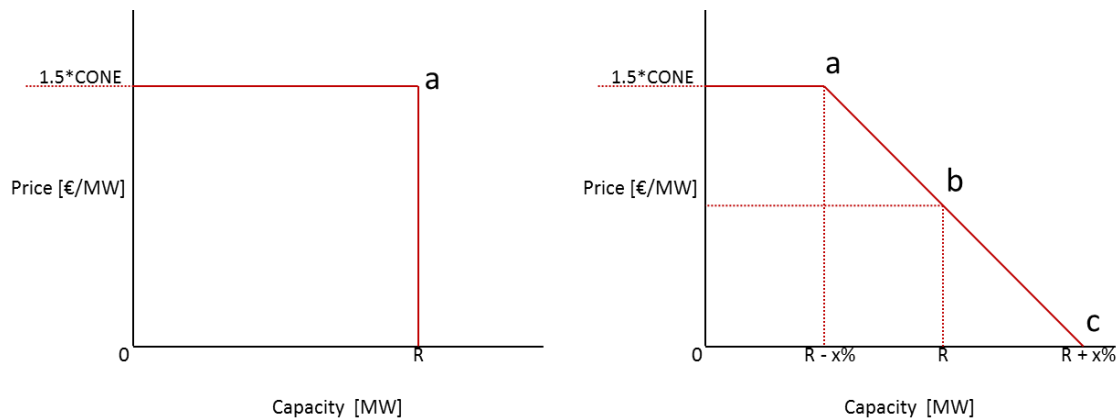


Figure 5.5 Demand curve design

Intermittent resources in the capacity market

Including renewable capacities in the capacity market might be problematic given the intermittent nature of these power supplies. The capacity factors of wind and PV in 2012 were 29% and 10%. However, this does not mean that this can literally be translated into capacity credits. The capacity market aims at providing reliability in terms of availability of power plants at some point in time in the future. Wind energy might ensure the right amount of virtual capacity but is never entirely sure whether the capacity is available when necessary. Several studies used different rates for renewables in a capacity market. For this study a capacity rate of 5% is taken for all renewables. However, the renewables will be modeled as must run in the system meaning that the total system demand is equal to the total demand minus renewable production. This means that the residual load can be seen as the demand that should be covered by conventional plants.

5.4 Modeling assumption

- Renewable energy scenarios are based on future estimations by Energy Brainpool (2014).
- Production, consumption and cross border capacity data is collected from ENTSOE, EUROSTAT and BFE.
- Historic commodity prices are collected from EEX, OMEL, GME and BAFA.
- Old power plants are being decommissioned according to their year built and lifetime.
- Carbon price is assumed to be €10/ton CO₂.
- The following prices for Lignite (€5/MWh), Coal (€10,3/MWh), Gas (€25/MWh) Uranium (€2,5/MWh) and Oil (€48/MWh) are assumed.

- VOLL is equal to €10.000/MWh, but the price cap is equal to €3000/MWh.
- Nuclear power plants in Germany are decommissioned according to the current plans. These plans include that by 2022, all German nuclear power plants are decommissioned and in 2020 only 8KW is available (nrc, 2011).
- The assumed discount rate used is 10% equal to the number used by Stoft (Stoft, 2002). However, the discount rate is adjusted for different technologies as described.

5.5 Model inputs

The investment decision in the system is done by evaluating the power plant options in Table 5.3. In the literature, a wide range of overnight costs can be found. The large ranges make it quite hard to compare the data. A reason might be that US data differs from European data. Therefore, a Dutch report (ECN, 2008) will be used in order to make sure that the data is reliable and consistent for the Dutch market. Note that these values only count for new generation capacity. Existing plants have their own plant specific values. Data, such as efficiencies, are complemented with data from recent investments, from CE Delft (2011) and Electropaedia (2005).

Table 5.3 Assumptions for available technologies for power plant investments

Power plant type	Overnight costs(€/kW)	Lifetime	Efficiency	Operational costs (€/kW _y)
Gas - GT	675	30	0,32	20,0
Gas - CCGT	825	30	0,60	19,5
Coal	1400	40	0,45	26,0
Lignite	1625	40	0,40	28,0
Oil	750	30	0,3	10,0

6 Formalization

Having determined the conceptual design of the investment and capacity market module, the conceptual model is translated to an actual simulation model in this chapter. The goal of this chapter is to show how the conceptual model is used as a basis for the formal simulation model by means of equations and flow diagrams. The formal model structure is presented in Figure 6.1. For each of the process steps, a paragraph is written to discuss the implementation.

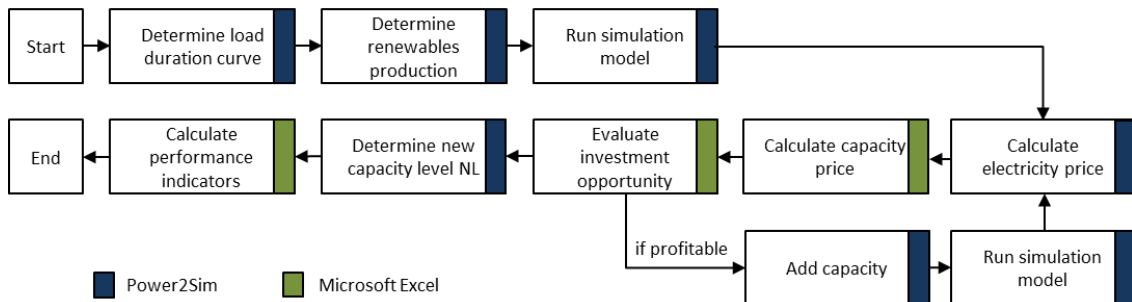


Figure 6.1 Simulation model flow diagram

Determine load duration curve and renewables production

Power2sim automatically generated load patterns taking into account historic demand fluctuations, seasons and holidays. This data can easily be exported to excel to construct a demand curve. However, it is important to extract the right demand curve. Since renewables are implemented as intermittent must run electricity generation, these need to be subtracted from the load to retrieve the load that needs to be covered by conventional power plants. Since wind is intermittent it will have a significant impact on the demand curve. Once the data is adjusted for renewables, the data is sorted to create a load duration curve. In figure 6.2 the difference between a regular demand curve and residual demand curve is given.

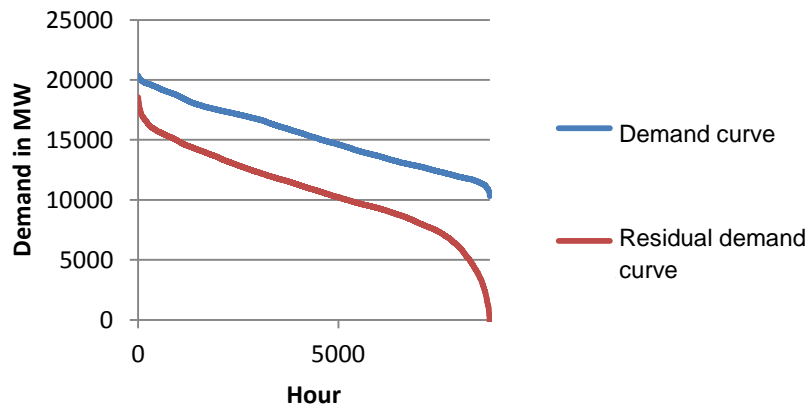


Figure 6.2 Demand curve adjusted for renewables

Calculate capacity price

The capacity price is calculated as an outcome rather than a process in which different plants can bid their operational and maintenance costs into the market based on expectations. For a given amount of capacity a capacity price can be calculated resulting from the market clearing point given a certain sloping demand curve. As explained in section 5. Producers bid their capacity in the market priced at the fixed operational and maintenance costs of the power plant in a year. These O&M costs are known for existing and new power plants. Therefore it is possible to determine the market outcomes iteratively. Every time an investment is profitable, the capacity is added a new investment analysis is done. Of course this means that the capacity price differs (since the demand curve is sloping, more installed capacity will lead to lower capacity prices). In the next paragraph, the investment procedure is elaborated on. The formula for a capacity bid is as follows:

$$\text{CapBidPrice} = \text{Annual revenue}^4 - \text{Fixed O\&M costs}$$

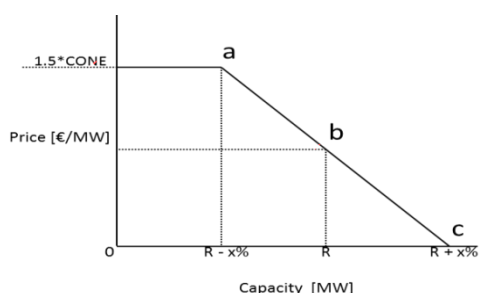
To illustrate this example, imagine a power plant having fixed O&M costs equal to €20/kW. For a reference year, the expected revenue from the market is €5.000/MW of installed capacity. This means that the generator is €15.000 short per MW of installed capacity. The corresponding bid will thus be €15000/MW. Another power plant has revenue of €50.000/MW. The corresponding bid in this case is €0/MW since the revenues fully cover the fixed O&M costs.

For every producer, the capacity bid is calculated individually. The following procedure is used in excel to construct the capacity bid of a producer.

1. Import electricity price output from Power2Sim
2. Determine marginal costs of power plant
3. Calculate the number of running hours and the profit per running hour
4. Determine fixed O&M costs based on power plant technology
5. Calculate the missing money, if the case, to cover fixed O&M costs
6. Determine capacity bid (€/MW ; MW)

⁴ The annual revenues are calculated by simulating the 2020 market given a certain amount of investment. Every iteration capacity is added to the model and the electricity price, and thus the revenue of producers, is calculated. The revenue is therefore based on simulated market outcomes.

Once all the power plants in the system constructed a bid, the market needs to be cleared. This is done by using the sloping demand curve showed in Figure 5.5.



Variable	Value
CONE	€40.000/MW
R	15%
R - x%	15% - 3%
R + x%	15% + 1%
a	$(D_{\text{peak}} * 1,12; 60.000)$
b	$(D_{\text{peak}} * 1,15; 60.000)$
c	$(D_{\text{peak}} * 1,16; 0)$

Figure 6.3 Formalisation of sloping demand curve

Evaluate investments

For every new investment, specific plant attributes are assumed following Table 5.3. For a given situation, the electricity price is calculated by Power2Sim and the capacity price is calculated by excel. An investment is added to the system if the annual revenues are at least equal to the annual capital costs. In the system, therefore capacity will be added until the point is reached that a new investment is not profitable anymore.

The cost can be considered as fixed and known in advance since assumptions have been made about the investment- and O&M costs for new investments. The revenues on the other hand, are calculated through model output. The corresponding profit is then calculated by subtracting the marginal cost of the revenues for the electricity market. In case the electricity price is below the marginal costs of a producer, the plant did not produce electricity and the profit for that particular hour is 0.

$$\text{Profit} = P_e - MC \text{ if } P_e \geq MC$$

$$\text{Profit} = 0 \text{ if } P_e \leq MC$$

Where:

P_e = Electricity price

MC = Marginal costs

In excel this calculation is performed for each hour in a year. The total profit is calculated by taking the sum of the profit for all hours in a year. In case the profit exceeds 0 for a reference year in the future, the corresponding investment is done.

The following sequence is used to add capacity and evaluate the investment.

1. Calculate total revenue from electricity market
2. Subtract fuel costs, fixed O&M costs and amortized investment costs
3. Determine Profitability of power plants
4. Calculate rate of return

Performance indicators

For the evaluation of the experiments, the performance indicators from section 3.3 are used. These are, the average electricity price, electricity price volatility, import and export and the profitability of power plants. Table 8.3 shows these performance indicators and shows the unit of measurement.

Table 6.1 Performance indicators

Indicator	Unit
Average electricity price	€/MWh
Electricity price volatility	%
Import/export	MWh
Profitability of power plants	€/year
Lost load hours	h/year
Reserve margin	%
CO ₂ emission	Tonne/year
Total consumer costs	€/year

The use of VBA

The simulation model consists of three parts. The Power2Sim model, the investment module and the capacity market module. The three modules need to communicate in order to iteratively add investments to the model but they do not communicate directly to each other. For this purpose VBA is used. The VBA code used is similar to the working of an excel macro. In the figure below, a visual impression of the role of VBA is presented. The VBA code used in this analysis is presented in appendix D.

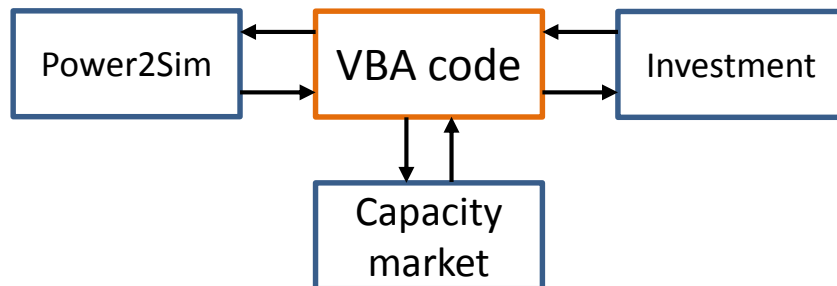


Figure 6.4 Schematic overview VBA

7 Verification & Validation

In order to be able to interpret the model results, it is important that the model concepts are translated correctly into the implementation in the model. Basically, it tests whether the actual simulation model meets the requirements set in the conceptualization phase. It answers the question whether the model is implemented correctly. The question whether the model results are reliable will be answered in the second part of this chapter, the validation. The purpose of this chapter therefore is to correct error that occur in the model though logically analyzing the simulation model. Within this study, several different methods are used to verify the model. These methods are theoretical prediction and sanity check and extreme inputs. In the following paragraphs, these specific methods will be elaborated on. The third part consists of a sensitivity analysis. The purpose of this sensitivity is two folded. It validates relations between variables in the model and secondly, it presents an overview of the robustness of the model to changes in parameter settings.

7.1 Verification

Several different methods are used to verify the model. These methods are theoretical prediction and sanity check and extreme inputs. In the following paragraphs, these specific methods will be elaborated on.

7.1.1 Equation and dimensional examination

All the equations in the model are checked against the conceptual design to see whether they are correctly implemented. It might for example happen that a likely model input of outcome results in a model error. An example is for instance division by 0. This happens for example when trying to calculate the optimal hours of scarcity in a year. In case of overcapacity, the most expensive unit in the system will most likely produce zero. This returns an error when calculating the long term marginal costs of production because the unit is costs/MWh and since the number of running hours is 0, this will result in an error. For the dimensional analysis, the implemented equations are checked for dimensional consistency. No errors exposed here.

A natural part of the verification process is the correction of errors in the VBA code. During the process, numerous errors exposed like “out of memory”, “stock overflow” and “object not set” and various other errors. Every error has been dealt with individually resulting in a model that runs without running into an error. Although this does not say anything about the equations being right it at least says that the model is able to process the equations correctly. In combination with the equation check and the theoretical prediction in the next paragraph this should be a good basis for the verification.

7.1.2 Theoretical prediction and sanity check

This verification method makes use of regular model inputs of expected outcomes can be formulated beforehand in order to check whether a particular concept was implemented correctly. In case a different outcome appears than expected, the

implementation needs to be revised to correct the error. Generally the errors can be distinguished into implementation errors and equation errors. In the paragraphs below the most important issues, underlying problems and corrections to the implementation are presented.

Optimal investment level

Hypothesis: Once the optimal level of capacity is implemented, the number of scarcity hours should be equal to optimal level of scarcity hours.

Initially, the model returned significantly more scarcity hours than expected. The problem was that the optimal capacity calculations did not consider availability of plants but assumed an availability of 100%. This was corrected by adding the availability factor to the optimal capacity calculations.

→ Corrected and confirmed

Profitability of plants

Hypothesis: the less capacity available, the higher the profit of plants.

The model shows an increased amount of revenue per power plant in case the capacity is halved. This is logical since this will result in an increased amount of scarcity hours thus increasing the power price.

→ Confirmed

7.2 Validation

This paragraph describes the validation process of this modeling study. The main question to be answered is whether the model reflects adequate behavior necessary to answer the research questions. Traditional validation consists of comparison of model outcomes with real life behavior. However, the implementation of a capacity market in a Northwest European country has no real life data to be compared with. Comparison with France and the UK are neither a solution since no real data is available yet. In this study, two different forms of validation are used. These are historic replay and literature comparison. The latter one is discussed in section 10 in the interpretation of the results.

Data validation

The data supporting a model can be critical for the model outcomes. Therefore it is important to concisely check whether all the data used is supported by reliable sources. A second thing is to check whether the data is complete and in case estimations have been done, to validate these estimations. The input data for new investment decisions has been retrieved by collecting several data tables from reports on electricity market investments. It has been crosschecked too to see whether, in general, the data show similar results. The choice has been made to use reports about the European electricity market, trying to look for data that exactly matches the modeling needs. Regarding model inputs in terms of commodity prices, August 2014 prices have been used as

ceterus paribus assumptions for 2020. Real life prices are widely available and show no differences in values when comparing different sources. The discount rate used differs greatly between different sources. A frequently made assumption is a discount rate of 10%. However, the fact that different technologies in the model have different discount rates in combination with large ranges used in literature makes this assumption hard to validate. A solution can be found in performing a sensitivity analysis to determine to what extent the discount rate has an effect on model outcomes. This sensitivity test is provided in section 7.3.

Validation of the base model

The base model simulates the European energy market. The main issue is whether the model produces electricity prices that correspond to historic prices. For a given time interval, the actual demand, available units and renewable generation are known. This makes it possible to see how accurate the model actually is. The most important aspect of the existing model is that it accurately calculates hourly electricity prices. These electricity prices are the input for the investment and capacity market model and are thus crucial regarding model validation. Figure 7.1 shows yearly and hourly electricity prices. Although the prices do not match exactly, the behavioral patterns show similarities between the simulated data and the historical electricity prices. The data for these graphs is APX 2013 data in the Netherlands. Again, the purpose of this analysis is to provide confidence in the reliability of the model. Based on these graphs it can be concluded that the simulated data approximates the historical data. The peaks in the simulated data and the historical data show similar results although they are not always present at the same time. For the hourly data, the same behavioral pattern is observed for the simulated and the historical data. For this particular hour the historic data shows a larger range between peak and dale but the peaks and dales occur at the same time of the day. To conclude, the simulated price is an approximation of the historic price. The values do not match exactly but the behavioral patterns show similar behavior which provide confidence in the usability of the model for this research.

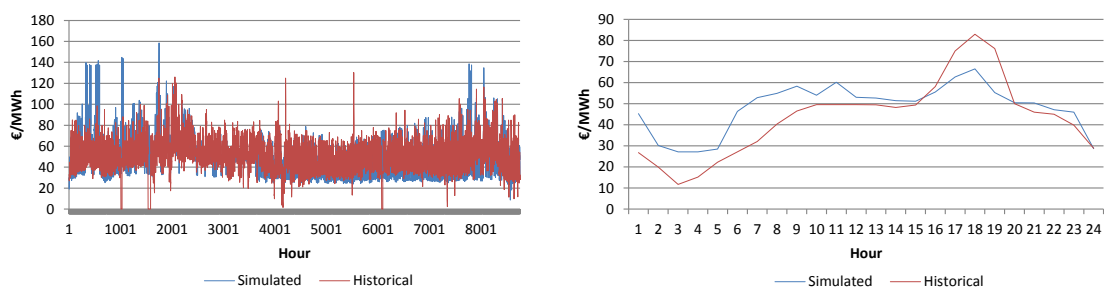


Figure 7.1 Yearly (left) and hourly (right) power price historical and simulated

Validation of the capacity market

There is no data available on the real world outcomes. This means that no direct historic comparison can be made. However, it is possible to compare the capacity market outcomes with outcomes of operation capacity markets elsewhere in the world.

Source: rtoinsider, 2013

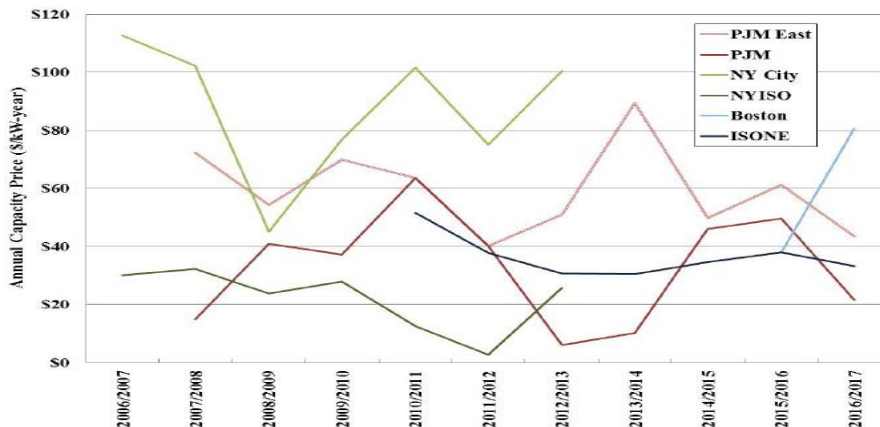


Figure 7.2 Capacity market clearing prices over time

The graph above (Rtoinsider, 2013) shows capacity clearing prices for six capacity markets. The capacity price seems quite volatile. When looking at all the different capacity clearing prices combined, the graph shows that the highest density is in the \$40/kW-yr range. Converting this to euros this is around €30/kW-yr. The result of the first capacity market run shows a capacity price of €31,2/kW-yr. Although the volatility of the different capacity market cover a wide range, it still is an indication that the capacity market provides reliable results.

The capacity bid itself should look similar to a general merit order of an energy only market. In the left figure below (Rtoinsider, 2013), the dark blue line represents the real capacity auction supply curve. It has a similar structure as the bid curve from the model constructed for this research. Again it is hard to draw conclusions straight away, but it provides another indication supporting the general model validation.

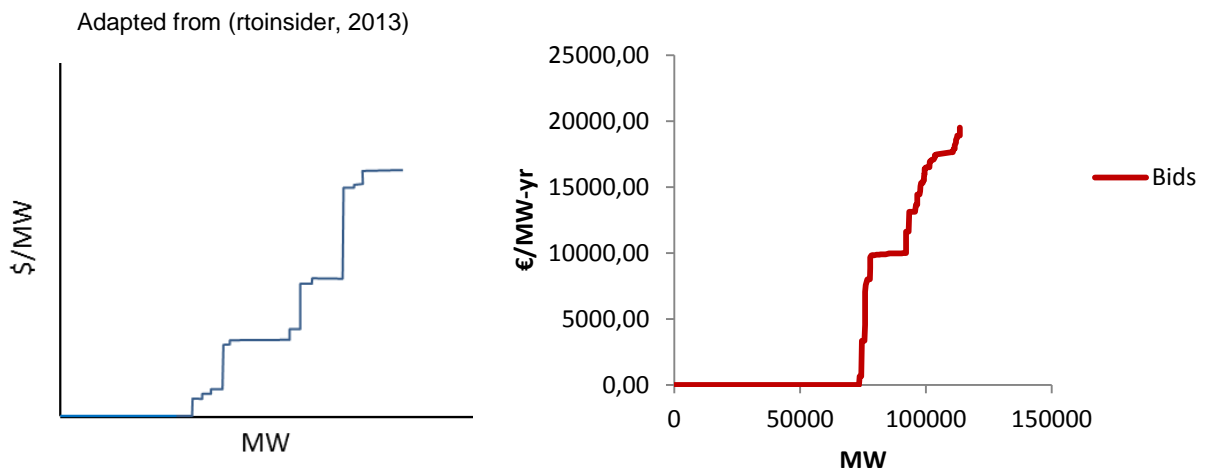


Figure 7.3 Example capacity market bid (left) and model output of capacity bid (right)

Model to model validation

Within the literature various studies can be found that research similar topics. The fact that they all use completely different methods is a strong basis for model to model comparison. The goal of this validation method is to see whether different approaches

end up with the same results. A. extensive comparison with other models is provided in chapter 11. Here the model results will be compared to other model outcomes and literature.

7.3 Sensitivity analysis

The goal of a sensitivity analysis is twofold. The first goal is to study the impact of uncertain parameters in the model. Secondly it is a way to validate relations between parameter and model outcomes in the model. It investigates the impact of changes in parameters on the model outcomes. It is especially interesting to look at parameters that are uncertain in the model. A good starting point is to look at the assumptions made in section 5.4. The assumptions consist of several different kind of assumptions. It is especially interesting to look at the parameters that might change over time. The most interesting assumptions to test are the price of CO₂, fuel prices, amount of renewables, discount rates used for investments and the value of the price cap in the capacity market. The CO₂ price and the amount of renewables are already included in the experiments in section 8.1. Therefore the sensitivity analysis is performed by varying the fuel prices and discount rate in the model. Table 7.1 shows the different set-ups that are used in the sensitivity analysis.

Table 7.1 Sensitivity analysis set-up

Scenario	Parameter	Value
LowCap	Capacityprice	€30.000/MW
MedCap	Capacityprice	€60.000/MW
HighCap	Capacityprice	€90.000/MW
LowDiscount	Discount factor “technology”	DiscountChangeFactor ⁵ = 0,5
MedDiscount	Discount factor “technology”	DiscountChangeFactor = 1
HighDiscount	Discount factor “technology”	DiscountChangeFactor = 1,5
LowFuel ⁶	Fuel price “commodity”	Oil \$86,2/bbl ; Coal \$92,8/tonne ; Gas €11,2/MWh; Lignite €5/MWh
CentralFuel ³	Fuel price “commodity”	Oil \$119,7/bbl ; Coal \$122,9/tonne; Gas €19,6/MWh; Lignite €5,25/MWh
HighFuel ³	Fuel price “commodity”	Oil \$150,1/bbl ; Coal\$139,2/tonne; Gas €27,5/MWh; Lignite €10/MWh

The data for gas, coal and oil is extracted from a report by the Department of energy and climate change (DECC, 2013). Lignite is not included in this report. Lignite is not

⁵ The variable DiscountChangeFactor refers to a multiplication of the initial discount rate. 0,5 in this case means that if the original discount rate was 10%, the new discount rate is 5%.

⁶ The original data presented the gas data in pence/therm. The conversion rate therm/MWh is set at 0,0293 and the currency rate €/pound is 1,28.

traded on the world market as coal, gas and oil are because transportation of lignite is not economical (Bardt & Striebeck, 2013). Therefore no price estimations of lignite have been found. Therefore, the lignite price variations will be based on demand estimations. In 2020, the expected grow of lignite demand is 5,4% (Cohen, 2014). The assumption is made that the price increase is equal to the demand increase. The assumption is made that this is the central estimate and that a lower estimate is 0% and the high estimate is 10%. Although this estimation is rather rough it is the closest estimation given the absence of actual reports. The CO₂ price is assumed to be constant for all runs at €10/tonne.

Results

Sensitivity to discount rate

The discount rate is an uncertain factor. Nevertheless the discount rate sensitivity provides a good insight in the changes in model results can be ascribed to changes in the discount rate. For the investment algorithm the amortization formula used by Stoff (2002) is used. From this formula a first indication of the sensitivity can be observed. To illustrate a power plant with a overnight costs of 800.000/MW is chosen and a lifetime of 30 year. Table **Error! Reference source not found.** shows the annual nvestment costs for different discount rates.

Table 7.2 Discount rate sensitivity for annual investment

	Discount rate					
	4%	6%	8%	10%	12%	14%
Annual investment (€/yr)	46264,08	58119,13	71061,95	84863,40	99314,93	114242,24

From the above table a sensitive annual investment costs can be observed with the changing discount rate. The higher the discount rate, the higher the annual investment costs. The relation is one to one, so an increase of 50% leads to an increase of 50% in annual investment costs. Translating this to an expectation considering the sensitivity of the model outcomes to a change in discount rate, it is expected that a higher discount rate negatively influences investment levels. This is not a surprising hypotheses, but still a good indication for model validity. Furthermore, it is interesting to see to what extent the sensitivity of the annual investment costs result in sensitivity in other model outcomes like actual investment, electricity price etc.

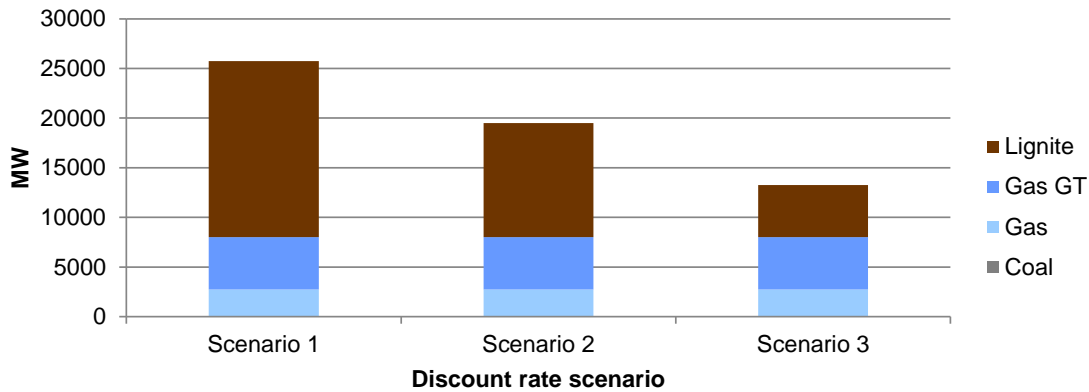


Figure 7.4 Discount rate sensitivity on investment

From the figure above, it can be observed that the lower the discount rates, the higher the final level of investments. This matches the expectations since a lower discount rate decreases the required amount of revenue to make an investment profitable. Investments will thus remain more profitable at higher levels of investment ultimately leading to higher level of investment. With regards to the technology mix, the increase in investment can be assigned to the increase in lignite. In contradiction to gas GT and CCGT plants, lignite is very sensitive to shifts in discount rate. To conclude on the investment levels, the capacity investment increases with decreasing discount rates and this changes is almost entirely ascribed to the change in lignite investments.

Table 7.3 Sensitivity analysis discount rate

Performance indicator	Scenario 1	Scenario2	Scenario 3
Electricity price	33,71	37,10	41,48
Volatility	19,21	19,26	36,98
LOLE	0,00	0,00	1,00
Reserve margin	1,38	1,32	1,26
Capacity price	19.969	19.971	55.474
Clearing volume	113.192	113.560	109.938
Electricity price including capacity price	37,55	41,03	51,82

The table above shows the results of the discount rate sensitivity analysis. As expected, the electricity prices shows lower values for lower discount rates. This is a direct result of the amount of investment in the electricity market. The more investment, the lower the electricity price. The same holds for the reserve margin, which increases with higher investment levels. The increased investment also results in smaller LOLE, which decreased from 1 to 0. It is interesting to take a look at the capacity price and clearing volume among the different discount rate. The high discount rate shows a lower clearing volume, which is in line with the lower level of total investment. The two lower scenarios show approximately the same results, even though the level of investment is higher in the lowest discount rate scenario. The result can be explained by the sloping demand curve of the capacity market. In the lower discount rate scenario, some of the capacity is not accepted in the market because it exceeds maximum value

corresponding to the level of investment. Therefore, the increased level of investment pushes some less profitable capacity out of the market. Figure shows this behavior visualized in the capacity bid merit order. It can be observed that not all capacity bids (red) are accepted because of the presence of a capacity price cap of the sloping demand curve (black).

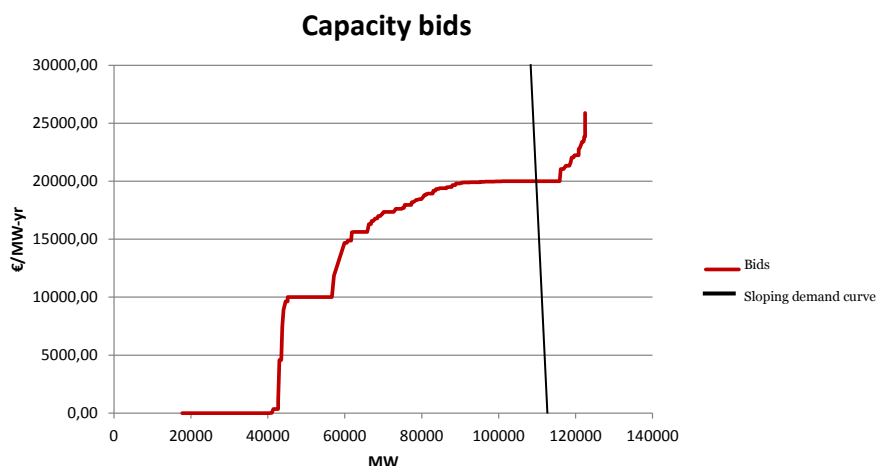


Figure 7.5 Capacity bids with low discount rate

Sensitivity to price cap

The price cap of the capacity price functions as a maximum price. The height of this cap is the incentive that is given to the market in case of undersupply. The three different values of the price cap are €90.000/MW, €60.000/MW and €30.000/MW. The expectation is that the higher the cap, the longer investment is incentivized, and thus the higher the ultimate level of investment.

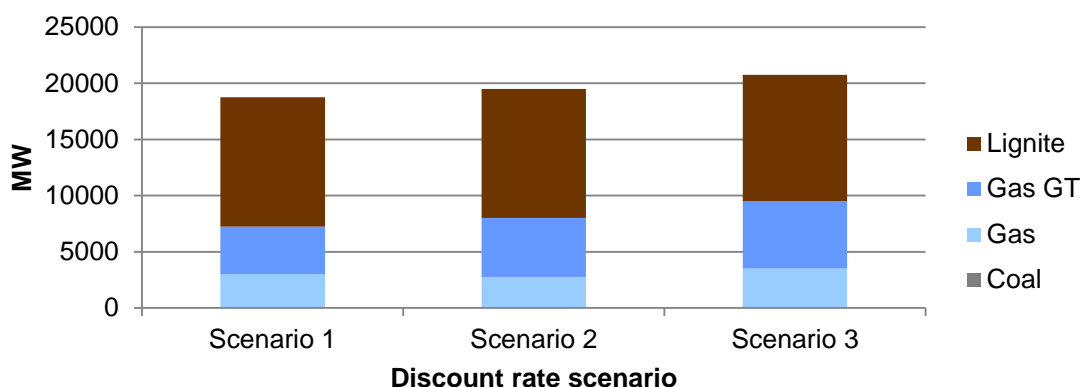


Figure 7.6 Price cap sensitivity on investment

The above figure shows that the investment increases with the capacity market price being increased. The different technologies show different behavior. The lignite investments stay approximately equal while the investment in gas increases with a

capacity market price cap increase. Compared to the discount sensitivity, the change in investment is marginal.

Table 7.4 Capacity market price cap sensitivity

Performance indicator	Scenario 1	Scenario2	Scenario 3
Electricity price	37,03	37,10	37,03
Volatility	19,36	19,26	19,51
LOLE	0,00	0,00	0,00
Reserve margin	1,41	1,32	1,33
Capacity price	19971	19970,69	19969
Clearing volume	112068	116188	108068
Electricity price including capacity price	37,50	41,03	40,68411

From the above table it can be observed that an increase in capacity market price cap, does not lead to large changes in terms of reliability (LOLE and reserve margin). The same holds for the capacity clearing price. According to the sensitivity analysis results, the capacity price is not influenced by the height of the price cap. The clearing volume does differ with the different scenario. This is logical because the capacity price is a function of the clearing volume and since the capacity price remains equal, the difference must be explained by changes in the volume of capacity in the market. The volatility and the electricity price show little change over the different scenarios so the expectation is that the height of the price cap does not influence the electricity price noticeably.

Sensitivity to fuel prices

The fuel prices are the basis for the margin costs and are thus the main determinants of the revenue that is obtained from the electricity market. For this sensitivity analysis three levels of fuel prices namely high central and low. Obviously, the higher fuel prices need to lead to higher electricity prices, since the prices of all technologies are higher than in the low scenario. The interesting part is whether higher prices lead to different investment both in terms of total investment as in the technology mix.

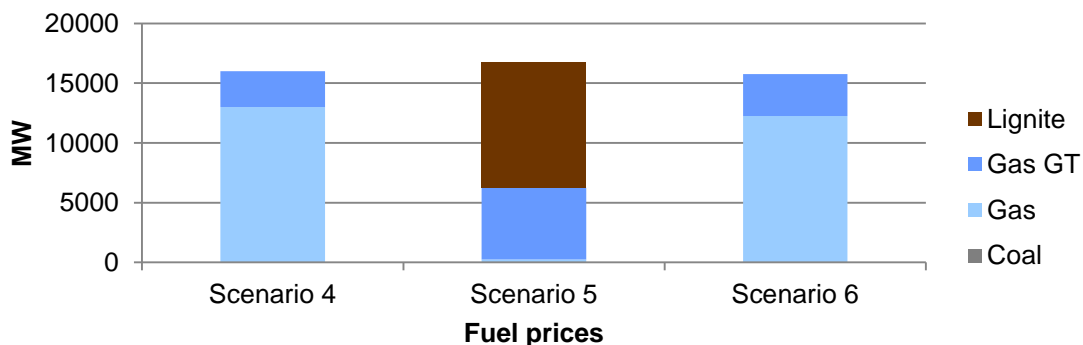


Figure 7.7 Fuel price sensitivity on investment

From the above figure, interesting behavior is observed with regard to the technology mix. The investment levels themselves remain approximately equal for the different

scenarios. The interesting aspect is whether this behavior can be explained by the input and model structure. Because scenario 4 and 6 show similar results the starting point is to see what differences can be found between the two and scenario 5.

Comparing scenario 4 and 5, it can be observed that the increase in fuel price between the two scenarios is much lower for lignite than for the other fuel types. This is a possible explanation for the lignite being very attractive in scenario 5. Comparing scenario 5 and 6, an increase of around 100% for lignite is observed and lower increases are observed for the other fuel types. The observations suggest that the relative attractiveness of a particular technology is the cause of this major shift. In order to check this a least costs analysis is performed on a CCGT plant and a Lignite plant. Figure 7.6 shows the results. The figure shows that a relative increase⁷ causes the cost effectiveness to change for different fuel levels. For the fuel cost of a lignite plant varying between €5/MWh and €10/MWh the amount of hours it should run to be more attractive than CCGT changes respectively from 40% to 100%. The latter outcome means that only if a lignite plant can run 100% of the hours in a year it is more profitable than a CCGT plant running the same amount of hours.

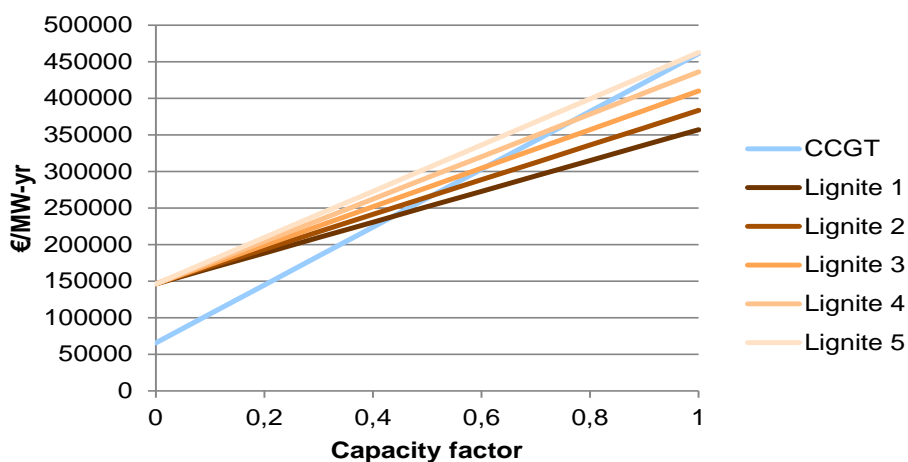


Figure 7.8 Least cost sensitivity analysis CCGT and Lignite

In table 7.5, the results of the fuel price sensitivity are presented. The results follow expectation in sense that the electricity price increases if fuel prices increase. From figure 7.6 only smaller differences in investments occurred. The volatility increases slightly when the fuel prices are higher. This can be explained by the absolute difference between the fuel prices. In general, the higher the prices, the higher the absolute differences between the different technologies and as a result lead to a higher volatility.

⁷ The relative attractiveness is visualised by fixing the costs of an CCGT plant and varying the costs of the Lignite plant. This way you can visualize relative changes.

Table 7.5 Sensitivity analysis fuel price

Performance indicator	Scenario 4	Scenario 5	Scenario 6
Electricity price	27,64	35,89	40,20
Volatility	17,94	18,63	20,06
LOLE	0,00	0,00	0,00
Reserve margin	1,21	1,32	1,20
Capacity price			
Clearing volume			
Electricity price including capacity price			

To conclude on the sensitivity of fuel prices on the model outcome, it can be said that the behavior that is observed from the sensitivity analysis shows results that can be explained and supported by model inputs and the model structure. It provides evidence that the model that is developed acts following expectations. However attention should be paid to the sensitivity of lignite which is high for different fuel prices. It was observed that especially the relative attractiveness, the competitiveness of the price compared to fuel prices of other technologies, influences the model outcomes.

7.4 Conclusion

The goal of this chapter is to check whether the conceptual model is implemented correctly and to see a sufficient amount of confidence in the model outputs is present. The verification process is an ongoing process in eliminating implementation error. The occurring errors have been resolved. However, the verification results are based on the basic capacity market model. It might be the case that different scenarios result in different errors which mean that new scenarios should be treated with caution as well. The validation process resulted in sufficient amount of confidence in the capacity market model. In order to both test the model sensitivity and validity, a sensitivity analysis was performed on three main assumptions respectively fuel prices, discount rates and price cap of the capacity market. The outcome of the sensitivity analysis provides confidence in the model in the sense that the observed sensitivity matches the expected relations in the model. The sensitivity furthermore showed that not particularly the height of the fuel prices is important for sensitivity in the results, but more the spread between the different technologies. The suggestion for a scenario set-up is the use of different CO₂ prices. CO₂ prices treat different technologies unequal while only need to change a single variable. This makes the CO₂ price an interesting variable to vary in the scenario analysis.

Having verified and validated the model, the following step is to set up an experimental design. This is done in the next chapter 8. The results of the sensitivity analysis will be taken into account when determining the scenarios for the experiments.

8 Design of Experiments

The model needs to be evaluated under different conditions in order to answer the research questions. The experimental design (DOE) is used for this purpose by using a targeted approach in which various model variables are being changes. It aims at setting up experiments to understand the relation between the model variables and the model output in a systematic way. The goal of this chapter is to show the what, why and how of the simulations that are being used to answer the research questions.

8.1 Hypothesis

In section 2, the research questions were formulated aiming to look at the cross border effects of a capacity market in Germany on the performance of the Dutch electricity sector. Besides that, particular interest was given to the following future developments:

- A renewables dominated electricity market
- Large amount of interconnector capacity between Germany and the Netherlands
- The possibilities of a shared capacity market

Given these questions that need to be answered, four hypotheses have been set up following these knowledge gaps. H1 and H2 are used to determine the impact of a German capacity market in general on the performance of the Dutch electricity sector. H3 and H4 are more policy oriented since they include different design options that a government might lobby for. The latter two therefore test policy options in case H1 and H2 prove that a capacity market has significant impact on the Netherlands.

1. **H1:** A capacity market in Germany has a negative impact on the performance of the Dutch power sector.
2. **H2:** A capacity market in Germany, combined with a large share of renewables, has a negative impact on the performance of the Dutch power sector.
3. **H3:** A large interconnector capacity will increase the cross border impact of a German capacity market on the Netherlands.

8.2 Design of Experiments

The design of experiments is implemented by making use of the following steps.

- a. Set up the scenarios
- b. Determine base case experiment for the benchmark
- c. Set up the experiments
- d. Determine the parameters that are going to be varied together with determining feasible ranges of these variables
- e. Determine performance indicators
- f. Execute experiments

g. Interpret results

The first five steps are described in this chapter. The interpretations of the results are show in chapter 9.

Scenario set up – sensitivity analysis

There are several reasons to expose the simulation to various scenarios. For this research, the most important reason is to test the robustness of the model under various conditions. The investment behavior in the system is expected to be sensitive to multiple factors. Research by the Clingendail International Energy Programme (Slingerland, Tönjes, & De Jong, 2006) provided insight in several factors to be considered when making an investment decision. Factors include commodity prices, existing portfolios including renewables, location factors and some more regulatory factors. Of these factors, the most important ones, taking into account the capabilities of the model, are the external factors. Since the amount of renewables and interconnector capacity is included in the hypothesis, uncertainty regarding commodity prices is most relevant for this research. Under certain scenarios, shifts in the merit order can occur which will probably influence the simulation outcomes. From a theoretical point of view, not the value of the fuel and CO₂ prices is important, but rather the spread of different technologies in relations to the spread of other technologies. Preferably, the difference between the clean dark spread and clean spark spread, which gives an indication of the profitability of coal and gas per unit of electricity produced, corrected for the price of CO₂. Therefore it is important to choose the scenarios in a way that significant changes to the spreads of coal and gas occur.

In order to test the effect CO₂ prices have on the investment algorithm in the model, a small sensitivity analysis is performed. The outcomes of this test will determine the range of CO₂ prices that are relevant to be used as scenarios for testing the hypothesis.

Table 8.1 Sensitivity analysis overview

Sensitivity Experiment					
	1	2	3	4	5
CO₂ price	€10/ton	€20/ton	€30/ton	€40/ton	€50/ton

Figure 8.1 shows the sensitivity of investments and the merit-order to changes in the CO₂ price. The analysis gives a clear indication that the CO₂ price has a significant impact on investments in different technologies since the investments and shifts in merit-order differ widely. On the other hand, investments might not be significantly different over the entire range of CO₂ price values. Note that the difference between €10 and €20 is marginal. The same holds for €30 and €40 when it comes to changes in balance between the investments. Therefore, it can be concluded that CO₂ needs to be taken into account, but that only €10, €30 and €50 will be used as scenarios.

CO₂ price

Investment

Merit-order

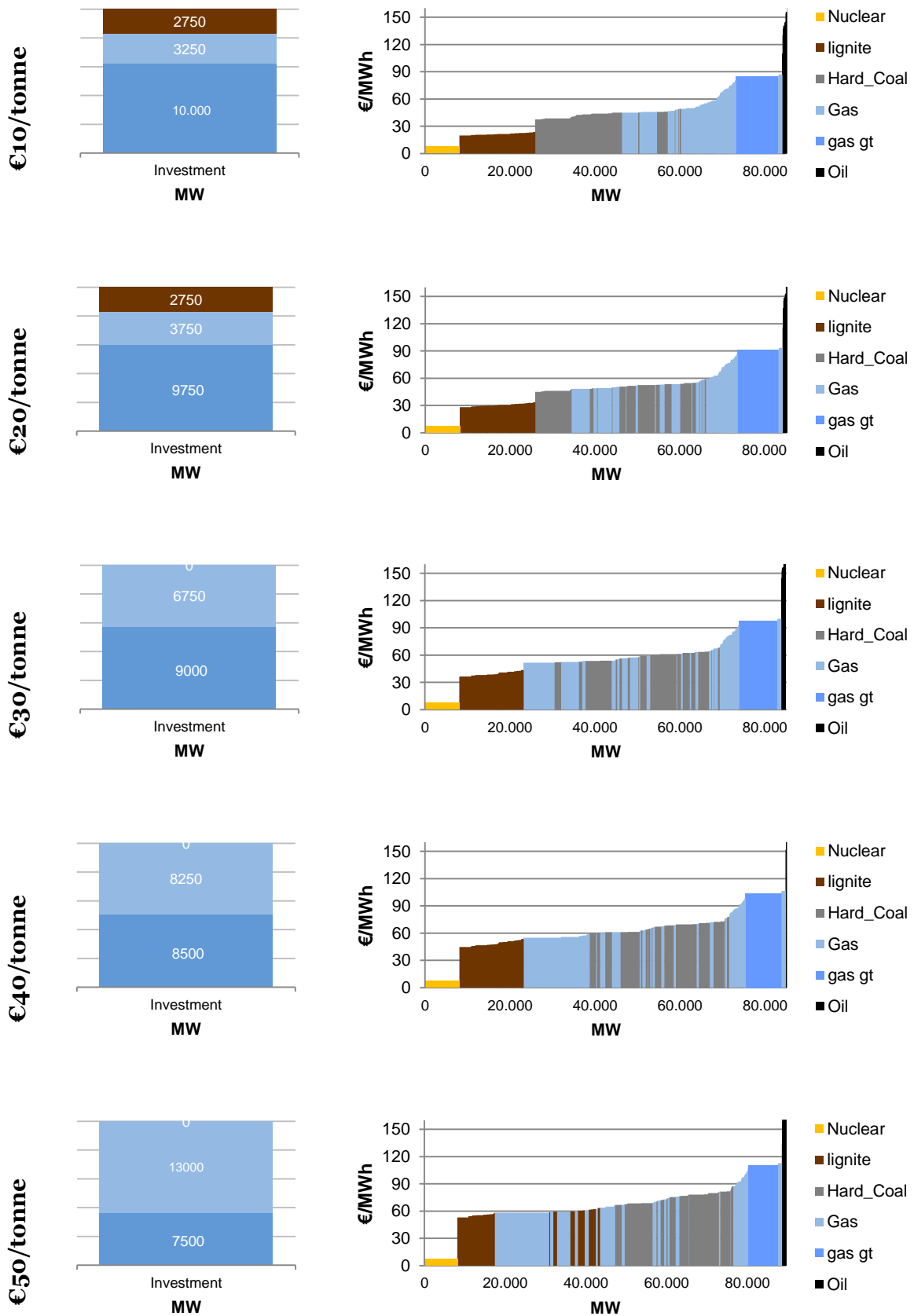


Figure 8.1 CO₂ sensitivity analysis

Base case experiment

With the intention of a comparison between the base case and a change in the market by means of a capacity market a benchmark experiments needs to be set up. In this case, this will be the 27 node model, as described in section 4.1, in which the individual nodes will be optimized in isolation using the procedure described in section 5.2. This makes it possible to compare an energy only (non-capacity market) situation with a capacity market situation. For Germany and the Netherlands, the initial generation portfolios, before optimization, correspond to the expected generation portfolio without new investments, taking into account the Energieakkoord and decommissioning of old plants. The base case is simulated including the 3 scenarios from **Error! Reference source not found.**. The starting point for the simulation will be the technology mix in 2020 taking into account closing and mothballing plants. Figure 8.2 shows the initial values at the starting point of the simulation.

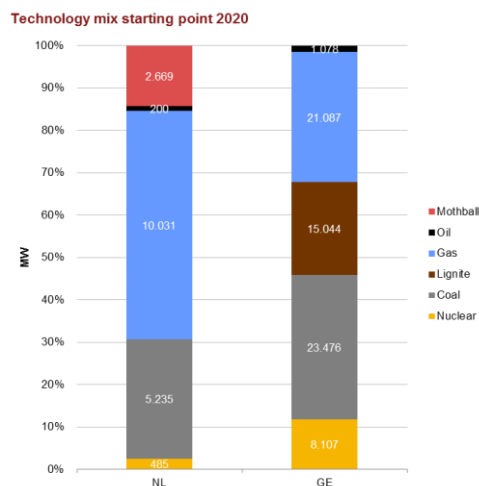


Figure 8.2 Technology mix starting point

Experiments

The experiments can be divided in 5 groups. One base case scenario and four experiment to test the hypotheses. Because the model that is being used is deterministic, running multiple replications of the model to average out stochastic variables does not play a part in this simulation. The four experiments next to the base case are presented below. Table 8.2 shows the experiments included a small description and the number of experiments that is ran.

1. Base case
2. A capacity market in Germany
3. A capacity market in Germany & a large share of renewables
4. A capacity market in Germany & a large interconnection capacity

Table 8.2 Summary of the five experiments

Experiment	# Exp.	Description
Base	3	Energy only scenario. Two markets are optimized and performance is monitored. The base experiment is run under three different CO ₂ price simulations in order to capture shifts in the merit order and spreads of different technologies.
Capacity market	3	Germany implements a capacity market. This scenario is simulated taking into account different CO ₂ scenarios resulting in 3 simulations. The main purpose of this experiment is to compare the outcomes with previous research on capacity markets to validate the model.
Capacity market & renewables	3	In addition to the second experiment, the amount of renewables has increased significantly to test the effect of a capacity market in long term with expected large amounts of renewables.
Capacity market & increased interconnection	3	The increase in interconnection capacity can be seen as a policy which can be implemented to possibly change effects of a capacity market in Germany.

In total, 12 experiments will be executed

Performance indicators

For the evaluation of the experiments, the performance indicators from section 3.3 are used. These are, the average electricity price, electricity price volatility, import and export and the profitability of power plants. Table 8.3 shows these performance indicators and shows the unit of measurement. Appendix E presents the parameter values and equations used to calculate these performance indicators.

Electricity price and volatility

The electricity price is presented as the average electricity price of all the hours in 2020. The volatility is defined as the standard deviation of the electricity prices for all hours in 2020.

Capacity price

The capacity price is defined as the absolute increase per MWh in order to match the total capacity price resulting from the system. Mathematically this is calculated by multiplying the capacity clearing price and the clearing volume and dividing this by the total demand in MWh in 2020.

Loss of load expectation

The LOLE can be defined as the expected number of hours per year that supply cannot meet demand (DECC, 2013). The term expected implies that the exact number might differ from this expectation following a certain distribution. The deterministic nature of

the Power2Sim model makes this impossible. Therefore, the LOLE in this research is defined as the number of hours in a year that supply cannot meet demand. The term expected is left out. Translating this indicator to model output, the LOLE is calculated as the number of hours that the electricity price is equal to the price cap. Please note that the LOLE is not the same as a blackout since most loss load hours can be dealt with without serious consequences for consumers. For example by deliberately lowering the voltage, also called brown out (Blume, 2007).

Profitability of existing producers

The profitability of power producers in this study is defined as the extent to which producers manage to recover their costs in the market. Translating this to a measurable, the profitability is defined as the percentage of power plants that succeed in at least recovering their fixed operating and maintenance cost. These are the costs that a plant at least needs to stay online and not make a loss. This number is split into the different technologies.

Reserve margin

The reserve margin in this study can be seen as the ratio of capacity over peak demand. The value for peak demand is taken by looking at the maximum value that occurs in the simulation model simulated for 2020. Tennet uses three ways of capaculating the reserve margin which vary the weight of capacity, interconnection and renewables. The following calculations will be made:

1. Reserve margin without interconnection, renewables count for 100%
2. Reserve margin without interconnection, renewables count for 20%
3. Reserve margin including interconnection, renewables 20%

CO₂ emission

CO₂ emission is a pretty straight forward indicator. The emissions are calculated for the electricity market only. The yearly fuel input per technology for the entire system of a country is multiplied by a technology specific emission factor. The sum of these emission is the country's yearly emission. The emission factors used can be found in appendix E.

Total consumer costs

Consumer cost is defined as the total cost consumers have to pay for their electricity. Consumer cost is more than the costs from buying electricity in the market. The total costs also include the cost German consumers need to pay for the capacity market payments and also differences in renewables subsidies that might increase the total costs. The total costs from electricity are calculated by multiplying the hourly electricity price with the hourly demand. The renewables subsidy change is the decrease of revenue for renewable producers as a result of lower electricity prices. The cost of capacity is calculated by multiplying the capacity market clearing price with the clearing volume and dividing the number over the annual demand in MWh.

Table 8.3 Performance indicators

Indicator	Unit
Average electricity price	€/MWh
Electricity price volatility	%
Import/export	MWh
Profitability of existing producers	# profitable plants
Lost load hours	h/year
Reserve margin	%
CO ₂ emission	Tonne/year
Total consumer costs	€/year

9 Results

This chapter presents the results from the simulation. In order to draw conclusions from this research, the outcomes need to be presented according to the performance indicators set up in the design of experiments. Once this is done, the results will be ready for interpretation and discussion. The purpose is to objectively present the results and provide an in depth interpretation of these results in chapter ten.

9.1 Results

The results can be presented in various ways. The analysis contains multiple performance indicators and several different experiments. The results need to be broken up into logical segments. To present the results in a structured way, the choice has been made to present the results per performance indicator. This makes it easier to compare the results of the different experiments. The structure used for this chapter is presented in Figure 9.1.

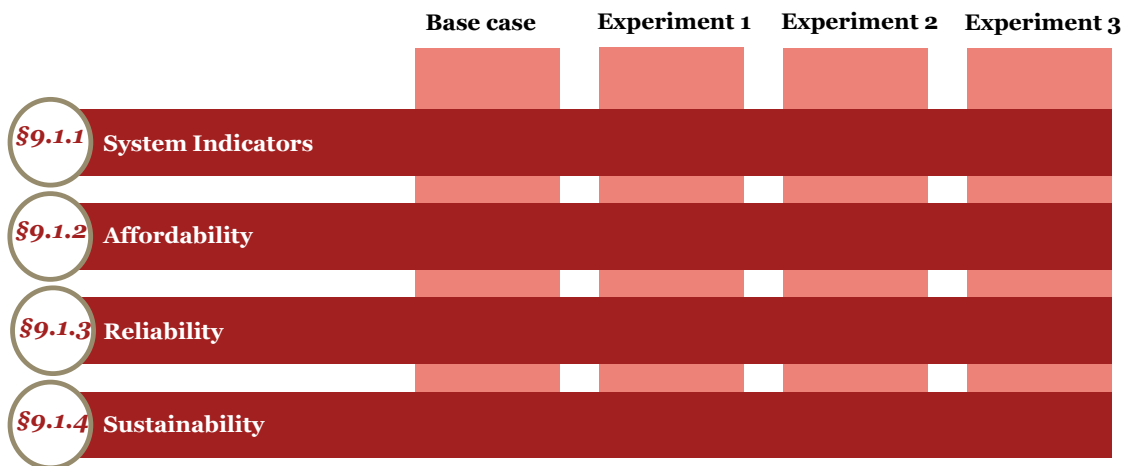


Figure 9.1 Results presentation structure

The results will be presented according to the operationalized performance indicators determined in section 8.2. A clear distinction is made between the results and the interpretation of the result. The goal of the following paragraphs is to objectively present the model outcomes. The results will be interpreted in chapter 10.

The following abbreviations are used:

B = Base model

E1= Capacity market

E2= Capacity market + interconnection

E3= Capacity market + renewables

9.1.1 System indicators

Investment

Figure 9.2 and 9.3 below show the amount of investment in generation capacity in Germany and the Netherlands for the different experiments.

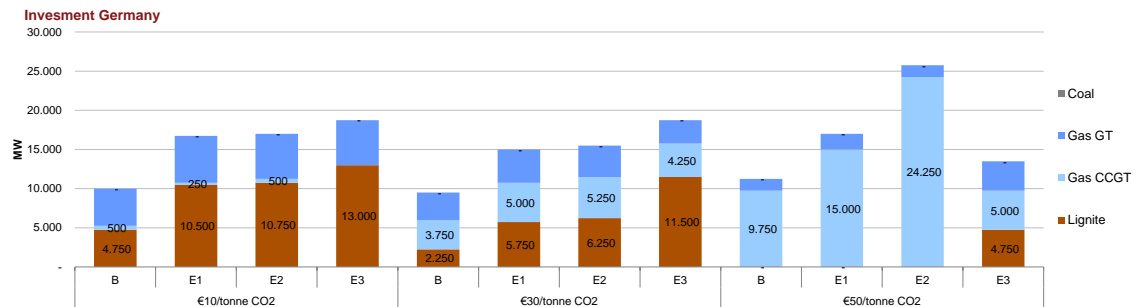


Figure 9.2 Results investment in Germany

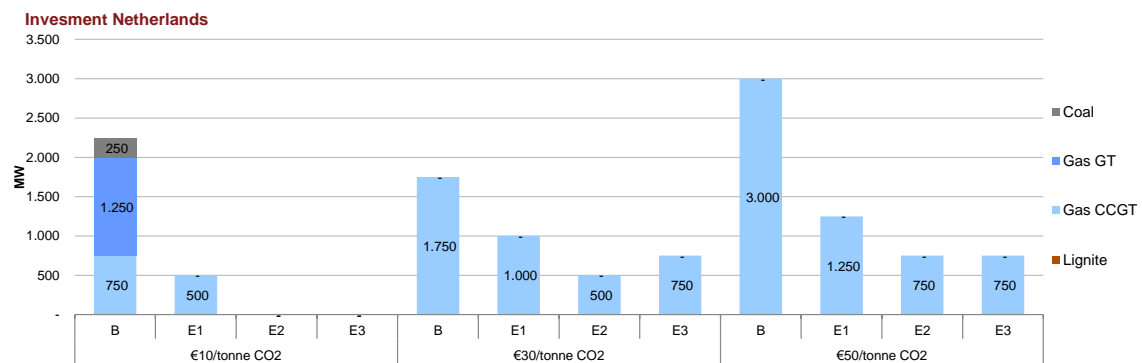


Figure 9.3 Results investment in the Netherlands

From figure 9.2 three major observations can be made considering the Germany electricity market. Firstly, it can be observed that a capacity market results in an increased amount of investment in conventional technologies. Although the values differ for the different experiments, the capacity market has a positive effect on the amount of investment. A second observation is the shift from “dirty” power plant investment to cleaner technologies with increasing CO₂ prices. For the €50/tonne CO₂ only experiment 3 shows some investment in lignite. The investment is much lower than in the first two CO₂ scenarios. A third observation is that the first two CO₂ scenarios show similar behavior in the total amount of investment, while the €50/tonne CO₂ scenario shows an increased amount of investment. In the two lower CO₂ price scenarios, the total amount of investment does not change with an increase in interconnector capacity. In section 10.1 this deviant behavior is analyzed.

The results from the analysis of the Dutch sector show that investment in generation capacity is affected in a negative way by the introduction of a capacity market in Germany. In all experiments, the investments show a decrease compared to the base case. Whereas the German system is not affected if interconnection is

increased, the Dutch system is affected in a larger degree with investment decreasing compared to the normal capacity market scenario. This accounts for all CO₂ scenarios.

Comparing the countries, it can be observed that a capacity market in Germany shifts investment from the Netherlands to Germany. This conclusion is based on experiment 1 and the base case only differing in the existence of a capacity market in Germany. All experiments show an increase in German capacity investment and a decrease in Dutch capacity investment.

Electricity price and volatility

In this section, the following performance indicators are presented. Electricity price and volatility. The results are presented in figure 9.4 and 9.5.

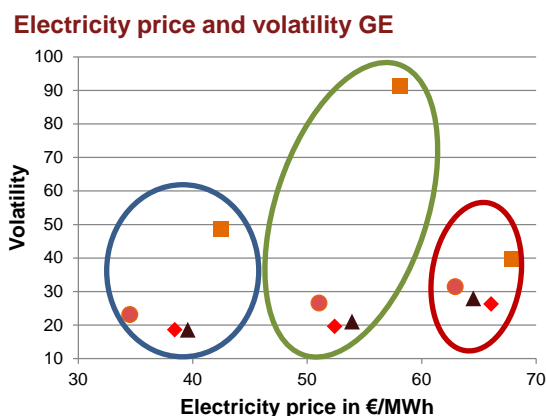


Figure 9.5 Electricity price and volatility GE

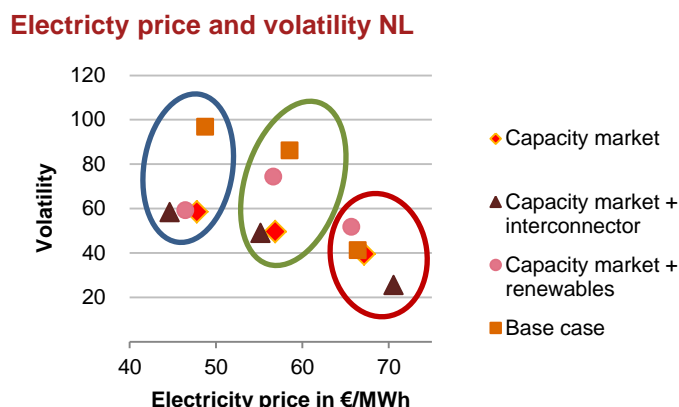


Figure 9.4 Electricity price and volatility NL

In both figures three groups of points can be observed which represent the three CO₂ scenarios. The left group (blue circle) represents the low CO₂ scenario followed by the other two scenarios (green for €30/tonne and red for €50/tonne) because an increase in CO₂ directly influences the electricity price.

From Figure 9.5 it can be observed that the implementation of a capacity market in Germany results in a decrease in both the electricity price and the volatility of the electricity price. In the two lower CO₂ scenarios, the capacity market is located below and left of the capacity market points. An increased interconnection capacity results in a decrease in electricity price compared to the capacity market scenario but does not lead to a difference in volatility. Again the €50/tonne CO₂ scenario differs the two other CO₂ scenarios.

The Dutch sector shows a decrease in electricity price and volatility for the two lower CO₂ scenarios. For these two scenarios, a capacity market in combination with an increased interconnection capacity results in the largest decrease in both electricity price and volatility. Interestingly, in the CO₂ €50/tonne, an increase in electricity price is observed in both the regular capacity market scenario as well as in the capacity market including renewables scenario. This is counterintuitive since the general idea is that a capacity market leads to lower price in the country in which it is implemented and consequently also to lower prices in neighboring countries. This interesting phenomenon is further elaborated on in section 10.1

Capacity price

Capacity price per MWh

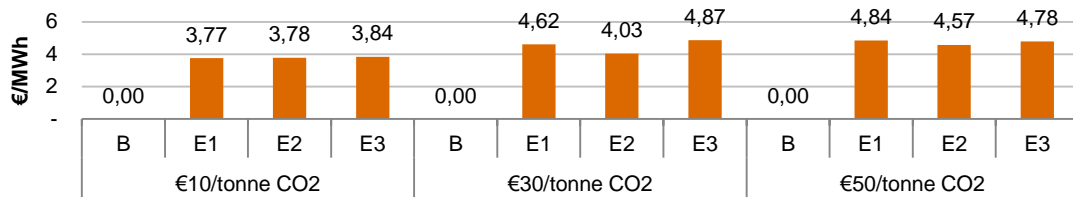


Figure 9.6 Capacity price

Import and export

Figure 9.7 and 9.8 present the results of analyzing the import and export between Germany and the Netherlands.

GE export to NL

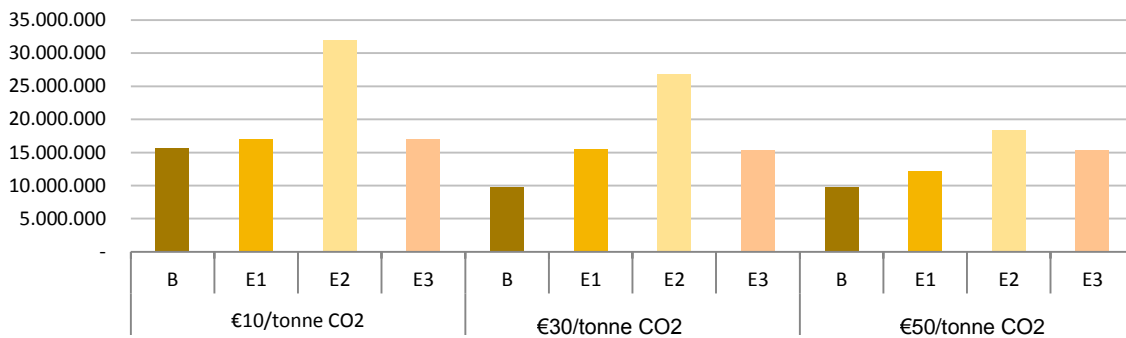


Figure 9.7 Results GE export to NL

NL export to GE

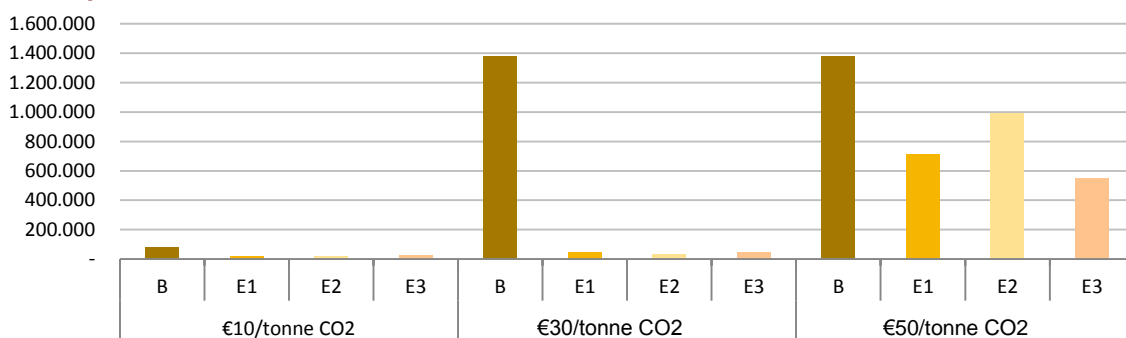


Figure 9.8 Results NL export to GE

From the above graphs it can be concluded that the implementation of a capacity market increases the amount of export from Germany to the Netherlands and that the cross border flow from the Netherlands decreases. The largest difference is witnessed in the capacity market with extra interconnection capacity. This is logical because the interconnection capacity allows a higher capacity to be transported.

Looking at the CO₂ influence, the cross border flows are less influenced in the €50/tonne CO₂ scenario. This is caused by CO₂ prices having a levelling effect on the marginal costs of electricity and thus on the electricity price. Because cross border flows are triggered by differences in price levels, the CO₂ price causes price spread between the counties to decrease resulting in less import and export.

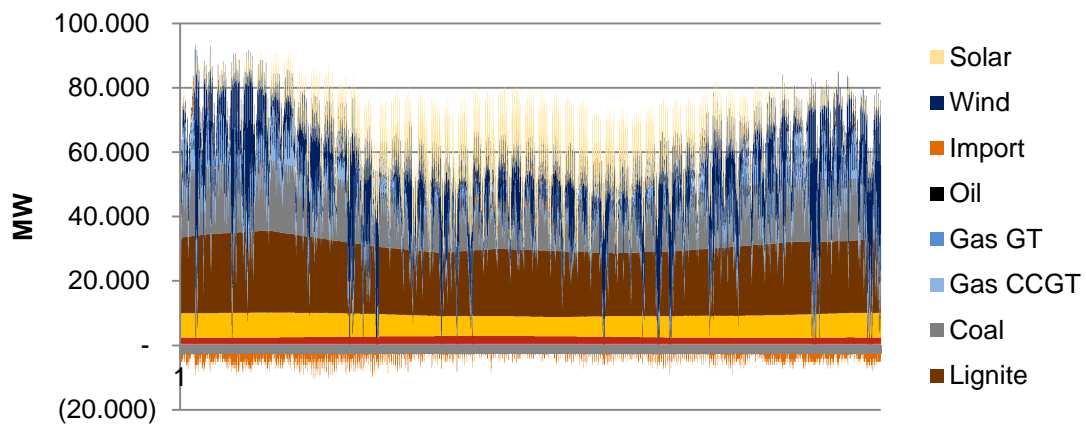


Figure 9.9 Generation Germany 2020

The orange spikes indicate cross border flows. In this case, the negative import means that Germany is exporting electricity to neighboring countries. The spikes are often higher than the maximum interconnection capacity between the Netherlands and Germany indicating that Germany is also exporting to other countries.

9.1.2 Affordability

Total consumer cost

Figure 9.10 and Figure 9.11 present the total consumer costs for the different scenarios and experiments. The total consumer costs consists of three elements namely cost of electricity, costs of capacity and costs of change in renewable subsidies.

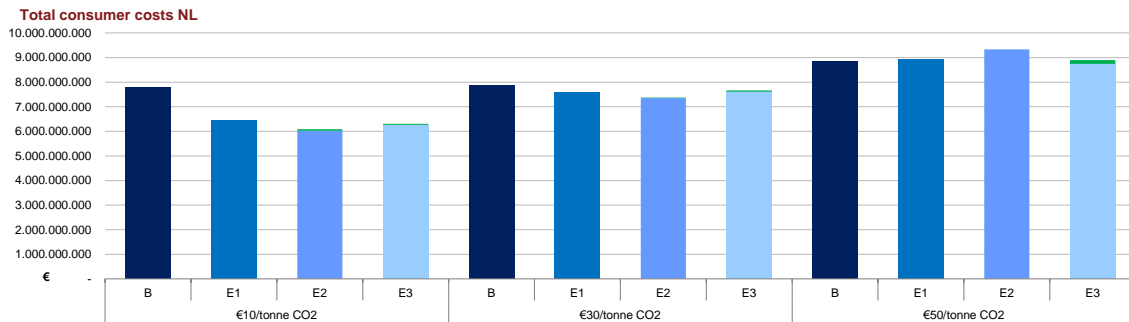


Figure 9.10 Total consumer costs NL

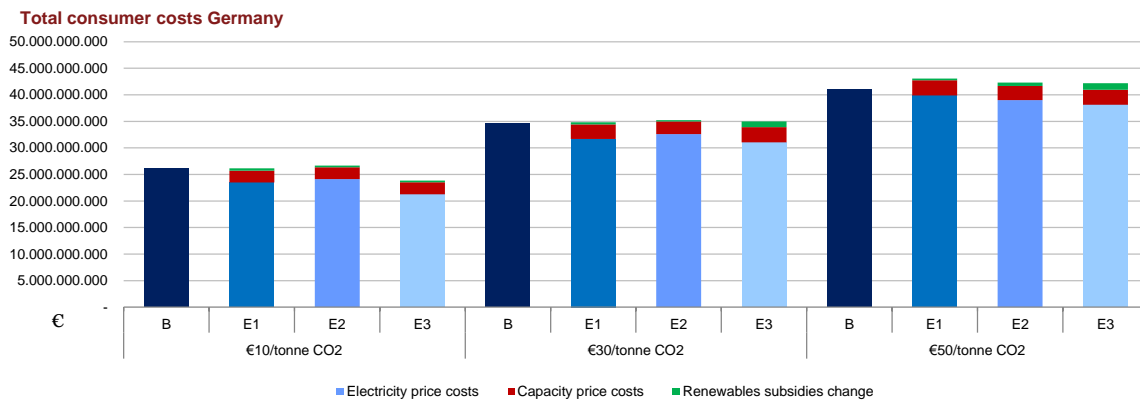


Figure 9.11 Total consumer costs GE

When looking at the Netherlands total cost for consumers, several observations can be made. Firstly, the total costs for consumers decrease for all experiments in the two lower CO₂ scenarios. The decreasing effect is strongest in the case of a capacity market in combination with an enlarged interconnection capacity. The opposite is observed in the €50/tonne scenario and needs some further investigation. This is done in section 10. A last observation on the Dutch graph is the very limited contribution of renewables subsidy changes which in no experiment leads to changes.

The German electricity market shows contrasting behavior. In the German electricity market, all combinations of scenarios and experiments lead to an increase in total consumer cost. The interesting thing is that the costs from the electricity market itself shows a decrease in all combinations of experiments and scenarios. However, this decrease is compensated and even surpassed by the capacity market payment and the change in renewable subsidies. A capacity market thus leads to a net increase in total consumer costs in the country in which it is implemented.

Renewables subsidies

The results of the change in renewable subsidies is presented in Figure 9.12 and Figure 9.20.

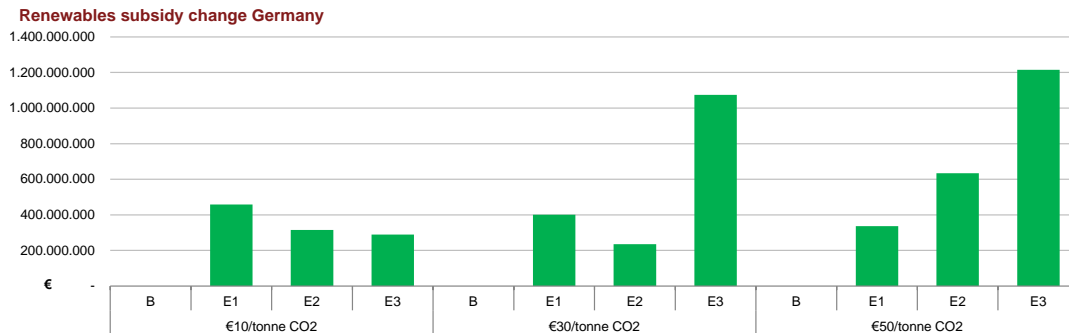


Figure 9.12 Renewables subsidy change Germany

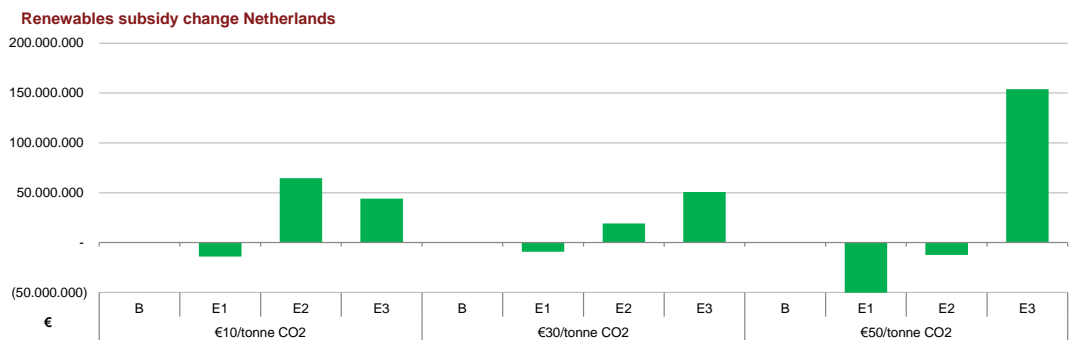


Figure 9.13 Renewables subsidy change Netherlands

Considering change in renewable subsidies, a capacity market results in an increase in demand for subsidies. All combinations of scenarios and experiments show the same results. However, the extent to which this happens seems to differ per CO₂ scenario. The three capacity market experiments show both improvements and disimprovements over the range of CO₂ experiments. Especially the capacity market in combination with higher CO₂ prices result in an increased need for renewables subsidies in both countries. This can be explained by the way the increased renewables scenario is implemented in the model. The renewables are implemented as an increase in installed capacity. The extra renewables result in a decrease in electricity price which is enlarged by the presence of a capacity market.

From the Dutch system, interesting behavior can be observed. From section 9.1.2 it was concluded that a capacity market leads to lower average electricity prices. This would imply that renewable subsidies need to go up. However, this is not the case for the general capacity market scenario. In all CO₂ scenarios, the capacity market results in a negative change. This interesting behavior is further analyzed in chapter 10.

9.1.3 Reliability

The reliability of the electricity system is presented in two ways: the reserve margin and the expected loss of load hours in a year. The reserve margin is measured as the ratio between the peak demand and installed capacity in a country. A ratio larger than one implies that the installed capacity exceeds the peak demand. The loss of load expectation is calculated by looking at the number of hours that the electricity price reaches the price cap.

Reserve margin

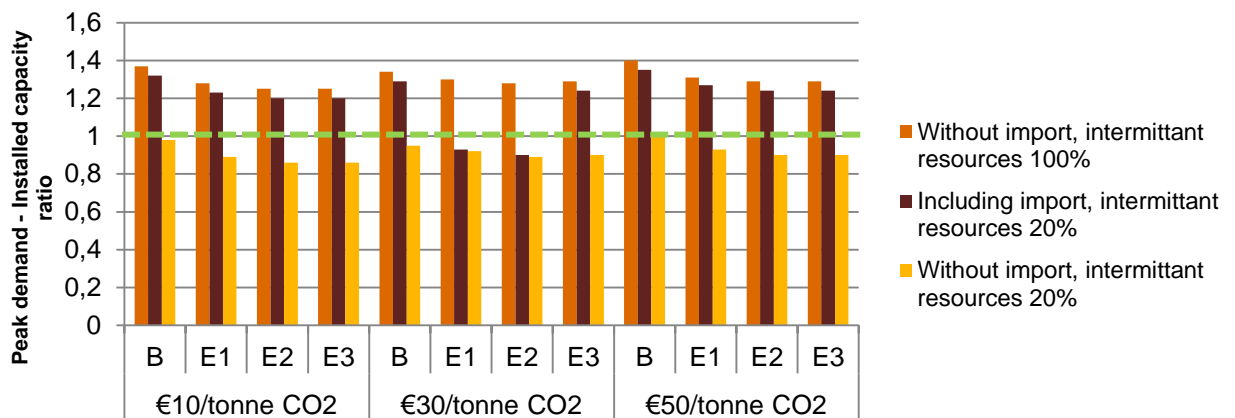


Figure 9.14 Reserve margin Netherlands

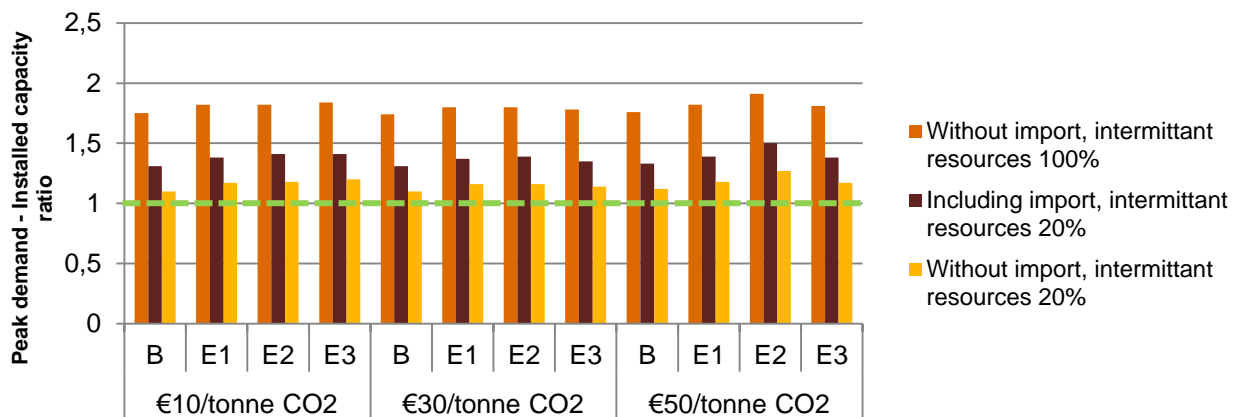


Figure 9.15 Reserve margin Germany

The reserve margin in the Netherlands is affected by the implementation of a capacity market. First observation to support this is the decrease in reserve margin when comparing the capacity market scenarios with the base case scenarios. Again this decrease is observed for the two lower CO₂ scenarios, but not for the €50/tonne scenario. In the base cases, the lowest reserve margins are around (slightly under) 1. In the capacity market scenarios this reserve margin decreases, falling even below the 90% mark for the capacity market including interconnection increase experiment.

The German reserve margin is affected in the opposite direction. All scenarios and experiments show an improvement in reserve margin compared to the base case. It

can be observed that the reserve margin never falls below 1 as was the case in the Netherlands. The capacity market in combination with increased interconnection capacity results in the highest reserve margin. This is no surprise since the reserve margin also depends on the amount of interconnection between two countries.

The results for the German and Dutch sector show the same trend as the results for investment in both countries. This is logical since an increase in investment automatically means an increase in reserve margin.

Loss of load expectation

The results on the loss load hours per year are presented in figure 9.15 and Figure 9.16.

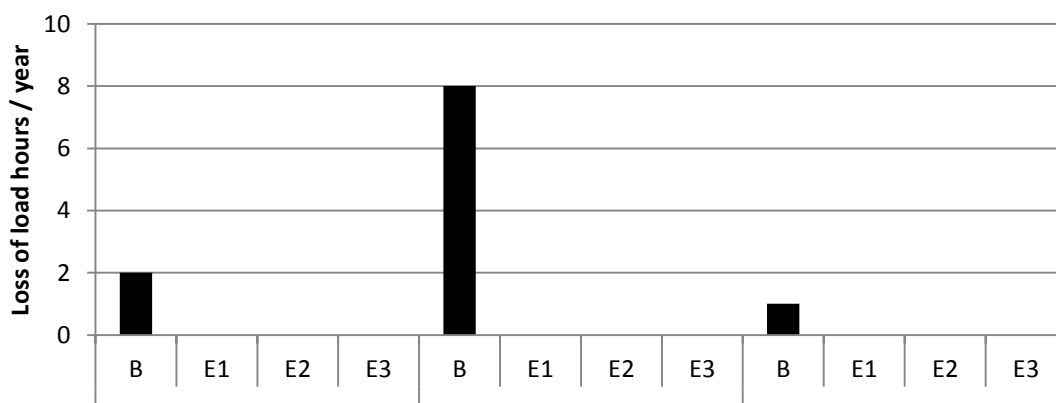


Figure 9.16 Loss of load hours Germany

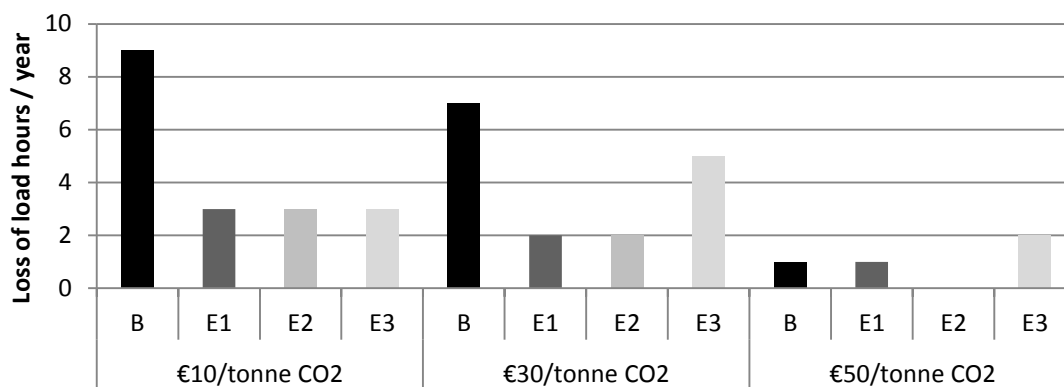


Figure 9.17 Loss of load hours Netherlands

In the Dutch market, the implementation of a capacity market in Germany results in a decrease in the number of unserved load hours in the Netherlands. Only in the capacity market with increased renewables in combination with a CO₂ price of €50/tonne different behavior is observed. In the two lower CO₂ scenarios an increase in interconnection capacity does not lead to a decrease in the amount of loss of load hours. Earlier on, the investment, figure 9.2 and 9.3, showed a decrease in investment in the Netherlands and an increase in Germany. The increase in investment in Germany is larger than the decrease in the Netherlands which should result in a decrease in the amount of loss load hours.

The German market shows unilateral behavior. In all combinations of scenarios and experiments the number of loss load hours is reduced to 0. The implementation of a capacity market in Germany and the investments that come with it, as observed in 9.1.1, diminish the number of hours that demand is not being met by supply.

9.1.4 Sustainability

CO₂ emission

Figure 9.17 and 9.18 present the results for the CO₂ emission in both the Netherlands and Germany.

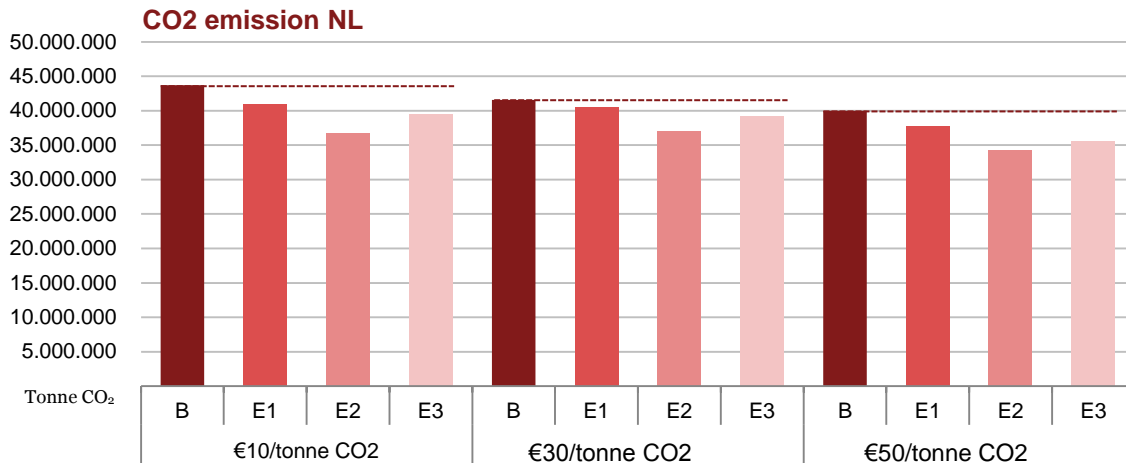


Figure 9.18 CO₂ emission in the Netherlands

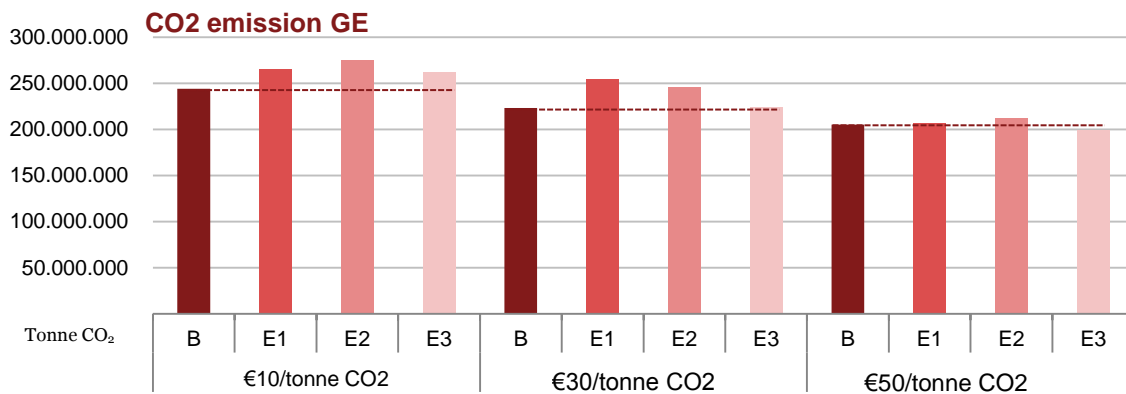


Figure 9.19 CO₂ emission in Germany

The results for the Netherlands show that all capacity market experiments show an improvement in CO₂ emission compared to the base case. Especially the capacity market in combination with a high amount of renewables in both the Dutch and German electricity market results in considerably lower CO₂ emissions. The three different CO₂ scenarios do not lead to structural changes in different experiments, although a downwards trend can be observed with increasing CO₂ prices. This can be seen as a validity factor since higher CO₂ prices favour cleaner technologies which lead to lower emission in the system.

The German emission shows reverse results in the sense that all scenarios result in an increase in CO₂ emission in Germany. CO₂ emission has the highest value in the capacity market and increased interconnection capacity. The results follow the same trend as the investment which is logical since in section 9.1.1 it was observed that the

investment is shifted towards Germany. The CO₂ emission logically does so as well. Another observation is that CO₂ emissions show less variation between the scenarios in the €50/tonne scenario. This can be explained by the fact that a high CO₂ price changes the technology mix of investments in favour of clean technologies like gas. This results in a CO₂ emission increase, but a smaller increase compared to the lower CO₂ scenarios.

9.1.5 Profitability of existing plants

The results for the profitability of existing power plants are presented in figure 9.19 and figure 9.20. The green bars indicate plants that are able to recover both their operating and investment costs, the blue bars indicate the plants that only recover their operating costs, but that earn enough not to make a loss. The red bars indicate a plant making a loss.

Gas

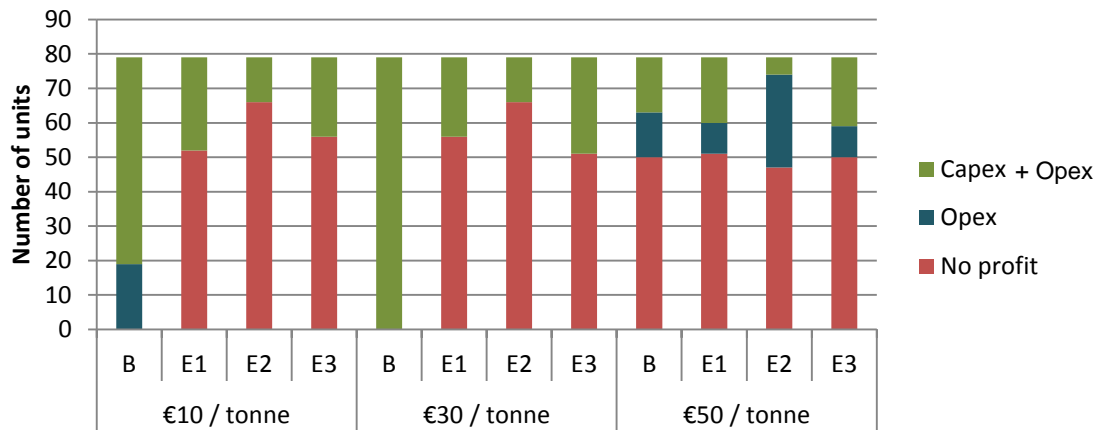


Figure 9.20 Profit existing gas producers NL

Coal

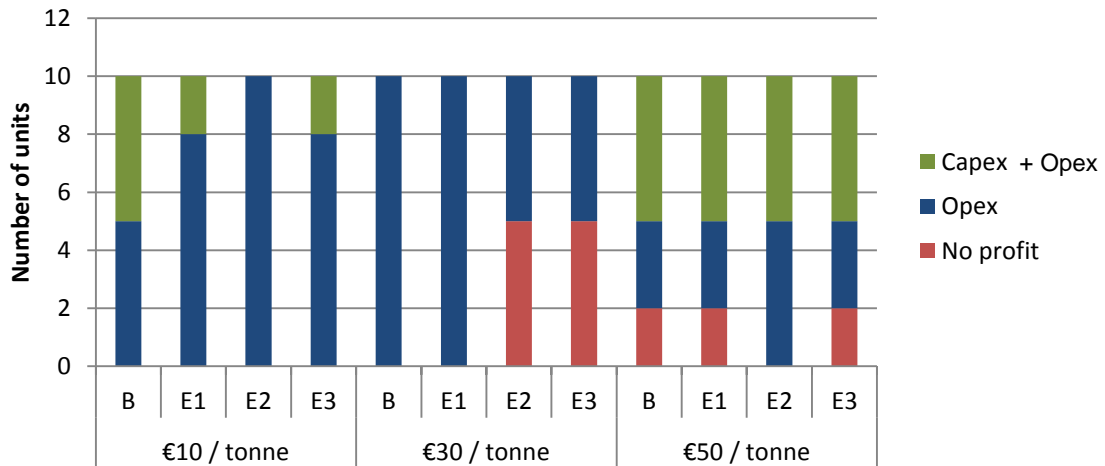


Figure 9.21 Profit existing coal producers NL

From the above graphs, several interesting observations can be extracted. In general, the introduction of a capacity market in Germany has a greater impact on gas plants than on coal plants in the Netherlands. In the base case, there are no plants that make a loss for the two lower CO₂ scenarios. The introduction of a capacity market in Germany results in a considerable number of gas plants that make a loss. More than half of the plants is not able to make a profit. This effect is enhanced by increasing the interconnector capacity between the two countries.

The profitability of coal plants show a less abrupt pattern. The introduction of a capacity market leads to a small shift from plants that recover their full investment costs to plants that earn enough to stay online and still recover some of their investment. The two highest CO₂ scenarios show no difference between the base case and the capacity market. It is interesting to see that a combination of circumstances does lead to coal plants not being profitable anymore. The introduction of a capacity market with increased interconnection in combination with higher CO₂ prices results in about half of the coal plants earning less than their operational expenditures. From the model results, coal plants show non-profitable behavior only in the higher CO₂ scenarios. This is logical because coal has a relatively high emission factor and is thus severely affected by an increase in CO₂ price. An outlier in these results is the €50/tonne CO₂ price scenario for coal plants, which shows an improvement when interconnection capacity is increased while the opposite behavior is found in the lower CO₂ scenarios. This needs some further investigation and will be dealt with in chapter 10.

9.1 Conclusion

The presentation of the results provide a clear overview of the effects of the implementation of a capacity market in Germany. The most important findings are stated below.

The results show that a capacity market in Germany causes a shift from capacity towards Germany. The investment in generation capacity in the Dutch sector decreases due to an improved business case for plants investing in Germany because they get an additional capacity payment. Electricity prices drop in both countries as a results of the capacity market. This is also the case with the volatility in both countries. This, however, does not mean that the total costs for consumers decreases. For the Netherlands this is true, but the German drop in wholesale price is compensated by a capacity payment and a change in need for renewables subsidies which ultimately result in a net increase in costs for the German consumers. A logical consequence of the shift in investment towards Germany is the increased CO₂ emission in Germany while the emission in the Dutch system decreases. A second logical consequence is that the import from Germany to the Netherlands increases a lot while export in the other direction decreases a lot. Considering reliability, the results show that the Netherlands become increasingly dependent on German capacity. This is observed from a declining reserve margin and increasing imports. Surprisingly, the renewable subsidies do not go up in the Netherlands while prices drop. This needs some further investigation and is elaborated on in section 10.1.4. A larger interconnection capacity results in a need for more renewables subsidies.

The general effect of increasing the interconnection capacity is that all of the above mentioned consequences enlarge. This means that the positive effects like loss of load expectation improves, but also that the business case of existing producers in the Netherlands worsens as well.

The general effect of increasing renewable capacity in both countries is that it limits investment. The reason for this is that the renewable increase is modelled as a physical increase of 30% on 2020 renewables levels. This means that there is in general more capacity available in the market which has a limiting effect but still results in the same behavior as the other two experiments show.

An important conclusion that can be drawn as well is that CO₂ prices interact with the capacity market sometimes resulting in outcomes that differ from the behavior that can be observed in the lower CO₂ price range. This needs some further investigation. Section 10.1.4 provides a more detailed analysis of the interaction between a capacity market and CO₂ prices.

The results will be interpreted in chapter 10. The consequences of the results will be discussed per actor group and surprising results will be further explored.

10 Interpretation and literature comparison

Chapter nine mainly focuses on objectively presenting the model results and comparing the results of the experiments to the base case. This chapter will elaborate on the results more extensively providing an interpretation of the results and an explanation how these results can be derived from the model mechanics. In the first paragraph, the model results are interpreted. The second paragraph presents a follow up base on the model results. The third paragraph focusses on the comparison between the model results and the results from literature. A final paragraph is dedicated to presenting recommendations for policy makers in The Dutch electricity sector.

10.1 Model results

The following paragraphs present a detailed analysis of the results in which the relationships between the results themselves, and the model structure is investigated. If divergent behavior is found, an explanation for this deviating behavior is tried to be found. As was suggested in chapter 9 a distinction between the effects of CO₂ and the effects of a capacity market and their interaction effects.

10.1.1 Capacity market

From the model results it can be concluded that a capacity market increases the investment in Germany and that the investment in the Netherlands is dampened compared to the base case. This is not unexpected but still it is interesting to look at the internal dynamics of the simulation model. Since the assumption is made that all investment options are equal in the two countries as well as the fuel prices and CO₂, investments are only based on electricity prices. This means that investment opportunities are more or less equal for the two countries. The model identifies the most attractive investment iteratively, making a new calculation every time an investment is added to the model. In case Germany implements a capacity market, investment in Germany means that the investment is now not only based on electricity prices but also on an “additional” capacity payment. This directs investment to Germany instead of the Netherlands. The decreased amount of capacity in the Netherlands is now absorbed by an increase in cross border trade between Germany and the Netherlands. This is backed up by the simulation results which show a significant increase in the flows from Germany to the Netherlands.

The model results show an increase in the amount of lignite as well. The main purpose of a capacity market is to provide reliability in the system and incentivize investment in a sufficient amount of peak capacity. However, since lignite power plants are not excluded from the bidding, the capacity payment is a bonus revenue for a lignite power plant. Due to low lignite prices, this technology is already quite competitive. What you clearly see is that in case the CO₂ price rises, the competitiveness of lignite power plants diminishes, and is even eliminated altogether at €50/tonne CO₂. The same variation in technologies is present in the trade-off between CCGT and GT gas

plants. The higher the CO₂ price, the more investment is directed towards the relatively clean CCGT plants.

In all scenarios, the volatility of the Dutch electricity market decreases. The origin of this result is the increase in capacity that is built in Germany. The enlarged available level of capacity in Germany is used to supply the Netherlands with electricity. This also explains the decrease in the average electricity price in the Netherlands. Summarizing, the increased capacity in Germany is used to supply the Netherlands with electricity which lowers the price in the Netherlands and shaves the peaks. This is also translated in the number of lost load hours, which show a decrease in lost load hours in all scenarios. This might be a positive thing since the system is able to ensure adequacy to a greater extent. However, a second indicator for reliability in the electricity sector, the reserve margin, tells the exact opposite story. The reserve margin is decreasing for all scenarios and for all different ways in which Tennet calculates this reserve margin. While in the base case, the reserve margin were close to 1, the reserve margins in the Netherland dropped to even 0,86 for the CO₂ €10/tonne. The reserve margin including interconnector capacity is on average 35% point higher. This difference from significantly below 1 to well above 1 indicates a dependence on import of electricity during peak hours. The question that remains is whether the number of unserved load hours in this case is a good indicator for the reliability. Therefore, a follow-up analysis is performed in section 10.2.

A surprising result in the capacity market experiment is that the change in renewables subsidies does not show a higher need for renewables as the electricity price on average goes down. The expected outcome would be an increase in need. In order to find the cause of this behavior, the price duration curves are plotted to show the difference in price duration curves between the base case and the capacity market experiment. The renewable production has been plotted as well to get an impression of the effects a change in the price duration curve has. Figure 10.1 shows the top and bottom part of the curves. It can be concluded that the bottom parts are equal and the top parts differ in the sense that a capacity market reduces peak prices. This, however, does not explain why renewables subsidies do not go down. Figures 10.2. and 10.3 do provide a possible cause for this behavior.

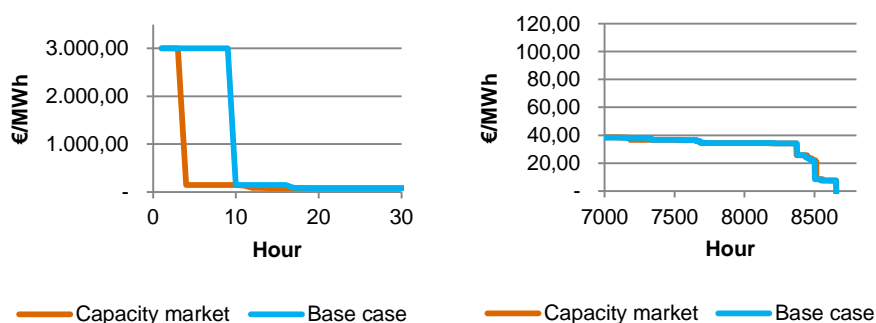


Figure 10.1 Load duration curve first (left) and last (right) part

Price duration curve and renewables production

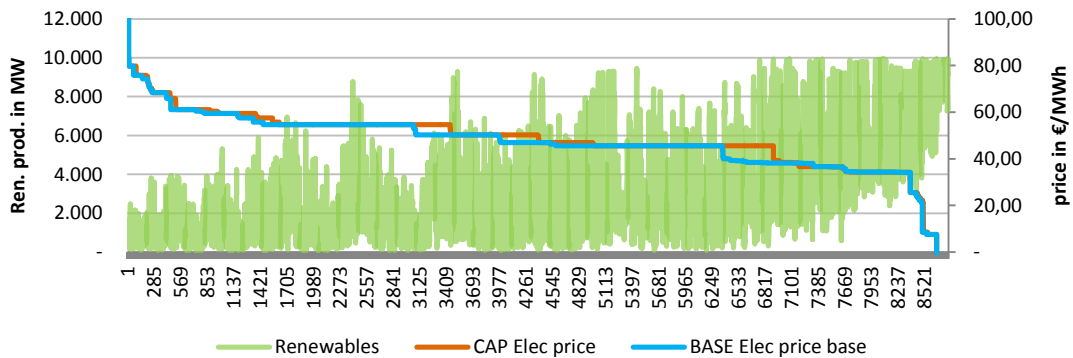


Figure 10.2 Price duration curves and renewables production (1)

Price duration curve and renewables production

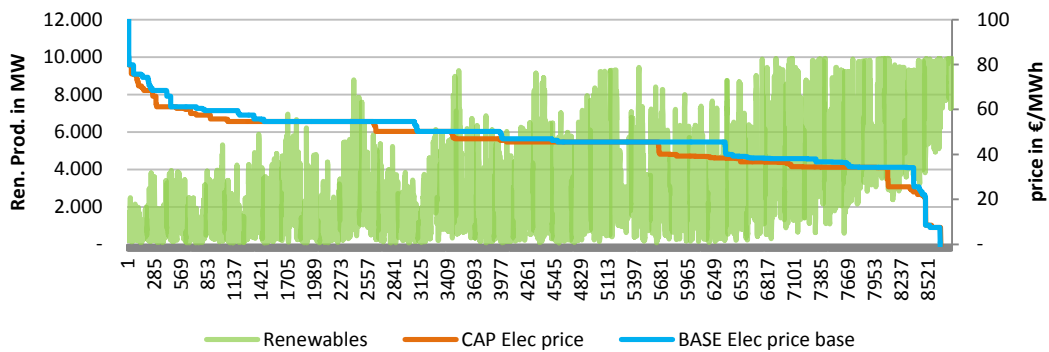


Figure 10.3 Price duration curves and renewables production (2)

From figure 10.2 it can be observed that the price levels in the Netherlands do not always go down and sometimes are even higher than the prices in the base case. Especially from the middle up to two third part of the graph higher prices are observed. The renewable production shows that the average production is correlated with the curve, which means that production is higher when the prices are lower. The need for renewables subsidies might have gone up in the very top part of the curve, but this is compensated by sometimes higher prices over the middle part of the curve where renewable production is generally higher than in the top part. The increased interconnection capacity experiment presented in figure 10.3 shows that the price duration curve is below the base case curve for almost the entire curve resulting in an increase in need for renewables subsidies. It is imaginable that an hour of unserved load is an hour in which demand is at its peak, and renewable production at its minimum. This is verified by figure 10.4 which shows generally higher demand and lower renewables production during periods of higher prices. The values of the renewables production and demand have been rescaled to fit the graph.

Price duration curve and renewables production

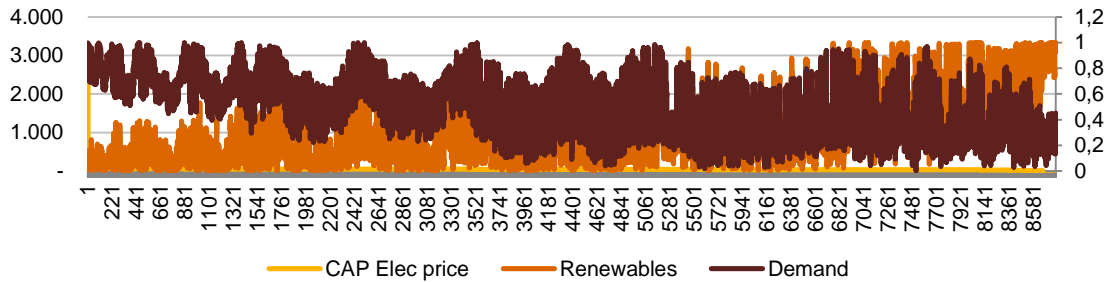


Figure 10.4 Price duration, renewables and demand

10.1.2 Capacity market with enlarged interconnector capacity

The interconnection capacity was increased by 2000 MW for this analysis. In all scenarios, the amount of investment has increased in Germany. A logical consequence of this increase in capacity is the decrease in capacity investment in the Netherlands even resulting in no investments at all in the €10/tonne CO₂ scenario. This decrease in capacity in the Netherlands probably follows the same argumentation as in the previous paragraph. The change in capacity investments is equally spread over the different technologies. The most obvious change regarding the electricity price is that the electricity price is lower than the capacity market scenario. The difference between a capacity market and the base case is a 2,05% decrease. Increasing the interconnector capacity leads to a 8,46% decrease in electricity price. The volatility remains relatively unchanged. The low electricity prices obviously have an effect on the total consumer costs, which decrease in the system as expected. This holds for both countries, but the capacity payments and change in renewable subsidies in Germany results in a net increase in consumer costs in Germany while the Dutch consumer costs decrease.

The renewables revenue difference in the presence of a capacity market and increased interconnector capacity shows that the need for subsidies rises. Renewables suffer from the capacity market in combination with the increased interconnector capacity. Figure 10.3 already pointed out that the price duration curve for the capacity and increased interconnection experiment is almost always lower than the base case price, which supports the claim of a price drop of the whole range of wholesale prices. The price drop results in a decrease of income for the renewable production. In other words, in order for the renewables to remain profitable, the subsidy needs to be increased. Converted to €/MWh the renewable subsidies need to be increased with €0,4/MWh and €2,4/MWh for the first two scenarios.

A surprising result of the model is that although interconnection capacity is increased and prices are lowered, the number of unserved load hours remains equal to the capacity market scenario without extra interconnection capacity.

Regarding the price levels, interesting behaviour is observed as well. In all scenarios, the volatility decreased which can be related to the overcapacity in Germany which is used to cover peak load in the Netherlands through the interconnection.

However, when looking at the average price, only a decrease is observed in the €10 and €30 scenarios. Apparently the €50 scenario does not result in a decrease in price.

10.1.3 The impact of the CO₂ price on the functioning of a capacity market

To complete our understanding of the functioning of a capacity market, the CO₂ effects and the capacity market effects need to be judged separately.

The most important fact of CO₂ prices is the leveling effect on marginal costs. From the results it can be concluded that a higher CO₂ price shifts the technology mix towards cleaner fuels because emission is charged more heavily. As expected, a higher CO₂ price leads to a higher electricity price because the CO₂ price directly influences the marginal costs of production and thus the electricity price. In terms of CO₂ emission, the CO₂ price triggers two effects. First, a higher price leads to a shift in investment to cleaner technologies like gas which have a limiting effect on the CO₂ emission. Secondly, CO₂ prices cause a shift in the merit order, pushing “dirty” technologies out of the merit order resulting in a smaller CO₂ emission. The CO₂ price seems to have a not more than expected influence on the functioning of a capacity market except for the combination between a capacity market and an increased amount of interconnection capacity.

One result that shows particularly interesting behavior is the investment in generation capacity in the presence of a capacity market and an increased amount of interconnection capacity with a CO₂ price of €50/tonne. In this case, the amount of investment is a lot higher than the investment in the €30/tonne scenario. An extra analysis is performed to see what causes this behavior.

The first test is to check whether this is an outlier or whether the behavior shows a trend. Therefore the algorithm is run again using a CO₂ price of €60/tonne. The outcomes show a level of investment that is about 20.000MW higher than the base case. This means that at high CO₂ prices, the effect on investment increases to a large extent. The question that remains is why these large investments occur.

A possible explanation can be found in the design of the capacity bids. A power plant always retrieves the capacity clearing price if their own bid is lower than the clearing price. In this paragraph it was already concluded that CO₂ prices cause the merit order to level out. In other words, the difference between the electricity price of two technologies converges. This is shown in figure 10.5.

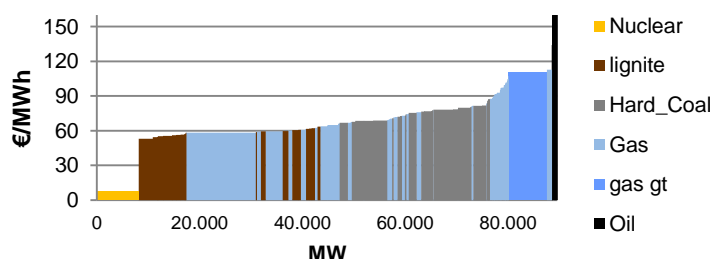


Figure 10.5 Merit order Germany at CO₂ price of €50/tonne

With CO₂ prices at €60/tonne this effect is even greater. This means that new gas CCGT plants are in the beginning of the merit order while having relatively low investment

costs compared to lignite and coal. A low range of marginal costs means that investment leads only to small changes in the merit order. This means that once a technology is profitably, for example CCGT, it will continue to invest due to small variations in price. Without a capacity market, the revenues would stop at a particular time, stopping the investment as well. In case of a capacity market, the revenue stream is complemented with a capacity payment making investment attractive to higher investment levels. Apparently, the capacity payment is high enough to complement the revenues from the electricity market keeping investment attractive. Looking at the capacity bids in figure 10.6 the majority of the plants has been pushed out of the market (right of the blue line).

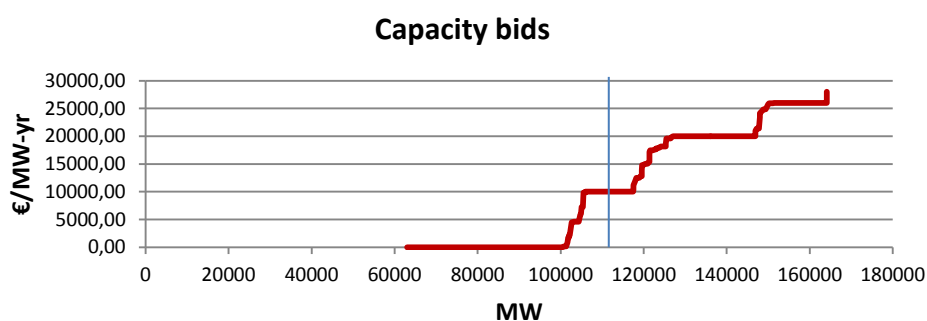


Figure 10.6 Capacity bid curve German capacity market

This means that investment only causes small changes in capacity price. The CCGT benefits most because it is in the lower parts of the merit order and therefore earning a small market premium on most hours. Due to the small variation in both capacity bids and merit order, the CCGT will remain attractive pushing other technologies both out of the merit order as well as out of the capacity merit order and leaving a large share of existing generators without any capacity payment since they have been pushed out of the market.

10.2 Literature comparison

To strengthen the model outcomes and to put them, in perspective, the results from this study are compared with previous literature on capacity market. The distinction is made between the theoretical comparison, empirical data from capacity markets and a comparison with other modelling studies addressing similar issues.

Theoretical comparison

In the literature, the functioning and purpose of a capacity market, and capacity mechanisms in general, is discussed extensively. A literature review from De Vries (2007) concluded that the goal of capacity mechanisms in general is to provide an investment incentive to provide an adequate level of generation capacity in the system. It can be concluded from Assuming the adequacy to be explained by the reliability performance indicators it can be concluded that the implementation of a capacity market in Germany has a positive effect on investment levels as well as on the reserve margin and loss of load hours in a year following the theoretical predictions.

A study by Timera Energy (2012) on the functioning of the future UK capacity market concluded that the implementation of a capacity market reduced both electricity prices and volatility in the market. Comparing this with the model results, similar behaviour is observed. When looking at the cross border effects, the same results would be expected as the two countries are connected. This holds for the lower CO₂ prices but not for the €50/tonne scenario. An explanation for this deviant behaviour has been provided in section 10.4. The cause was to be found in the cross border cost of electricity trade.

According to Cramton and Stoft (2005) the underlying goal of a capacity market is to incentivise investment by restoring the missing revenues from peak prices. The model results show both a positive capacity price for all scenarios and experiments and besides that they show an increase in the amount of investment. This means that the revenues of the wholesale market are complemented by the capacity payment as some of the missing money is replaced by the capacity payment.

In an optimal market, a capacity market is a solution to a non-existing problem which means that the results should be exactly the same in the sense that consumer costs should be equal. Following Borenstein and Holland (2005), the sum of the producers' short term profit should be equal to the investment costs. This implies that all the bids for the capacity market would be equal to 0, which makes a capacity market superfluous. However, since the market is not optimal, the expectation is that the costs for consumers will be higher. The model results support this argument. However, it must be said that the costs of electricity decrease, but this decrease is counteracted with a capacity price and a change in need for renewables subsidies.

Empirical data comparison

There has been no capacity market fully functioning in a Western European country so there are no data available on this. However, it is possible to compare the model outcomes with empirical data from capacity markets in other parts of the world like the US. Although a direct comparison with, for example, the PJM capacity market is not completely adequate since PJM also includes locational pricing and allows demand response and efficiency improvements to bid in the capacity market.

A report by the Brattle Group (Pfeifenberger & Spees, 2013) concludes that the PJM RPM successfully achieved its reliability and economic objectives in terms of attracting new capacity and preventing old capacity to be decommissioned. This is also supported by Hobbs (2010). This tendency is similar to the capacity increase observed from the model. The same holds for the increased level of reliability that is observed in the country in which a capacity market is implemented.

There is very little evidence that capacity markets actually lead to lower costs of electricity (Drom, 2014). The model results show that the implementation of a capacity mechanism actually leads to a reduction in wholesale price. This reduction is however compensated by the change in need for renewables subsidies and the capacity price that needs to be paid to the producers resulting in a net increase in total costs. These results do not contradict the hypothesis.

Another example of the effects of implementation of a capacity mechanism in general can be found in Russia. The market reform there had serious consequences for

the trade between Russia and Finland (SWECO, 2014). Although the situation itself is not really comparable with the Dutch-German situation, it still is an indication that unilateral implementation of capacity mechanisms might have severe effects on trade with neighbouring countries. This effect is observed from the model results with exports increasing drastically for Germany and imports increasing in the Netherlands as a consequence of the implementation of a capacity market in Germany.

Modelling studies comparison

This paragraph compares and discusses the results obtained by the model with the literature on modelling studies considering this topic. Since every study uses its own method and assumptions, direct comparison proves difficult. However, it can be very helpful for validation purposes to see whether the same trends are present in the different studies.

Regarding cross border effects of a capacity market, three different studies were found. Firstly there is a report from SWECO (2014). SWECO looks at the implementation of a capacity market in a European context. The different experiments that were executed consist of different capacity market designs in either one or multiple countries or integrated over Europe. The Sweco report includes a couple of overlapping performance indicators which make it possible to compare model outcomes. The model used, is similar to the merit order model Power2sim and provides a good basis for comparison. However, a critical note must be placed on the results since the model outcomes by SWECO assume an optimal equilibrium market while this research's outcomes are based on non-optimal conditions. When it comes to electricity prices, a price drop in both the Netherlands and Germany is observed. According to the project, the prices will drop €4/MWh in the Netherlands when Germany implements a capacity market. The SWECO project scenario corresponds closest to the €30/tonne scenario. In experiment 2, the difference is €3,7/MWh which corresponds to the values from SWECO. Another important aspect of the capacity market is the cross border impact on investment. The SWECO report shows that the implementation of a capacity market results in no investment in Dutch capacity, which is similar to the results found in this report. Unfortunately, the SWECO report does not show the level of investment for a non-capacity market scenario so these results cannot be evaluated. The SWECO report supports the argument that renewable subsidies need to be increased as a result of the decreased electricity prices.

A second research by Iychettira (2013) investigates the long-term dynamic behaviour of implementing a capacity market in a North-Western country closely related to the Dutch and German market. The main conclusion regarding the cross border effects of a capacity market is that it dampens investment and that it leads to a marginally higher change of outages in the neighbouring country. The first conclusion is directly supported by the outcomes from the simulation. The second one is harder to compare since a probability is based on the average outage among a large number of runs. However, from the previous paragraph can be derived that the number of lost load hours is increased due to interconnection risk and cross country availability of generation capacity. This makes the conclusion that a capacity market leads to higher probabilities of outages plausible.

A third research that investigates the implementation of capacity market is a study by ECN (Özdemir, DeJoode, Koutstaal, & Hout, 2013). ECN uses an electricity market optimisation model. The electricity price and the capacity price and corresponding investment levels are the result of optimising the social welfare while minimising costs. This study assumes optimal investment. The question that can be asked is how the results should be interpreted since a capacity market is a solution to the energy market being non-optimal. Their main conclusion is that the unilateral implementation leads to higher investments and that it leads to mixed effects for neighbouring countries. The study by ECN shows similar behaviour as the results from this thesis. Investment in Germany is growing at the cost of capacity investment in the Netherlands. They argue that this decrease in capacity is a free rider effect for neighbouring countries in the short term. Also the need for reliable interconnector capacity is named as an important factor. The general dynamics are quite equal between the studies. However, the exact results show major differences. The biggest difference is observed in the absolute amount of capacity increase in Germany due to the capacity market. The ECN research shows a close to 50GW increase between the capacity market and non-capacity market situation. In this study, the increase is in the order of 5GW. Another difference is the technology mix. The major part of the capacity increase caused by the capacity market is made up with gas turbine power plants. No increase in lignite plants is observed while lignite plants do profit from the capacity market in the power2sim model. There are several differences between the ECN model and the model in this study that might explain these differences. First of all, ECN uses the VOLL as a price cap, while in this study a lower price cap is used, which leads to higher levels of investment in the ECN study. Besides that, renewables have less capacity credits in the ECN study which means that a larger part needs to be covered by conventional units. In addition, the amount of renewables used in the ECN study is higher than in this research. This means that the gap between investment with and without capacity market grows because there is less capacity needed to cover the demand without capacity market and the capacity market capacity is still covered by conventional technologies due to the small amount of capacity credits that renewables get in the ECN study. A final difference is the amount of nuclear capacity that is decommissioned. This is higher in the ECN study because some of the capacity is decommissioned after 2020 which has been incorporated in the ECN model and has not been incorporated in this research. Some further investigation shows another explanation based on the demand assumptions. ECN assumes the demand to grow 0.8% per year from 2010 onwards while the Ebrain scenarios used in Power2Sim assume a stagnating demand only to rise after 2025. A rough calculation shows that taking into account the required reserve margin, a difference of around 17GW can be explained. Although a large part of the difference can be explained, a 50GW change is still a really high difference.

A final comparison is a study by De Vries (2012) investigating the consequences of a capacity market in France. The study concludes that the cross border effects of a capacity market in France reduces the investment incentive in the Netherlands, without this decrease in investment being compensated. Similar effects were observed in this research with investment in the Netherlands decreasing with the implementation of a capacity market in Germany. A second observation is that electricity prices are higher

in times of high demand than without a capacity market in Germany. The latter outcome differs from the model results as the model results show a decrease in electricity price during hours of scarcity. A difference is that the Netherlands is directly connected to Germany and not to France.

10.3 Impact on different actor groups

The results section presented the behavior of the electricity market with and without the presence of a capacity market. In order to determine the impact of these results, the particular perspective from which it is being interpreted needs to be defined. The actor playing field mainly consists of three types of actors all with their own preferences. The differences in preference result in different interpretations among the actor groups. The main actors to distinguish between are:

- Consumers
- Producers
- Regulator

These actors are the same for both the Netherlands and Germany although the interpretation is dependent on the results which differ between the countries and therefore result in opposing attitudes towards the implementation of a capacity market in Germany. Understandably the results presented in chapter 9 will be interpreted differently by the various actor groups and will therefore also lead to differences in attitude towards a capacity market. The following paragraphs attempt to show what the consequences are for the different actor groups. These have an effect on the way they have to strengthen their own position and ultimately on what recommendations can be given to the different actor groups. Because the main focus of this study is the Dutch electricity market, the actors in the Dutch market will be discussed individually. The German electricity market will be discussed as a whole.

10.3.1 The German electricity market

Consequences

From the results and analysis several different consequences of the implementation of a capacity market can be named. The wholesale prices and volatility tend to go down. This seems positive for the consumers, but when looking at the total cost for consumers this advantage is corrected and even overrun by the capacity price and change in renewable subsidies that ultimately lead to a net increase in consumer costs. This price increase is the price that needs to be paid for the reliability of the electricity sector which is the prime goal of a capacity market.

From a producer perspective, the implementation of a capacity market creates an extra incentive for investing which results in an increased amount of investment. The additional capacity payment therefore stimulates investment. This means that the business case of German plants improves compared to their colleagues abroad.

Of course this improved business case and corresponding higher levels of investment come at the costs of other parties in the system namely the consumer. From a consumer perspective, the implementation results in a net increase in costs. However, the reliability of the system improves, but the sustainability of the system decreases.

From the German consumer point of view, the implementation has mostly negative consequences.

In the context of electricity markets at a European level, an interesting debate emerges as well. The European Union is devoted to creating a target model of model coupling (RAP, 2013). This means creating an electricity system that is more and more determined by regional, international supply and demand rather than just national demand and supply. The discussion of a capacity market focussing on capacity or the supply side at first sight contradicts the European view of flexibility in demand and supply. Although the paper concludes that co-existing is possible, the country in which the capacity market is implemented, should take into consideration the windfall profits of producers that result in higher costs for the consumers. This is based on the assumption that the target model already provides more flexibility in the system which makes a capacity market less needed while still paying the capacity price to producers. One of the issues that arises is whether the increase in investment in lignite is justifiable in times of a focus on sustainability and environmental quotas. The capacity price paid to the producers in order to provide reliability can also be seen as a subsidy to stimulate lignite. Lignite is the technology with the highest CO₂ emission per MWh. This means that Germany is stimulating renewables with subsidies and at the same time is subsidizing lignite by means of a capacity market. This might not be the right signal for a country that has the reputation of being a pioneer in sustainability of the electricity sector. The question has been asked several times whether Germany should include lignite at all in the capacity market. This is investigated in the next paragraph.

A final issue that is not so much related to the model outcomes, but more to the current debate on the design of the German capacity market is the active involvement of foreign capacity in the German market. This is not the first time that this discussion has been put on the agenda. Norway and Germany have been discussing the participation of a new interconnection cable between the two countries on the Germany capacity market in the future (Bloomberg, 2014). The article states that Norway questions the profitability of the new interconnector cable once Germany implements a capacity market. As a solution they want to participate with this cable in the capacity market. There are multiple options considering the active participation of interconnectors in a capacity market. As described by Frontier Economics (2014) these options include participation through and by the interconnector as well as different options for handling risk of non-delivery. A similar issue of cross border participation is discussed in section 10.2.4.

Possible actions

Now that the consequences are known it is interesting to see what measures can be taken to improve the capacity market function. The issue of lignite in a capacity market can be tested quite easily by not adding them to the capacity market. Only the other technologies will receive capacity payments. In order to test the consequences the €10/tonne CO₂ scenario is replicated ignoring lignite in the capacity market. The results are presented in Figure 10.8, Figure 10.9 and Figure 10.9

Investment

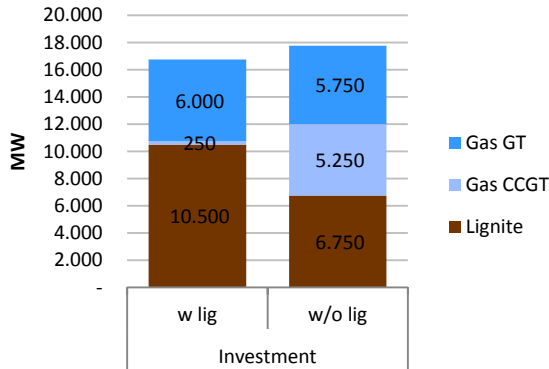


Figure 10.8 Investment without lignite

CO2 emission

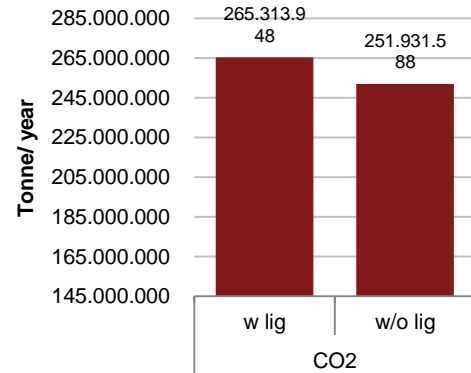


Figure 10.7 CO₂ emission without lignite

Total consumer costs

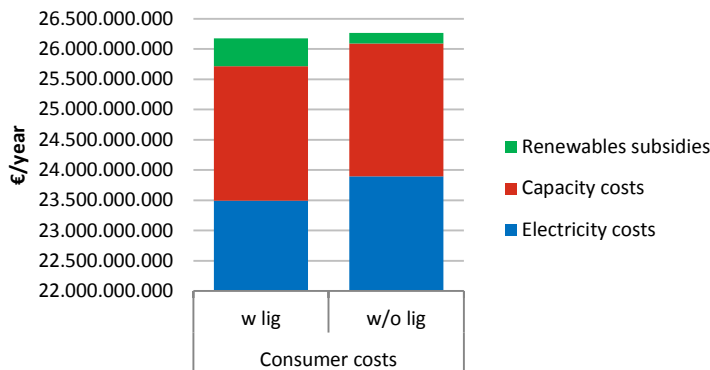


Figure 10.9 Total consumer costs without lignite

The results show that the consumer costs from the wholesale market increase when lignite is not allowed to bid in the capacity market. This is caused by lignite having relatively low marginal costs and in that way pushing the price up in its absence. The capacity costs remain equal while the increase in electricity prices result in less increase in renewable subsidies. This partly covers the increase of costs from the electricity market but the overall numbers show that a slight net increase in total consumer cost is the result.

A second instrument is the design of the capacity market itself. In this study, the sensitivity of capacity market to changes in the price is investigated. This analysis showed that only small differences occur with different capacity prices.

10.3.2 Consumers in the Netherlands

Consequences

The consequences for the Dutch consumers is that the total consumers costs decreases and the number of loss of load hours decreases as well in all possible combinations of capacity market and scenarios. This means that the consumer will benefit very much of a capacity market in Germany. Their situation would be even more improved if the

interconnection capacity is enlarged. This would lead to even lower electricity prices, which result in lower total consumer costs.

10.3.3 Producers in the Netherlands

Consequences

The question is to what extent the worsened business case in the Netherlands actually leads to capacity being mothballed. The impact on existing business is expressed in the percentage of power plants that is able to cover their fixed operating and maintenance costs and showed that a capacity market has a negative effect on power plant profitability in the Netherlands. This is an important indicator since not recovering your fixed O&M costs means that you are making a loss and are not recovering any of your investment costs. A consequence of not being able to recover these fixed O&M costs, is that in the longer term, it is preferable to close a plant. However, most power plants are not being decommissioned straight away, but are mostly put into cold reserve, or in other words they are mothballed.

The investment algorithm was used as a starting point and was adjusted to calculate the total mothballed capacity as a result of a capacity market. As with all the investments in the electricity market, every action results in a change in electricity price. Even though a power plant is not recovering its entire costs, it might still be in the merit order during a number of hours in the year. Therefore it is important to iteratively mothball generation capacity until all active plants recover their O&M costs.

The existing excel investment model needed to be altered to fit the purpose of simulating mothballing. For this analysis it is assumed that a power plant only mothballs if the fixed operating and maintenance cost are not being covered. Furthermore, the assumption is made that the power plants are mothballing in sequence of those making most loss. The standard way of Power2sim to deal with a capacity decrease is to decommission the oldest plant. However, this is not always the worst performing plant. An easy solution was to alter the commission date in sequence of efficiency. The excel model is now altered to be able to output the right capacity for Power2sim to recalculate the electricity market. The visual basic code used can be found in appendix D – VBA code. The mothball results for different scenarios are presented in Table 10.1.

Table 10.1 Mothballed capacity in the Netherlands

Scenario	Mothballed capacity (€10/tonne CO ₂)
Base-case	0
Capacity market	1.409 MW (16 units)
Capacity market + interconnection	4.784 MW (19 units)
Capacity market + renewables	419 MW (7 units)

10.3.4 The regulator in the Netherlands

Consequences

One of the prime concerns of the regulator is the reliability of the electricity system. The results show that the reliability of the electricity sector show somewhat ambiguous results. At the same time, the expected number of unserved load hours decreases when

a capacity market is introduced while the actual reserve margin decreases to a level far below the current level. From the point of view the Dutch regulator it is difficult to say what conclusion to draw from these results. Although this study does not include probabilities, the impression exists that a capacity market decreases the change of outages as indicated by the number of unserved load hours and that the Netherlands become increasingly dependent on German production. This creates a black swan risk related to the availability of the interconnector between Germany and the Netherlands. This dependency is supported by the import results, shift in generation towards Germany and results on reserve margin in the Netherlands. The main question the regulator needs to ask is what the consequences of this dependency on German capacity are.

In order to test the dependency on the interconnection capacity, a follow up test is performed. The goal is to see what the change in number of unserved load hours is when the interconnection between the two countries is shut down. The result is presented in Figure 10.10.

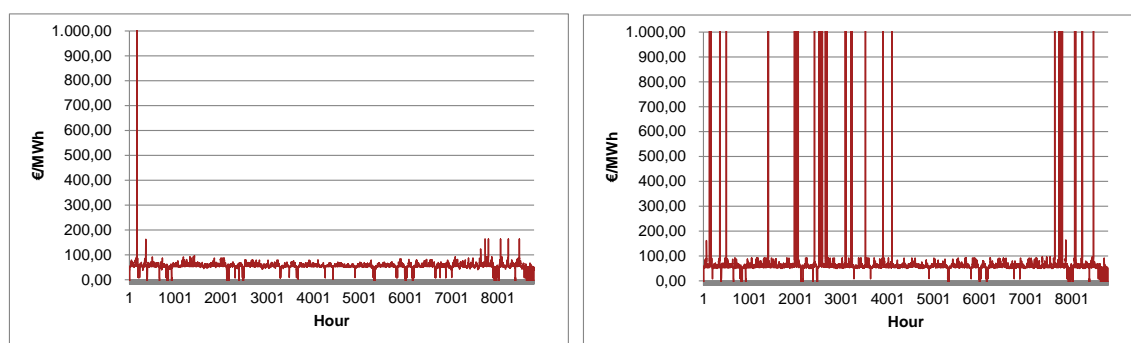


Figure 10.10 Impact of interconnector on reliability

This resulted in 97 hours of unserved load compared to 2 hours of lost load in the situation with interconnector online. The assumption that an interconnector is disconnected for an entire year is not really likely but it does support the argument of dependency on the German market. The same effect will be observed when the Germany system is under stress. In other words, when the German system has difficulties in supplying its own demand.

In periods of high demand and low production of renewables it is likely that the German electricity system is tight in supply. Unforeseen maintenance or the braking down of a plant might cause the Germany system to be under stress. Since Germany and the Netherlands have similar weather patterns, they also have similar demand and production of renewables patterns as well, as has been pointed out in chapter 4. Therefore it is likely that in situations of stress in Germany, the Dutch system is under stress as well. The regulator in Germany basically has two options when it comes to stress in the system. This first one is to allow trade even in periods of scarcity and even when committed to the capacity market. The second option is to restrict trade in periods of shortage. France for example chooses not to restrict cross border trade in periods of scarcity. The underlying idea is probably that the countries surrounding France have a different market structure than France, which is dominated by nuclear

energy, as well as they have different demand patterns. This, however, is not the case for Germany. It is likely therefore that export will be restricted in periods of scarcity.

Possible actions of the Dutch regulator

Besides the consequences itself, the regulator or government has means to diminish or at least limit negative effects of a German capacity market.

A solution for the mothballed capacity

In this paragraph, the €30/tonne CO₂, will be used to clarify the example. The results of the scenario show that 1000MW of CCGT capacity will have been built in the Netherlands by 2020. See figure 9.5. It furthermore shows that the increase in CCGT in Germany compared to the base scenario in Germany is 4500MW. The 4500MW increase in Germany can be devoted to the implementation of a capacity market. A surprising fact, when looking at Tennet's predictions for the amount of mothballed capacity in the Netherlands, is that there is currently 4700MW mothballed. Expected is that in the period 2015-2020 another 1219MW is mothballed in the Netherlands (Tennet, 2013). Immediately you feel that there is a discrepancy between the additional capacity in Germany and the mothballed capacity in the Netherlands. Intuitively, you would say that there is an opportunity for Dutch mothballed power plants to bid on the Germany capacity market. This way the Dutch producers will recover costs while at the same time investment costs are avoided in Germany.

Testing this situation is not possible within the current model. However, it is possible to make an indicative calculation on the impact of Dutch capacity in German capacity market. A situation in which mothballed capacity in neighboring countries is participating in the capacity market has not been found. In order to illustrate the potential of this idea, please look at the following example. In total, 4500MW of CCGT gas plants need to be built in Germany. The maximum capacity between Germany and the Netherlands is 3800MW. This means that the Netherlands can optimally provide 3800MW to Germany. For this example the same assumptions will be used as those being used in the simulation model. The investment costs for a CCGT plant were assumed to be €825/kW. In total, the investment costs would amount to €3.135 billion or 3,1 billion euros.

10.4 Recommendations for policy makers

The previous paragraphs provided insight in the trustworthiness of the model results and resulted in an interpretation of the model results for the different actor groups. The goal of this paragraph is to translate these insights into recommendations for policy makers. The three pillars of Dutch energy policy are reliability, affordability and sustainability. Figure 10.11 shows the effect of a capacity market on these three indicators looking at it from a system as a whole perspective.

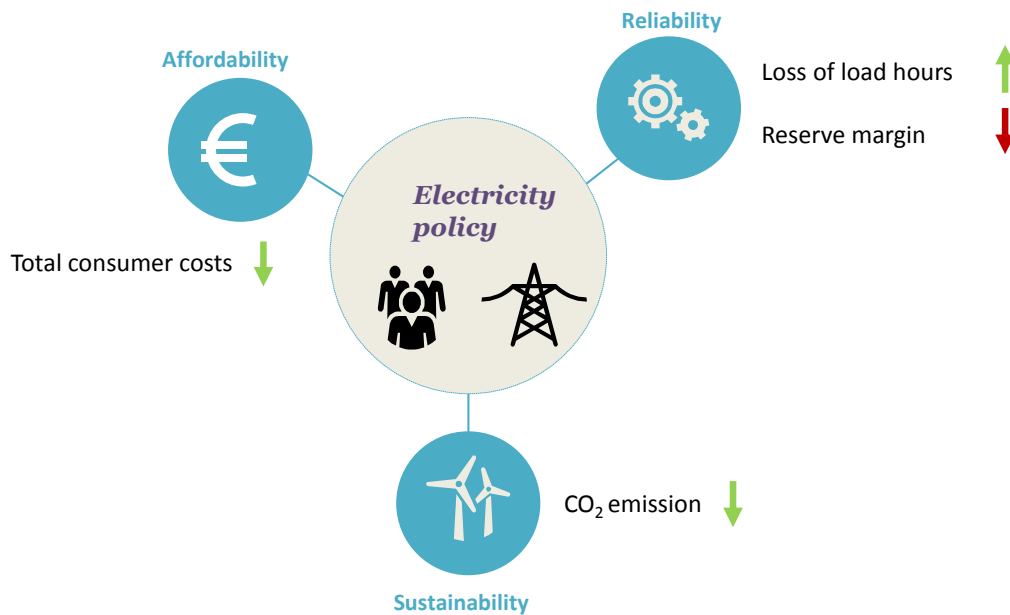


Figure 10.11 Qualitative overview of capacity market effects on NL

From a system as a whole perspective, the capacity market has a positive result on the Netherlands. the Netherlands benefit from the German increase in capacity at expense of the German consumer who pays for this capacity. From the results can be obtained that a lot of trade-off is present in the system. Examples of these are low electricity prices versus sustainable production and low consumer costs versus producer profit. The recommendations for policy makers are therefore not limited to a single recommendation, but on a recommendation regarding specific policy preferences. The policy makers in the Netherlands need to make a choice which of these pillars has their main priority. For the three pillars, three different recommendations need to be made, because of all the trade-offs that exist in the system.

General recommendation

In general, a capacity market seems to have a positive effect on the performance of the Dutch electricity system as pointed out in figure 10.10. The capacity market shows improvements on all but the reserve margin indicators. The general recommendation the Dutch policy makers is not to be anxious of the effects of a German capacity market on the performance of the Dutch electricity sector. The improvements however, arrive at the costs of one big issue. the Netherlands is losing a part of its independence in the way that the Dutch electricity system gets very much dependent on German capacity. Therefore, this recommendation needs to be adjusted to the preference of current policy makers. The main question that they need to answer for themselves is if they value an independent position more than they value independence of the Dutch electricity system.

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Recommendations regarding affordability

The general effect of a capacity market is a decrease in total consumer costs. Therefore the recommendation is not to be against the implementation in Germany. The results show that an increase in interconnection capacity results in a decrease in consumer costs. The results also made clear that the change in renewable subsidies is very limited with declining electricity prices. The recommendation therefore is to stimulate interconnection capacity to increase.

Recommendations regarding reliability

The reliability of the system shows two sides. The reserve margin goes down but the actual number of loss of load hours goes down too. the Netherlands become very much dependent on German capacity. The question is whether this is wanted. The majority of time, this will not be a problem, but in a German situation of stress the consequences will be severe. A possible solution would be to increase interconnection with other countries as well to remain more flexible.

A second aspect to take into account regarding reliability is the long term reserve margin. In the short term, reserve margins go down due to the shift of investments towards Germany, but in the long term also a large amount of capacity will be mothballed as was analysed. This will result in a decrease of the already low reserve margin which again makes the Netherlands more dependent on foreign capacity. A solution could be to set up some kind of strategic reserve that can be deployed in times of scarcity in Germany. The rest of the time, the Netherlands will then be able to benefit from the German capacity

Recommendations regarding sustainability

Besides having a larger share of renewables in the electricity system, sustainability can also be achieved by shifting CO₂ emissions away from the Netherlands. In general, a capacity market causes emission to shift and this shift is enlarged with an increased interconnection capacity. The recommendation therefore is to increase the interconnection capacity between the Netherlands and Germany. This reduces the total amount of emissions in the Netherlands. However, it must be taken into account that the electricity itself is not renewable but that the emission is only allocated. This might trigger the same discussion as the green electricity being not really green but only grey with a green certificate. A possible solution would be to lobby against lignite in the German capacity market to dampen the overall emission increase in Germany.

Recommendations to existing producers in the Netherlands

A final recommendation is the active participation of Dutch currently mothballed power plants in the German capacity market. The results show that a large amount of new capacity will be built in the German system while there is capacity mothballed in the Dutch system. If this mothballed capacity could be used in the German capacity market it would improve the producers revenues in the Netherlands while investment costs are avoided in Germany. This is a mutual gain.

11 Conclusion & Recommendations

This research aimed at providing an answer to the following research question:

“To what extent does the implementation of a Capacity Market in Germany influence the performance of the Dutch electricity market?”

At this point the conclusion can be drawn that a capacity market in Germany has an impact on the Dutch electricity market. However, the exact outcomes differ in different scenarios and capacity market experiments. This chapter is divided into three parts. First the sub-questions will be dealt with based on the observations in chapter 9 and the analysis of chapter 10 to support the conclusions with regard to the main research question. This is followed up by insights that can either contribute to literature or to practical recommendations for policy decisions within the Dutch electricity sector. Thirdly there is a description of the limitations of this study that need to be taken into account when judging the results. Finally, some directions for future research are presented.

11.1 Sub-questions

What performance indicators can be derived from literature that are relevant for assessing the cross-border consequences of a capacity market?

Throughout literature, the electricity price is a performance indicator that returns every single time and is the main drive for investment in an energy only market. Closely related is the volatility which appears in literature as an important variable when it comes to capacity mechanisms in general. The most important feature of a capacity market is to provide system reliability through incentivising investment, therefore the level of investment is taken into account as well. Cross border flows are taken into account since we are talking about cross border effects. Next to these four performance indicators, it is also interesting to look at the effect of a capacity mechanism on the public policy goals, affordability, reliability and sustainability, set up by the government. For these public goals, the following performance indicators were taken into account: total consumer costs, LOLE and CO₂ emission. These performance indicators were all used to evaluate the model runs.

How are the theoretical models of Capacity markets translated into implementable equations (conceptual model)?

The basis for this analysis is the electricity market fundamentals by Stoft (2002) in combination with literature on the theoretical concepts of a capacity market. The major issue to overcome is how to combine the two. Electricity theory assumes that electricity markets are optimal. A capacity market is a solution for the electricity market showing non-optimal behaviour. In order to evaluate the cross border impact of a capacity

market, the market needs to be made non-optimal first. Literature analysis showed that the problems that cause the market to be non-optimal are the existence of a price cap and the risk averseness of investors. The first condition was implemented by assuming a price cap of €3000/MWh instead of the VOLL of €10.000/MWh. The second was implemented by forcing different discount rates on technologies with different capital costs, forcing the investor to favour less capital intensive investments. The evaluation of investments themselves is based on the return on investment of a particular technology.

How is the conceptual model implemented in the Power2Sim simulation model?

For this research, two different modules were used. Power2Sim was used to calculate electricity prices according to investment decision that were made in excel. The investment algorithm, together with the capacity market model is built in excel. In order to let the two software programs interact, a visual basic code was written which can be run from the Power2Sim model. Investments are added to the Power2Sim model iteratively. After each iteration, an investment decision is analysed. This way, each investment decision is based on the market outcome of 2020. Simulation stops once there is no attractive investment option left.

What are the consequences for the Dutch market given the performance indicators from (1)

The implementation of a capacity market in Germany affects the Dutch electricity system. The capacity market in Germany improves the business case of German plants leading to a shift in investment towards Germany. The increased capacity in Germany supplies the Dutch electricity system which is concluded from an increased amount of export from Germany to the Netherlands. A capacity market in Germany results in a lower electricity price in both countries. This is caused by an overcapacity in Germany which is shaving the peaks of Dutch electricity price with the export of electricity.

Regarding reliability, a two-sided effect is observed. The reserve margin in the Netherlands goes down while the actual loss of load hours decreases at the same time. In general, the reliability of electricity supply increases, but further analysis showed that a situation of stress in the German system might have severe consequences for the Dutch system emphasizing the increased dependence on German capacity.

The affordability is improved as a consequence of the capacity market in Germany. The total costs of consumers go down in the Netherlands as a result of a price decrease. The German consumers on the other hand face a small increase in costs due to the capacity payment and the change in need for renewables subsidies.

Sustainability is improved through a capacity market in Germany. This effect is mainly caused by the shift in investment towards Germany. CO₂ is emitted in Germany while the electricity is exported to the Netherlands.

From the perspective of a producer, the implementation of a capacity market has a large effect on the profitability of existing plants. A large part of the gas plants will

have difficulties in recovering costs and with higher CO₂ prices also some coal plants will get in trouble. Further analysis on the profitability showed that an amount of 1409MW will be mothballed as a result of the capacity market. This is something to take into account for policy makers because the short term effect of a capacity market might be an improvement in terms of actual loss of load hours, but the mothballed capacity might put the reserve margin under pressure in the long term.

What are the consequences for the Dutch market under specific scenarios?

- a. A renewables dominated market, both in Germany and the Netherlands*
- b. Increased physical market coupling in terms of interconnector capacity*

Increasing the interconnector capacity increases the effect of a German capacity market on the Netherlands. In general, increasing the interconnection capacity increases the effect of the normal capacity market scenario. This means that prices drop to a larger extent. This is not only observed in the peak hours, but over the full range of price over a year in the Netherlands. This is different from the general capacity market case in which only peak shaving was observed. The decrease in price causes the total consumer costs in the Netherlands to decrease. It also results, however, in an even further declining amount of investment in generation capacity in the Netherlands. It therefore has a positive effect on CO₂ emissions as well, but at the expense of the Netherlands becoming increasingly dependent on German capacity. The business case of Dutch existing producers also worsens resulting in 4700MW of capacity being mothballed. The increase in mothballed capacity exceeds the extra interconnection capacity in this experiment. Further analysis showed that increasing the interconnector capacity between Germany and the Netherlands increases the dependency of the Dutch system on the German capacity. A related issue is the chance of outages in the Netherlands. Although this is not a stochastic model and no conclusions can be drawn regarding probabilities, it was observed that cutting off the interconnector between Germany and the Netherlands results in an increase in loss of load hours from 2 to 97 in a year, providing an indication of the possible consequences. It can be said that the general reliability in number of loss of load hours is decreased by a capacity market, but that the black swan risk of failing interconnection and consequently very high impact should be taken into account as well.

The effect of an increased amount of renewables has a limiting effect on the performance of a capacity market. In general, prices go down due to the marginal costs of renewables being close to zero. Besides, the increased capacity leads to lower amount of investments since more capacity is already in the market. This effect is strengthened by the price being driven down decreasing investment in generation capacity.

A positive result is that an increased level of renewables does not lead to situation worse than the base case. From a system as a whole perspective, this means that the renewables target could be met without losing the free riding benefits from neighbouring a German capacity market.

What recommendations for policy makers in the Dutch electricity sector can be given to improve the cross border effects of a German Capacity market on the performance of the Dutch electricity market?

The need for policy measures by Dutch policy makers in the electricity sector is largely dependent on the view current policy makers have. The three indicators that represent public policy in the Dutch electricity system include several trade-offs. The most important decision to be made is whether system independency is valued higher than the free rider cross border gains a capacity market in Germany has to offer. If policy makers favour consumer costs and sustainability, they must decide on possible increase in interconnection capacity between Germany and the Netherlands.

Reliability is the most ambiguous of the three indicators. The capacity market decreases the number off loss load hours which is an indication of increased reliability while at the same time the reserve margin is getting lower. In the short term, this might not be as problematic but in the long term the analysis show that a large share of capacity is mothballed. This will push down the reserve margin even more, getting even more dependent on foreign capacity. In the latter case it might be better not to increase interconnection capacity to limit the amount of capacity being mothballed. Another options is to keep some of the mothballed capacity as a strategic reserve in case interconnection faces problems.

11.2 Contributions

This study results in several insights and contributions that can be relevant to the scientific community, the users of the Power2Sim model and policy maker in the electricity sector. In this paragraph, these contributions are presented.

11.2.1 Model contributions

Investment algorithm

The basic Power2Sim model only consists of external investment scenarios when it comes to the evolution of capacity in Europe. By implementing an investment algorithm, investments are now indigenous. This has the advantage that in the future, evolution of capacity can be modeled instead of assumed in scenarios.

Capacity market module

An extension to the investment algorithm was the capacity market model. This extension showed that it is possible to add a capacity mechanism to the Power2Sim model. This means that in case a capacity market will be implemented in Europe, this model can be used to model the effects more precisely.

11.2.2 Methodological contribution

Non optimal market

Most studies that simulate electricity markets assume an optimal electricity market. However, literature shows that this is often not the case. Even in evaluating a capacity mechanism, a market is often assumed to be optimal while a capacity mechanism is a

mechanism that aims at solving a non-optimal market. In this study, two non-optimal conditions were implemented in the model. A price cap to limit peak prices and secondly a change in risk perception for different technologies to steer investment towards less capital intensive technologies.

Cross border impact of capacity market

This study also looks at the cross border impact on existing producers, instead of just the impact on prices and new investments. Once you analyze the existing producers, you realize that there is a feedback loop between the producers in a capacity market and in a non-capacity market. The decrease in prices and peak prices result in lower revenues for producers. These might be forced to mothball since they are not recovering fixed costs. This again improves the business case for Germany plants since they are subsidized by a capacity market and benefit from power plants being taken out of the market in a neighboring country.

Validation

This research has not been the first research regarding the implementation of a capacity market. However, the literature that has been found ranges widely in the modeling method and execution which makes it hard to compare and validate the results. This research adds value to the validation since it increases the pool of results that have been retrieved. Therefore, it can strengthen the results providing opportunities for further research on the topic and providing policy makers with more knowledge about the dynamics of a capacity market.

11.2.3 Contribution to PwC

The strategy department at PwC has worked closely together with various clients in the energy sector. Increasing the understanding about electricity market phenomena in general is important to PwC. It is a way of keeping the organization up to date considering new developments in the electricity market.

The use of Power2Sim can be seen as a proof of concept. The Power2Sim model has a lot of potential, but so far it had not been used for any research. This research was a test case to see what the capabilities are of the Power2Sim model, and how these capabilities can be translated into value for the clients.

The combination of VBA and Power2Sim made it possible to link excel files to the Power2Sim model, automate simulations and automatically generate output graphs. Especially the link with excel opens a lot of doors. The Power2Sim model now has a dynamic component which can be used for all kind of studies from regulatory changes over time to the evolution of capacity and the inclusion of an investment algorithm. The algorithm used for this study is quite basic, but the concept in general is easily scalable which makes it possible to include a much more detailed and accurate investment algorithm to research capacity evolution. Other future uses of Power2Sim are the evaluation of individual power plants both existing and newly build plants, and assessment of profitability of renewable energy projects.

With regards to the results, the results contribute to PwC's general knowledge about the dynamics of a capacity market in Germany. This can be used passively as

background information in case a client asks our opinion on the topic, or actively in advising clients how to improve their personal situation by using the knowledge obtained from the modeling study.

11.2.4 Contribution to policy makers in the Netherlands

This study contributes in various ways to decision making in the electricity market. The model that is used in this study has shown that it is able to be adjusted to fit alternative or additional market designs. In case of other countries implementing a capacity market or another form of capacity mechanism, the impact can be calculated with the model.

The results itself can be used for policy makers to support decision making. Currently there are plans to increase interconnector capacity with Germany. The results shed new light on the public goals of the Dutch electricity sector and might help in decision making. Furthermore, some directions for policy making can be provided. These are for example the active participation of Dutch mothballed power plants in the German capacity market.

11.3 Limitations of this research

Scenarios could be improved

One of the limitations of this research is the use of a small number of scenarios. Due to the time consuming effort of setting up and running different scenarios the number of scenarios was limited. Ideally, numerous other scenarios could have been run while changing parameters etc. This way a more Monte Carlo kind of procedure can be used and the number of results will increase significantly and will thus enable a more in depth analysis of the results.

Investment algorithm is still quite basic

Another limitation of this study is the investment algorithm that is used in this model. The investment algorithm is quite basic and is therefore highly sensitive to changes in parameters like the discount rate. An example of this limitation can be seen in the investment of coal and lignite. Although these two technologies proved quite competitive, only investment in lignite was observed when looking at Germany. In real life, the two technologies would probably have a different mix than these model outcomes suggest. A different technology obviously has an effect on the performance indicators.

Study limited to Germany and the Netherlands

For this research, only Germany and the Netherlands were simulated in detail, and scenarios were used for the evolution of installed capacity in other countries. The countries neighboring Germany all have a different structure and geographic differences. Probably, the effects on Poland and Switzerland differ widely from the effects on the Netherlands. This also holds for the interaction effects that might be present. By only simulating Germany and the Netherlands, and assuming certain investment levels in other countries, the outcomes will not be entirely accurate. It could

for example be the case that Belgium changes its investment level which could either positively or negatively influence the Dutch electricity system. This study showed that it is possible to extend the Power2Sim model in modeling Germany and the Netherlands by using an investment algorithm. The exclusion of any other countries therefore is a clear limitation of this study, but this study shows that it is feasible to adjust the other countries as well.

11.4 Recommendations for future research

From the results and limitations of the model several directions for future research can be assigned. These include model improvements as well as model outcomes that can't be explained by the results and analyses.

Investment algorithm

The main direction for future research is the improvement of the investment algorithm in the model. As discussed at the limitation's section, a more detailed investment algorithm might result in different technology preferences and will eventually lead to other outcomes. Doing this opens a way to assess technologies which are closer related to each other, like more variation of the same technology and therefore can give more realistic investment behaviour.

Capacity market in the Netherlands

A second option for future research is to look at the options for the Netherlands to implement a capacity mechanism as well. This research mainly focused on the effects of a capacity market in Germany, and the options that policy makers have to decrease negative effects of this capacity market in Germany. However, it does not look at the implementation of a capacity mechanism in the Netherlands which might be a feasible alternative as well.

Locational factors

Locational factors play a role in the investment decision of power plant. Although the locational factors are not implemented in the model, it is important to reflect on the impact of such a decision. From a system perspective it might be attractive to build a certain type of technology, but it must be feasible for the system to support the corresponding physical plant. It is for example not feasible to invest in an infinite number of coal plants since locations are limited. Incorporating locational factors in investment decisions is a practice that could overcome this problem, as researched by Paling (2013). To achieve greater number of realistic investments, investment constraints could be implemented that limit the amount of investment per technology. However, this would require more knowledge about which factors to include to determine these constraints.

Ramping costs

Although the model itself is capable of including ramping costs, the research is performed without. Several test runs pointed out that implementing these ramping

costs increased the complexity of the study significantly. Given the limited time for the writing of this thesis, the choice was made not to include ramping costs at all. However, that doesn't make it less important to reflect on the possible impact of this choice. The link between ramping costs and volatility is discussed in a paper by Werner (2014). Werner showed that the volatility of electricity prices increases when taking into account ramping costs. Given the different technologies in the model, including ramping costs will most likely have an impact on the technology mix in a country. Since gas plants have considerably lower ramping costs than lignite, coal and nuclear energy, a logical consequence would be that the technology mix tends to favor gas plants. Assuming that the volatility of the electricity prices does increase, the running hours of lignite and coal will decrease.

Renewable technologies

A final recommendation for future research is the inclusion of renewable technologies in the model. In the current model, renewables are assumed to be policy driven and are thus determined externally in the model. However, the analysis shows that renewable technologies are affected by a capacity market in a neighbouring country. This means that investment in renewable energy will probably be affected by a capacity market. It would be interesting to look at the long term development of both renewables and conventional power plants in the presence of a capacity market in Germany.

12 Reflection

Over a period of six months my thesis project was executed and documented. The final version of this research project is the endpoint of an inspiring, enjoyable and strenuous research process. It is important to not only take the results of this research into account but also look back and reflect on the entire research process and reflect on the process as a whole. The purpose of this chapter is to show what challenges were faced and what kind of improvements could have been made. Future research could benefit from this by means of being more efficient and precise and learn from mistakes that were made and choices that were made.

12.1 Reflection on the methodology and results

Scope

The scope of this master thesis is the result of an iterative process, which has evolved into the current stage over the last six months. The difficulty with determining the scope is that everything you read or talk about influences your thoughts about the scope. It is easy to get lost in the available literature, trying to grasp every single variable there is. My determination of the scope can be seen as an iterative process. Over time the scope adjusted to the model capabilities and vice versa. This resulted in a final scope which is well thought through and a model that is capable of generating the desired output. This process of going back and forth and not focusing could have been done much more efficiently. The thing I did wrong was that I started to model loose ends in the beginning just to get a feel of what the model is capable of and how to fit this in the scope. In the future I would spend more time to determine what exactly the question is that I want to answer by means of this model and which output parameter I need. This step is then followed up by actually adjusting the model so that it produces these predetermined outcomes. Of course there will always be problems you have to work around, but this will increase efficiency of the modeling process by to great extent.

Results

When comparing the results of the simulation, comparable results are found in literature on the functioning of a capacity market. This is an indication that the model is useful to be applied to contribute to policy making. The model provides good insight in the investment behavior in countries neighboring a capacity market as well. It is able to grasp allocation of capacity investment. This important feature can be used by policy makers to determine the reliability of the Dutch electricity sector.

The results also present some of the important policy decisions that can be taken in case Germany does actually implement a capacity market. Examples of these policy directions for example are: the active participation of Dutch mothballed capacity in a German capacity market, the effects of plans for increasing interconnector capacity. Although most of the results can be explained by the modeling methodology used, there are still some question regarding the combination between a capacity market with a large interconnection capacity and high CO₂ prices. Ideally, an additional experiment should be performed to determine the tipping point in CO₂ price. Secondly

the underlying cause should be explained in detail. However, due to time constraints this is not feasible and therefore this topic remains as a research field to explore in the future.

Reflecting on the methodology, this research has shown that it is possible to extend the current electricity market model, power2sim, with new market designs. Since more countries in Europe are discussing the implementation of a capacity mechanism, it is possible to test the effect of different kinds of mechanisms in Europe as well.

Methodology

The methodology used for this study is a short run marginal costs optimization model. The main question to be answered in this paragraph is whether this method was appropriate given the knowledge you have after using this model for a couple of months. The advantage of using a common approach to electricity markets is the direct comparison with other studies. This has an advantage in validating the model and strengthening the results. A downside of using this methodology is that there is no randomness included in the system, while demand and renewables can be seen as patterns with a certain amount of randomness. Randomness could have been used to evaluate differences in outcome caused by changes in model parameters. Large number of runs could also result in actual value judgments to check whether relations or outcomes differ significantly.

Assumptions

Reflecting on the assumptions, the main question that needs to be answered is what the impact of certain assumptions is on the model outcomes. In other words, why is it important to reflect on the assumptions, what would be the impact and how would you do this differently in a next research.

Countries treated equally

One of the main assumptions in this study is that fuel prices, discount rates etc. are equal for all countries. For most commodities this is not a problem because they are traded on the world market, which makes prices approximately equal for different countries. For lignite however, this is not the case. From the literature used in the sensitivity analysis on fuel prices (Bardt & Striebeck, 2013), the local aspects of lignite were obtained. Lignite is not traded on world market because transportation is too costly. This means that the lignite prices depends on local producers and thus local pricing. Assuming a constant lignite price for all countries is therefore not realistic. Lignite is an important technology which is affected very much by a capacity market, as observed in the model results. Because of the importance of this technology, a better understanding of its fuel costs will lead to more accurate results. So far I have not found any reports showing the lignite price per regions. In case there is a large difference in prices, I would take this into account. If not I would keep the current assumption of equal lignite prices.

A related issue is the use of discount rates. The same discount rate is used for the Netherlands and Germany. Although this choice can be justified, it might not be a

perfect representation of the real situation. The idea of a capacity market is that part of the revenue of a power plant is retrieved upfront, decreasing the investment risk of a power plant. Following this argumentation, this would mean that investors in Germany would require a lower discount rate than investors in the Dutch electricity market. This impact of lower discount rates would mean that investment in Germany is more attractive than investment in The Netherlands, compared to the current model results. The expectation therefore is, that investment will be shifted even more to Germany. For a next research I doubt whether I would take this difference into account. Using different discount rates would require extensive literature research and validation on the exact values of the discount rate. Besides that, it is questionable to what extent this change in discount rates leads to more insight in the functioning of a capacity market because the current model already grasps the shift of generation investment towards Germany.

Energy only market

For this study, the assumption was made to let the producers' income solely depend on revenues gained in the energy only market. This assumption neglects the existence of bilateral contracts, the imbalance market. In the real world these income streams are taken into account as well when determining future cash flows and thus investments. Although electricity prices on averages seem to be in balance, the participation on different markets might result in a different attitude towards risk. Plants involved in long term contracts for example decrease their market risk and thus require a lower discount rate.

Renewables in the capacity market

Renewables are included in the capacity market bidding with respectively 5% for both technologies. Within literature, the capacity factors that can be used for renewables in a capacity market differ widely. Some even say that 0% should be assumed. The main argument is that a capacity market is a market for reliability and the intermittent character of both wind and solar do not allow reliability at all. PJM uses capacity credits of 13% and 38% for wind and solar. According to them their peak demand is a hot summer day in which the air-conditioning is causing a high demand. Their argumentation is that a hot summer day not only results in peak demand, but also in peak production of solar energy.

The reserve margin of the capacity market is determined by the regulator. This optimal capacity is based on the optimal capacity that optimizes the number of back-outs in a country (Cramton, 2000). This optimal investment level is equal to the investment level indicated by Stoft (2002). Including renewables in the capacity market results in either a lower reserve margin or a lower amount of conventional power units to be available. Therefore, the amount of renewables cannot be determined from literature and an assumption had to be made. Further research would be needed to determine the ideal capacity credit level for wind and solar in Germany.

The impact of the above assumption is that a larger amount of conventional capacity is invested in because this part is not covered by the renewables. The capacity price will allow for more investment in conventional generation units because the

entire bid curve is shifted to the left if renewables are only allowed to bid a certain fraction of their capacity in the market. This also means that renewables get less compensation than other units. Less compensation in combination with lower wholesale prices might lead to a worsened business case.

12.2 Reflection on the process

The question that needs to be answered in this paragraph is what problems did occur and what would I do differently if I had to do this thesis over again? The execution of this master thesis proved to be quite a challenge. Starting off with selecting your own subject and working your way through in order to get to real results is a satisfying experience. However, I would be lying if I said it all went flawlessly. There have been times when I did not even know whether everything I was doing would be feasible in the end. But in the end you always find yourself a way to work around problems and deal with them. This paragraph provides insight in some of the challenges I faced during the last six months.

Manage your scope

One of the most difficult things I faced was the determination of the scope of the project. Every conversation with supervisors from university and PwC resulted in new perspectives and ideas. Of course this is very valuable but before you know, the scope becomes unmanageable. The quote “all models are wrong, but some are useful” by George Box made me think more about the effects I wanted to show and therefore becoming more critical in what to include in the model. The impact of this process on the model outcomes is that the different conversations iteratively lead to a simulation model and a set of performance indicators that helped to get an understanding of the impact of a capacity market. The continuous brainstorming has challenged me to be precise while at the same time keeping it feasible. For a next research, I would keep the brainstorming more structured instead of changing every part of the study every now and then.

Make use of the resources you have

For the research I used a merit-order electricity market model from an external party. The main advantage of a very extensive merit order model is that it is very good in calculating tomorrow's electricity price. Since all unknowns, like fuel prices and government policies, are relatively known, detailed predictions can be made about tomorrow's market. The biggest challenge is to adjust the model to make it suitable for 5-10 year future predictions or even longer predictions. I spent a lot of time figuring out how the model works and what outputs it generates. Reflecting on this process, I would advise to get in contact with people who have actually used the model sooner since they can tell you what the advantages and limitations of the model are. This could have saved me a lot of time, but on the other hand I would have probably never reached the level of understanding I currently have by figuring it out myself.

Spend time on automating model outputs

Considering the modeling process I would have paid more attention to the output generation of the model. Although the model itself worked fine and fully automatic, the generation of outputs did not. Automating outputs and graphs would have taken an investment in time at the beginning of the process, but would have saved a lot of time further on in the process. The model outputs were treated manually, which means that every change in scenario or model parameter resulted in manually having to change and update the graphs and tables. When repeating this research, I would spend more time on automating the generation of outputs. The impact on the outcomes cannot be found in the outcomes itself, but more in the limited number of scenarios due to the time consuming effort of handling the data and outcomes.

Do not underestimate the use of an existing model

A second important factor to reflect on is the use of an external model. Being able to use professional extensive software has the advantage of it being built just for the purpose of calculating detailed electricity prices for commercial use. This implies that the model has been validated already and that there is a support team that can help you in case things do not work out as they should. A logical consequence is the time consuming effort in mastering the model before being able to actually use the model. Hundreds of variables are present in the model, all influencing the model in some way. The downside is that most of the algorithms are calculated internally by the model not revealing the source code. The impact of this factor on the research outcomes is limited although the interpretation of results is more difficult. The relations between the variables in the model need to be supported with understanding of the model's internal calculations. This took a lot of time.

Balance your efforts

Another note can be dedicated to the planning process. During the research there have been times in which I worked all night and times in which the productivity was lacking greatly. A better planning might have resulted in a better balance in workload over this period. However, my impression is that this ultimately has a very limited effect on the research in the end. Only the level of personal stress is affected. It did, however, definitely affect the level of personal stress.

12.3 Conclusion

Looking back on this research project I am pleased with the results. During this last semester I had to face a lot of challenges. Of these, the most important was to determine the scope of my project. The main difficulty within this research is to keep the scope manageable. During my thesis I had a lot of meetings with my supervisors from university, my colleagues at PwC and other companies and organizations interested in the subject. At a certain point you just have to accept that your method is not perfect, but that even a non-perfect model can result in valuable outcomes. Every conversation resulted in new insights and possibilities for extension of the model. Implementing all of them would probably have extended my research for another six

months. Looking back I am pleased with the results I got, and the process I have gone through. The learning curve was steep, and satisfying.

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Appendices

A. - Model description

A Model input parameters

Power plants

PowersSim distinguishes between the following types of power plants.

- Nuclear: Nuclear power plants
- Lignite: Lignite power plants
- Hard_Coal: coal power plants
- Gas: Gas & combined cycle power plants
- Oil: Oil power plants
- Other: Other conventional thermal power plants
- Reservoir: water power plants (reservoirs)
- Biomass: Biomass power plants

Power plant attributes (model input)

- A power plant has the following attributes:
- Operating costs
- Transport costs
- Availability
- ID
- Country
- Name
- Fuel-type
- Capacity
- BuildDay
- RetireDay
- Efficiency

B. Detailed model description and mathematics

In addition to the model description in chapter 4, a detailed mathematical description of the model is provided.

Power price

The power price can be seen as an output of a linear optimisation problem. This is optimisation problem called economic dispatch in electricity market terms. The goal is to minimise total cost of production, while serving demand and power plant generation constraints. It can be formulated as the following optimisation problem.

<i>Decision variable</i>	P_{Gi}
<i>Objective function</i>	$MIN C(P_G) = \sum_{i=1}^n C_i(P_{Gi})$
<i>Subject to</i>	$\sum_{i=1}^n P_{Gi} = P_D$
	$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}$

Where:

- n = number of power plants
- i = particular power plant
- P_{Gi} = generation of unit i
- P_D = demand
- P_{Gi}^{min} = minimum capacity of power plant i
- P_{Gi}^{max} = maximum capacity of power plant i
- $C_i(P_{Gi})$ = cost of production of power plant i

The min and max constraints are related to the capacity of a power plant and the availability. The minimum capacity is assumed to be 0. The maximum capacity is calculated following:

$$P_{Gi}^{max} = CAP_i * f_a$$

Where

- CAP_i = nameplate capacity of power plant i
- f_a = availability factor of power plant i

The availability factor is technology specific and is calculated based on an average availability of a technology.

Supply

The supply in the model is a list of power plants with corresponding marginal cost of production for that particular power plant. All the capacity/marginal cost combinations of all available power plants together form the merit order. The merit-order can change every hour.

$$MC_i = \frac{OC_i + (C_{fuel_i} + C_{transp_i}) + P_{CO_2} * CO_2 \text{ emission factor}}{eff_i}$$

Where:

- MC_i = marginal cost of production of power plant i
- OC_i = operational costs of power plant i
- C_{fuel i} = fuel cost of power plant i
- C_{transp_i} = transportation costs of plant i
- P_{CO₂} = CO₂ price
- CO₂ emission factor = technology specific emission factor
- Eff_i = efficiency of power plant i

From this equation it can be observed that the marginal costs for every power plant will be different since all power plants differ in technology, efficiency and fuel costs.

Demand

$$Demand_t = Average\ demand_t * f(Temp_t) * g(t) * h(Day\ type_t)$$

Where:

- Temp_t = Temperature at time t
- t = time
- Day type = holiday, weekend, working day

The three functions f, g and h are the result of a regression analysis on historic data. Historic data has been analysed which has resulted in a best fit line. The formulas represent the corresponding values to the input. To give an example the figure below is used. The blue dots represent historic data. The red line is a regression analysis on these data point which result the a formula in which the demand is a function of temperature.

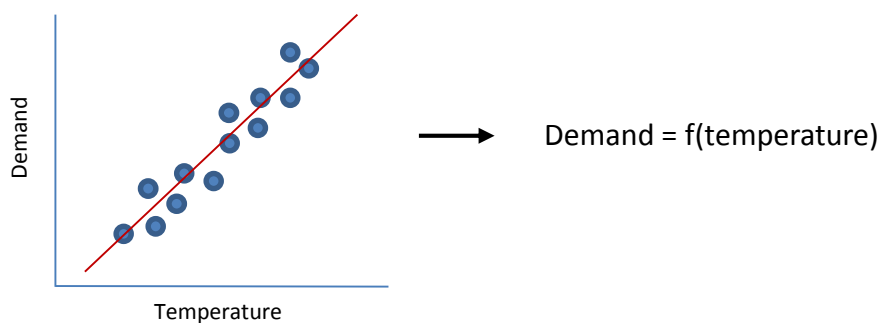


Figure 13.1 Example of regression analysis

The resulting formulas together calculate future demand based on an average demand set up by the user of the model.

Wind production

Power2Sim contains a data base with hourly wind patterns. As explained in the main text, these historical data point are reused for different years. The wind data for January 2005 might be used for January 2020. The wind data is available on an hourly basis. In the model, an average generation level can be defined. The historical data is rescaled to the change in average generation. If for example, the average generation is

doubled between two years the available data points used for determining the actual production are doubled as well. The total generation is capped by a separate variable which is the installed capacity in the system. This value can be set by the user of the model.

Interconnection

Determining the cross border flows the following algorithm is used:

1. Determine the two countries that have the highest difference in electricity price.
2. Fill up the interconnector until either the interconnector is fully used or a different set of two countries can be found with a higher difference in price.
3. The algorithm stops once there is either no price difference in the system or there is no interconnection capacity available to further converge electricity prices.

C. – Power plants

This appendix contains the power plants that have been used in the simulation. The initial portfolios for the simulations are summarised in figure ##. The original list as developed by Energy Brainpool is adjusted for the energieakkoord. This means that the following hard-coal power plants will be closed:

- Amer 8 (Essent), capacity 645MW, closed on 1-1-2016
- Borssele (Delta), capacity 406 MW, closed on 1-1-2016
- Maasvlakte I (E.on), capacity 520 MW, closed on 1-7-2017
- Maasvlakte II (E.on), capacity 520 MW, closed on 1-7-2017
- Gelderland-13 (GdF), capacity 602 MW, closed on 1-1-2016

Besides the Energieakkoord, several plants have been closed or mothballed over the last couple of years. These plants are shown in the table below. Mothballed plants have been marked orange. Power plants that are currently mothballed are:

- Bergen op Zoom 1, gas, 24MW
- Claus A, gas, 639 MW
- Claus C, gas, 1280 MW
- Erica 1, gas, 63 MW
- Den Bosch 1, gas, 34 MW
- Klazienaveen 1, gas, 59 MW
- Moerdijk 2, gas, 430 MW
- Delesto, gas, 360 MW
- Lage Weide, gas, 103 MW
- Salinco, gas, 74 MW
- Magnumcentrale, gas, 866 MW
- Eems 20, gas, 590 MW

In total this means that 4522 MW is currently mothballed.

Table C.1 List of power plant in the Netherlands

Plant name	Country	Fuel	Opened	Closed
AKZO DELESTO-1 GT 1	netherlands	gas	01/01/1972	
AKZO DELESTO-1 GT 3	netherlands	gas	01/01/1987	
AKZO DELESTO-2 CC 1	netherlands	gas	01/01/1999	
AKZO EDE 1	netherlands	gas	01/01/1992	
AKZO EMMEN GT 1	netherlands	gas	01/01/1982	
AKZO HENGELO GT 1	netherlands	gas	01/01/1993	
AKZO KLEEFSE WAARD GT 1	netherlands	gas	01/01/1993	
AKZO ROTTERDAM GT 1	netherlands	gas	01/01/1987	
AKZO/IJSSELMIJ PLANT GT 1	netherlands	gas	01/01/1994	
ALMERE-1 GT 1	netherlands	gas	01/01/1988	
ALMERE-2 GT 1	netherlands	gas	01/01/1993	
AMER 81	netherlands	hard_coal	01/01/1980	

AMER 81 GT 1	netherlands	gas	01/01/1979
AMER 91	netherlands	hard_coal	01/01/1993
BERGEN OP ZOOM GE GT 1	netherlands	gas	01/01/1984
BERGEN OP ZOOM GE GT 2	netherlands	gas	01/01/1991
BERGEN OP ZOOM PNEM GT 1	netherlands	gas	01/01/1995
BERGUM 20	netherlands	gas	01/01/1975
BERGUM GT 1	netherlands	gas	01/01/1987
BERGUM GT 2	netherlands	gas	01/01/1986
BERGUM GT 3	netherlands	gas	01/01/1987
BERGUM GT 4	netherlands	gas	01/01/1986
BORCULO WHEY 2 GT 1	netherlands	gas	01/01/1995
BORSSELE 12	netherlands	hard_coal	01/01/1987
BORSSELE 30	netherlands	nuclear	01/01/1973
BOTLEK AIR LIQUIDE GT 1	netherlands	gas	01/01/1997
BOTLEK REFINERY GT 3	netherlands	gas	01/01/1991
CLAUS A	netherlands	gas	01/01/1976
CLAUS B	netherlands	gas	01/01/1977 01/01/2011
CLAUS C	netherlands	gas	01/04/2012
DELFT GT 1	netherlands	gas	01/01/1973
DELFT GT 2	netherlands	gas	01/01/1973
DELFT GT 3	netherlands	gas	01/01/1973
DELFT GT 4	netherlands	gas	01/01/1973
DEN BOSCH HEINEKEN CC 1	netherlands	gas	01/01/1994
DEN HAAG-1 GT 1	netherlands	gas	01/01/1982
DEN HAAG-1 GT 2	netherlands	gas	01/01/1982
DEN HAAG-1 SC 1	netherlands	gas	01/01/1982
DIEMEN 33 GT 1	netherlands	gas	01/01/1995
DIEMEN 34 CHP	netherlands	gas	01/06/2013
DONGE GT 1	netherlands	gas	01/01/1975
DORDRECHT DUPONT GT 2	netherlands	gas	01/01/1998
EEMS 10 GT 1	netherlands	gas	01/01/1975
EEMS 20	netherlands	gas	01/01/1975
EEMS 20 GT 1	netherlands	gas	01/01/1988
EEMS 30 CC EC 1	netherlands	gas	01/01/1996
EEMSHAVEN 1	netherlands	hard_coal	01/01/2014
EEMSHAVEN 2	netherlands	hard_coal	01/01/2014
EEMSHAVEN CCGT A 3	netherlands	gas	01/08/2013
EEMSHAVEN CCGT B 3	netherlands	gas	01/01/2014
EEMSHAVEN CCGT C 3	netherlands	gas	01/01/2014
EERBEEK MILL GT 1	netherlands	gas	01/01/1992
EINDHOVEN PHILLIPS GT 1	netherlands	gas	01/01/1995
EMMTEC GT 1	netherlands	gas	01/01/1980
ENSCHUDE A	netherlands	gas	01/01/1985
ERIKA GT 1	netherlands	gas	01/01/1995
EUROPOORT CCGT 1	netherlands	gas	01/10/2011

EUROPOORT GT 1	netherlands	gas	01/01/1981	
EUROPOORT GT 2	netherlands	gas	01/01/1981	
FLEVO CCGT 2	netherlands	gas	01/07/2010	
FLEVO GT 1	netherlands	gas	01/01/1974	
GALILEISTRAAT GT 1	netherlands	gas	01/01/1988	
GASSELTERNIJVEEN GT 1	netherlands	gas	01/01/1994	
GELDERLAND 12	netherlands	hard_coal	01/01/1963	01/01/1995
GELDERLAND 13	netherlands	hard_coal	01/01/1981	
GELEEN 2	netherlands	gas	01/01/1970	
GELEEN RESEARCH GT 1	netherlands	gas	01/01/1968	
GELEEN RESEARCH GT 2	netherlands	gas	01/01/1991	
HARCULO 60 GT 1	netherlands	oil	01/01/1982	
HARCULO 60	netherlands	gas	01/01/1982	
HELMOND I GT 1	netherlands	gas	01/01/1982	
HELMOND II GT 1	netherlands	gas	01/01/1999	
HELMOND PROMEST VKC GT 1	netherlands	gas	01/01/1994	
HEMWEG 7	netherlands	gas	01/01/1978	01/11/2012
HEMWEG 7 GT 1	netherlands	gas	01/01/1988	
HEMWEG 8	netherlands	hard_coal	01/01/1994	
HEMWEG 9 CCGT CHP	netherlands	gas	01/10/2012	
IJMUIDEN UNA GT 1	netherlands	hard_coal	01/01/1997	
KLAZINAVEEN GASEDON GT 1	netherlands	gas	01/01/1995	
KLUMBERT PLANT GT 1	netherlands	gas	01/01/1986	
LAGE WEIDE 5	netherlands	gas	01/01/1976	
LAGE WEIDE 5 GT 1	netherlands	gas	01/01/1986	
LAURA 1	netherlands	hard_coal	01/01/1965	
LEIDEN GT 1A	netherlands	gas	01/01/2005	
MAASTRICHT MILL 1 GT 1	netherlands	gas	01/01/1982	
MAASTRICHT MILL 2 GT 1	netherlands	gas	01/01/1995	
MAASVLAKTE 1	netherlands	hard_coal	01/01/1975	
MAASVLAKTE 2	netherlands	hard_coal	01/01/1975	
MAASVLAKTE 3 (MPP 3)	netherlands	hard_coal	01/01/2014	
MAASVLAKTE BAYER GT 1	netherlands	gas	01/01/2003	
MAASVLAKTE ELECTRABEL 1	netherlands	hard_coal	01/01/2014	
MERWEDEKANAAL 10A	netherlands	gas	01/01/1978	
MERWEDEKANAAL 11A	netherlands	gas	01/01/1984	
MERWEDEKANAAL 12A	netherlands	gas	01/01/1989	
MOERDIJK AZN GT 1	netherlands	gas	01/01/1995	
MOERDIJK CCGT CHP 2	netherlands	gas	01/04/2012	
PARENCO PAPER MILL GT 1	netherlands	gas	01/01/1979	
PERNIS REFINERY CC GT 1	netherlands	gas	01/01/1997	
PERNIS REFINERY CC GT 2	netherlands	gas	01/01/1997	
PERNIS REFINERY GT 1	netherlands	gas	01/01/1981	
PERNIS REFINERY GT 2	netherlands	gas	01/01/1999	
PERNIS REFINERY GT 3	netherlands	gas	01/01/1987	

PURMEREND GT 1	netherlands	gas	01/01/1988
RIJNMOND ENERGIE GT 1	netherlands	gas	01/01/2004
RIJNMOND ENERGIE GT CHP 2	netherlands	gas	01/06/2010
ROCA (ROTTERDAM) 1 GT 1	netherlands	gas	01/01/1982
ROCA (ROTTERDAM) 1 GT 2	netherlands	gas	01/01/1982
ROCA (ROTTERDAM) 3 CC GT 1	netherlands	gas	01/01/1995
ROTTERDAM EASTMAN GT 1	netherlands	gas	01/01/1998
ROTTERDAM EASTMAN GT 2	netherlands	gas	01/01/2001
ROZENBURG AIR PRODUCTS GT 1	netherlands	gas	01/01/1987
ROZENBURG EUROGEN GT 1	netherlands	gas	01/01/1994
ROZENBURG EUROGEN GT 2	netherlands	gas	01/01/1994
ROZENBURG EUROGEN GT 3	netherlands	gas	01/01/1994
SLUISKIL WORKS 5	netherlands	gas	01/01/2005
SLUISKIL WORKS GT 1	netherlands	gas	01/01/1976
SWENTIBOLD GT 1	netherlands	gas	01/01/1999
TER APELKANAAL CC GT 1	netherlands	gas	01/01/1995
TERNEUZEN ELSTA GT 1	netherlands	gas	01/01/1998
VELSEN 24	netherlands	hard_coal	01/01/1974
VELSEN 25	netherlands	hard_coal	01/01/1986
VELSEN GT 1	netherlands	gas	01/01/1975
VELSEN MILL 4	netherlands	oil	01/01/1965
VELSEN MILL GT 1	netherlands	gas	01/01/1984
WAPENVELD GT 2	netherlands	gas	01/01/1996
WILLEM ALEXANDER GT 1	netherlands	hard_coal	01/01/1994

D. – VBA code

I – standard investment module and capacity market code

```
# This part is used to clear all previous investments

Set Country = CO2Sim.Countries("Germany")
Set Points = Country.PowerSector.UnitTypes("gas").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Points = Country.PowerSector.UnitTypes("hard_coal").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Points = Country.PowerSector.UnitTypes("lignite").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Points = Country.PowerSector.UnitTypes("other").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc

Set Country = CO2Sim.Countries("Netherlands")
Set Points = Country.PowerSector.UnitTypes("gas").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Points = Country.PowerSector.UnitTypes("hard_coal").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Points = Country.PowerSector.UnitTypes("other").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  Points.Quiet = False
  Points.recalc
Set Country = CO2Sim.Countries("Netherlands")

# This part of the code calculates and outputs the model outcomes and exports these to the excel file to
reset the investment modules as well.

frmMain.check1.Value = 1
```

```

frmMain.check1.Value = 0
frmMain.GenOutput "Standard"

Application.Workbooks.Open("C:\Users\cswager003\Desktop\Power2Sim495\out\Power-
Price_simulated(€pMWh).xlsx")
Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
Application.Range("B2:C8785").Select
Application.ActiveWorkbook.close

Msgbox "all cleared"

# Here the actual simulation starts, first by setting the starting values

Set Country = CO2Sim.Countries("Germany")
'frmMain.check1.Value = 0
'frmMain.check1.Value = 1

Gned = 10000
Cned = 5250
Lned = 0
GTned = 0

Gger = 21000
Cger = 23500
Lger = 15000
GTger = 0

# Determine whether investment is attractive

Do While MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(37,22) > 0

# Check whether it is investment in the Netherlands or in Germany

IF
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,18)>MyExcel.MyWorkBook.WorkSheets("Cal
culations").Cells(44,18) then
Set Country = CO2Sim.Countries("Germany")
frmMain.check1.Value = 1
frmMain.check1.Value = 0

frmMain.GenOutput "Standard"

Application.Workbooks.Open("C:\Users\cswager003\Desktop\Power2Sim495\out\Power-
Price_simulated(€pMWh).xlsx")
Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
Application.Range("B2:C8785").Select
'Application.Range("B2:B8785").Copy
Application.ActiveWorkbook.close

MyExcel.MyWorkBook.WorkSheets("Calculations").activate
'ThisWorkbook.UpdateLink
'Name:=ThisWorkbook.LinkSources
'Application.Range("A36:A8819").Select

```

```
'Application.ActiveSheet.Paste
```

```
'Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
```

#Check what is the most attractive technology to invest in, the value of the preferred technology will be adjusted and the model is recalculated with the new values.

```
If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14) > 0 And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13)And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) then  
  'MsgBox "investeren in gas"  
  Gger = Gger + 250  
  MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,3) = Gger - 21000  
  Set Points = Country.PowerSector.UnitTypes("gas").TargetCapacityPoints  
  Points.Quiet = True  
  Points.Clear  
  For y = 2019 to 2020  
    D = DateSerial(y,1,1) - CO2Sim.DayStart  
    Points.Add cLng(d), cSng(Gger)  
  Next  
  Points.Quiet = False  
  Points.Recalc
```

```
else If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13) > 0 And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14)And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15)And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) then  
  'MsgBox "investeren in coal"  
  Cger = Cger + 250  
  MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,2) = Cger - 23500  
  Set Points = Country.PowerSector.UnitTypes("hard_coal").TargetCapacityPoints  
  Points.Quiet = True  
  Points.Clear  
  For y = 2019 to 2020  
    D = DateSerial(y,1,1) - CO2Sim.DayStart  
    Points.Add cLng(d), cSng(Cger)  
  Next  
  Points.Quiet = False  
  Points.Recalc
```

```
else If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) > 0 And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13)And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14)And  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) >  
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) then
```

```

Lger = Lger + 250
'MsgBox "investeren in lignite"
MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,5) = Lger - 15000
Set Points = Country.PowerSector.UnitTypes("lignite").TargetCapacityPoints
Points.Quiet = True
Points.Clear
For y = 2019 to 2020
D = DateSerial(y,1,1) - CO2Sim.DayStart
Points.Add cLng(d), cSng(Lger)
Next
Points.Quiet = False
Points.Recalc
else If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) > 0 And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,13)And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,14)And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,15) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(32,16) then
'MsgBox "investeren in gas"
GTger = GTger + 250
MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,4) = GTger - 0
Set Points = Country.PowerSector.UnitTypes("other").TargetCapacityPoints
Points.Quiet = True
Points.Clear
For y = 2019 to 2020
D = DateSerial(y,1,1) - CO2Sim.DayStart
Points.Add cLng(d), cSng(GTger)
Next
Points.Quiet = False
Points.Recalc
Else MsgBox "niet investeren"
End If
End If
End If
End If

# If investment in the Netherlands is more preferable.

Else Set Country = CO2Sim.Countries("Netherlands")

# Run model and output electricity price.

frmMain.check1.Value = 1
frmMain.check1.Value = 0

frmMain.GenOutput "Standard"

#Load output into excel investment module

Application.Workbooks.Open("C:\Users\cswager003\Desktop\Power2Sim495\out\Power-
Price_simulated(€pMWh).xlsx")
Application.Worksheets("Power-Price_simulated(€pMWh)").Activate

```

```
Application.Range("C2:C8785").Select
'Application.Range("C2:C8785").Copy
Application.ActiveWorkbook.close
```

```
MyExcel.MyWorkBook.WorkSheets("Calculations").activate
```

#Determine preferred technology

```
If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,14) > 0 And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,14) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,13)And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,14) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,15) then
  'MsgBox "investeren in gas"
  Gned = Gned + 250
  'MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,3) = Gned - 21000
  Set Points = Country.PowerSector.UnitTypes("gas").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  For y = 2019 to 2020
    D = DateSerial(y,1,1) - CO2Sim.DayStart
    Points.Add cLng(d), cSng(Gned)
  Next
  Points.Quiet = False
  Points.Recalc
```

```
else If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,13) > 0 And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,13) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,14)And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,13) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,15) then
  'MsgBox "investeren in coal"
  Cned = Cned + 250
  'MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,2) = Cned - 23500
  Set Points = Country.PowerSector.UnitTypes("hard_coal").TargetCapacityPoints
  Points.Quiet = True
  Points.Clear
  For y = 2019 to 2020
    D = DateSerial(y,1,1) - CO2Sim.DayStart
    Points.Add cLng(d), cSng(Cned)
  Next
  Points.Quiet = False
  Points.Recalc
```

```
else If MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,15) > 0 And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,15) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,13)And
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,15) >
MyExcel.MyWorkBook.WorkSheets("Calculations").Cells(44,14) then
  'MsgBox "investeren in gas"
  GTned = GTned + 250
  'MyExcel.MyWorkBook.WorkSheets("CapBidCalculations").Cells(15,4) = GTned - 0
  Set Points = Country.PowerSector.UnitTypes("other").TargetCapacityPoints
```

```

Points.Quiet = True
Points.Clear
For y = 2019 to 2020
D = DateSerial(y,1,1) - CO2Sim.DayStart
Points.Add cLng(d), cSng(GTned)
Next
Points.Quiet = False
Points.Recalc
Else MsgBox "niet investeren"
End If
End If
End If
End If

# Start simulation over again, or if investment not attractive anymore, stop macro.

Loop

Msgbox "calculation finished"

```

II – Mothball code

```

Set Country = CO2Sim.Countries("Netherlands")
frmMain.check1.Value = 0
frmMain.check1.Value = 1

Gned = 10500
R = 0

frmMain.check1.Value = 1
frmMain.check1.Value = 0

frmMain.GenOutput "Standard"

Application.Workbooks.Open("C:\Users\cswager003\Desktop\Power2Sim495\out\Power-Price_simulated(€pMWh).xlsx")
Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
Application.Range("B2:C8785").Select
'Application.Range("B2:B8785").Copy
Application.ActiveWorkbook.close

Do While MyExcel.MyWorkBook.WorkSheets("Mothball").Cells(33,94) > 0

frmMain.check1.Value = 1
frmMain.check1.Value = 0

frmMain.GenOutput "Standard"

Application.Workbooks.Open("C:\Users\cswager003\Desktop\Power2Sim495\out\Power-Price_simulated(€pMWh).xlsx")

```

```
Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
Application.Range("B2:C8785").Select
'Application.Range("B2:B8785").Copy
Application.ActiveWorkbook.close
```

```
MyExcel.MyWorkBook.WorkSheets("Mothball").activate
'ThisWorkbook.UpdateLink
'Name:=ThisWorkbook.LinkSources
'Application.Range("A36:A8819").Select
'Application.ActiveSheet.Paste
```

```
'Application.Worksheets("Power-Price_simulated(€pMWh)").Activate
R = R + 1
MyExcel.MyWorkBook.WorkSheets("Mothball").Cells(31,94) = R
S = MyExcel.MyWorkBook.WorkSheets("Mothball").Cells(30,94)
'Msgbox S
Gned = Gned - S
```

```
Set Points = Country.PowerSector.UnitTypes("gas").TargetCapacityPoints
Points.Quiet = True
Points.Clear
For y = 2020 to 2021
D = DateSerial(y,1,1) - CO2Sim.DayStart
Points.Add cLng(d), cSng(Gned)
Next
Points.Quiet = False
Points.Recalc
```

Loop

```
Msgbox "calculation finished"
```


E. – Performance indicators

Electricity price and volatility

Average = AVERAGE(“electricity price range”)

Volatility = STDEV(“electricity price range”)

Loss of load expectation

LOLE is calculated in excel using the following formula.

LOLE = Countif(“electricity price range”;3000)

CO₂ emission

Emissions are calculated by using the following parameters and equations.

Table E.2 Emission factor per technology

Coefficient	unit	Hard coal	Lignite	Gas	Oil
a	CO ₂ per TJ	94,60	101,20	56,60	
b	1TJ in GWh	0,278	0,278	0,278	0,278

$$CO_2 \text{ emission} = \sum_1^n \frac{\text{Fuel input}_x}{b_x} * a_x \quad x = 1 \dots n$$

Where x is a particular technology

Renewable subsidy change

Renewable subsidy change

$$= \prod_1^H P_{e \text{ base case } h} * G_{ren \text{ base case } h} - \prod_1^H P_{e \text{ capm } h} * G_{ren \text{ capm } h}$$

Where:

H = number of hours in a year

Pe = electricity price at time h

Gren = Generation renewables at time h

Capacity price

$$\text{Capacity price per MWh} = \frac{\text{clearing price} * \text{clearing volume}}{\text{Electricity demand in MWh}}$$

Total consumer cost

$$\text{Total consumer costs} = C_e + C_r + C_c$$

Where:

C_e = Costs of electricity from the wholesale market

C_r = Costs of change in renewables subsidy

C_c = Costs of capacity market payment

F. – Results

E1 Netherlands

Base case

Table F.3 Results electricity price NL

€10/ tonnen CO ₂		Electricity price summary						€50/ tonne CO ₂	
		€30/ tonne CO ₂							
Min	(100,00)	Min	(100,00)	Min	(100,00)	Min	(100,00)	Min	(100,00)
Q1	39,06	Q1	52,97	Q1	52,97	Q1	64,89	Q1	64,89
Median	46,93	Median	56,26	Median	56,26	Median	71,05	Median	71,05
Q3	54,69	Q3	62,87	Q3	62,87	Q3	73,19	Q3	73,19
Max	3.000,00	Max	3.000,00	Max	3.000,00	Max	3.000,00	Max	3.000,00
Average	48,73	Average	58,53	Average	58,53	Average	66,42	Average	66,42
Volatility	96,83	Volatility	86,21	Volatility	86,21	Volatility	41,19	Volatility	41,19

Table F.4 Results total consumer costs NL

€10/tonnen CO ₂		Total consumer costs		€50/tonnen CO ₂	
		€30/tonnen CO ₂			
7.787.664.091		7.890.405.897		8.830.357.012	

Table F.5 Results CO₂ emission NL

€10/tonne CO ₂		Total CO ₂ emission		€50/tonne CO ₂	
		€30/tonne CO ₂			
43.714.665		41.573.029		40.009.644	

Table F.6 Results reserve margin NL

Scenario	Total conventional	Total renewables	Reserve margin				
			Intercon- nector cap	Peak Demand	reserve margin		
	GW	GW	GW	GW	1	2	3
€10/tonne	17,50	9,60	6,70	19,85	1,37	0,98	1,32
€30/tonne	17,00	9,60	6,70	19,85	1,34	0,95	1,29
€50/tonne	18,25	9,60	6,70	19,85	1,40	1,02	1,35

- 1) Without import, intermittent resources 100%
- 2) Without import, intermittent resources 20%
- 3) Including import, intermittent resources 20%

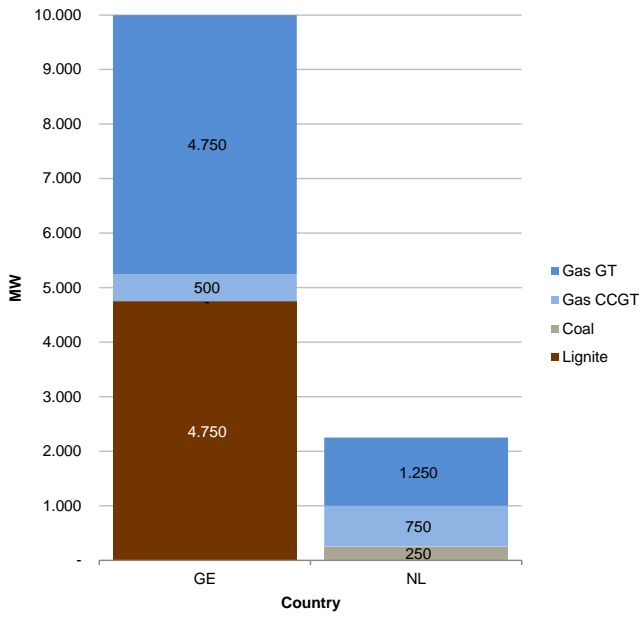
Table F.7 Results LOLE NL

€10/tonnen CO ₂	Lost load hours	
	€30/tonnen CO ₂	€50/tonnen CO ₂
9	7	1

Table F.8 Results import export NL

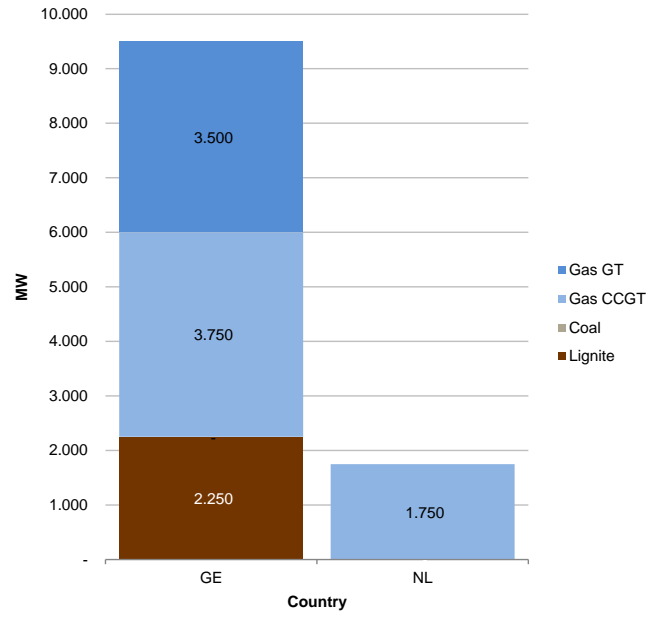
Scenario	Import & export	
	Germany>Netherlands	Netherlands>Germany
€10/tonne	15.643.648	75.776
€30/tonne	9.637.888	1.377.280
€50/tonne	9.637.888	1.377.280

Investment NL and GE



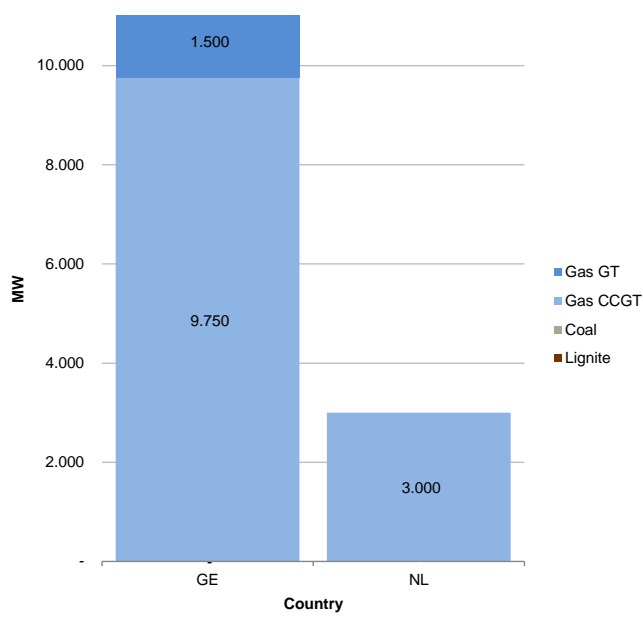
Figuur F.3 Results investment NL €10/tonne CO2

Investment NL and GE



Figuur F.2 Results investment NL €30/tonne CO2

Investment NL and GE



Figuur F.1 Results investment NL €50/tonne CO2

Experiment 1

Table F.9 Results electricity price NL E1

€10/ tonnen CO ₂		Electricity price summary		€50/ tonne CO ₂	
		€30/ tonne CO ₂			
Min	(100,00)	Min	(100,00)	Min	(100,00)
Q1	45,54	Q1	52,97	Q1	64,89
Median	49,81	Median	56,26	Median	71,05
Q3	54,69	Q3	62,87	Q3	73,15
Max	3.000,00	Max	3.000,00	Max	3.000,00
Average	47,78	Average	56,86	Average	67,15
Volatility	58,53	Volatility	49,53	Volatility	39,48

Table F.10 Results total consumer costs NL E1

Total consumer costs		
€10/tonnen CO ₂	€30/tonnen CO ₂	€50/tonnen CO ₂
6.435.350.191	7.596.566.479	8.914.126.029

Table F.11 Results CO2 emission NL E1

Total CO ₂ emission		
€10/tonne CO ₂	€30/tonne CO ₂	€50/tonne CO ₂
40.854.074	40.568.359	37.725.572

Table F.12 Results renewables subsidy NL E1

Renewables subsidies		
€10/tonne CO ₂	€30/tonne CO ₂	€50/tonne CO ₂
14.100.659	9.192.812	50.329.845

Table F.13 Results reserve margin NL E1

Scenario	Total conventional	Total renewables	Reserve margin				
			Interconnector cap	Peak Demand	reserve margin		
	GW	GW	GW	GW	1	2	3
€10/tonne	15,75	9,60	6,70	19,85	1,28	0,89	1,23
	16,25	9,60	6,70	19,85	1,30	0,92	1,25
€20/tonne							
€30/tonne	16,50	9,60	6,70	19,85	1,31	0,93	1,27

- 1) Without import, intermittant resources 100%
2) Without import, intermittant resources 20%
3) Including import, intermittant resources 20%

Table F.14 Results LOLE NL E1

Lost load hours		
€10/tonnen CO ₂	€30/tonnen CO ₂	€50/tonnen CO ₂
3	2	1

Table F.15 Results import export NL E1

Scenario	Import & export	
	Germany>Netherlands	Netherlands>Germany
€10/tonne	16.976.896	17.408
€20/tonne	15.476.736	41.984
€30/tonne	12.088.320	714.752

Investment NL and GE

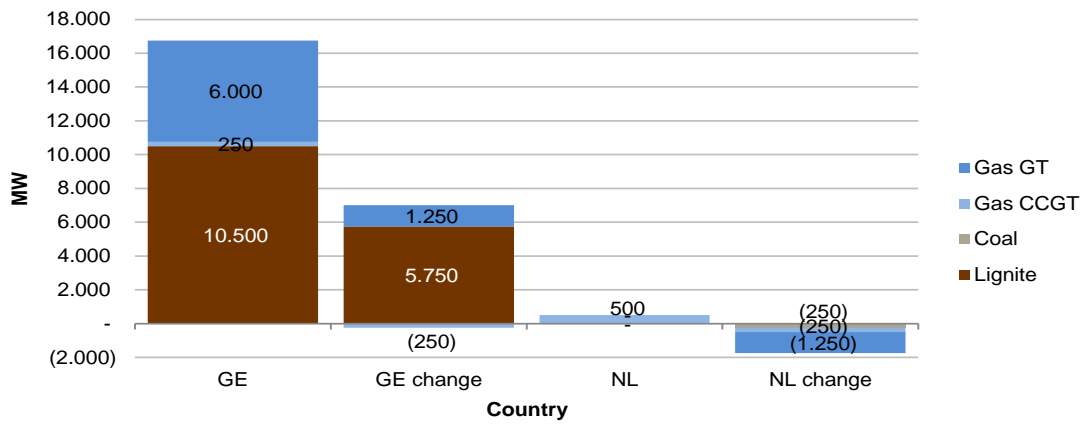


Figure F.4 Results investment NL E1 CO2 €10/tonne

Investment NL and GE

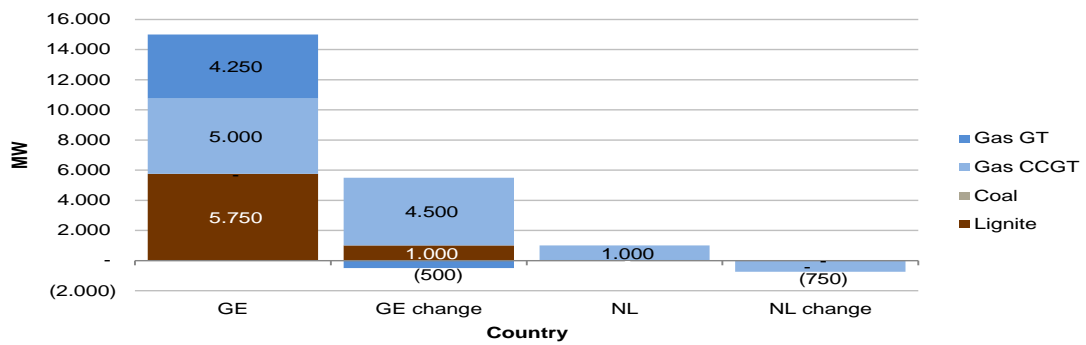


Figure 13.2 results investment NL E1 CO2 €30/tonne

Investment NL and GE

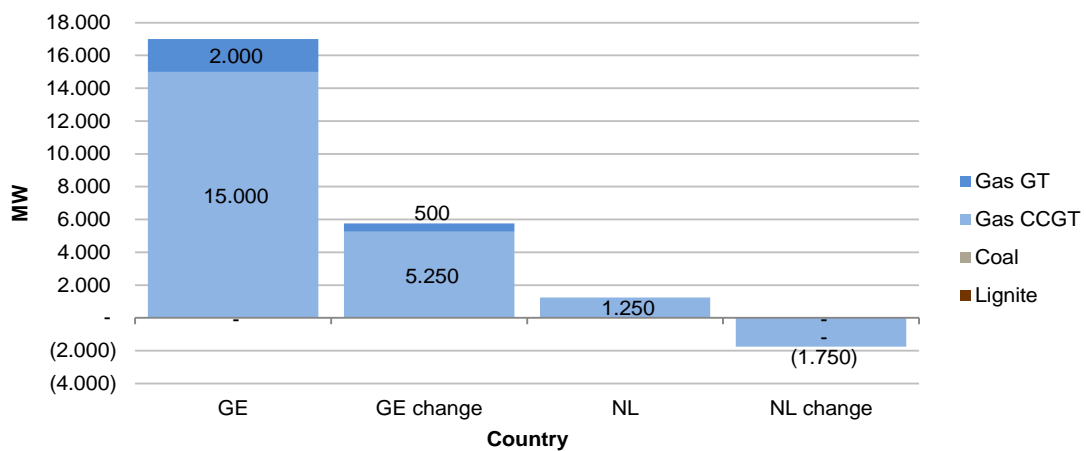


Figure F.5 Results investment NL E1 CO2 €50/tonne

Experiment 2

Table F.16 Electricity price summary experiment 2

Electricity price summary					
€10/ tonnen CO ₂		€30/ tonne CO ₂		€50/ tonne CO ₂	
Min	(100,00)	Min	(100,00)	Min	(100,00)
Q1	36,65	Q1	52,80	Q1	71,62
Median	45,54	Median	55,61	Median	75,14
Q3	54,69	Q3	62,87	Q3	81,62
Max	3.000,00	Max	3.000,00	Max	104,11
Average	44,65	Average	55,16	Average	70,57
Volatility	58,30	Volatility	49,02	Volatility	25,53

Table F.17 Total consumer costs experiment 2

Total consumer costs		
€10/tonnen CO ₂	€30/tonnen CO ₂	€50/tonnen CO ₂
6.026.045.767	7.355.602.862	9.333.769.394

Table F.18 CO₂ emission experiment 2

Total CO₂ emission		
€10/tonne CO ₂	€10/tonne CO ₂	€10/tonne CO ₂
36.733.557	37.047.255	34.248.614

Table F.19 Renewables subsidies experiment 2

Renewables subsidies		
€10/tonne CO ₂	€30/tonne CO ₂	€50/tonne CO ₂
(64.696.749)	(19.138.480)	12.494.118

Table F.20 Reserve margin experiment 2

Scenario	Reserve margin						
	Total conventional	Total renewables	Intercon- nector cap	Peak Demand	reserve margin		
€10/tonne	GW	GW	GW	GW	1	2	3
e	15,25	9,60	6,70	19,85	1,25	0,86	1,20
€20/tonne	15,75	9,60	6,70	19,85	1,28	0,89	1,23
€30/tonne	16,00	9,60	6,70	19,85	1,29	0,90	1,24

1) Without import, intermittant resources 100%

2) Without import, intermittent resources 20%

3) Including import, intermittent resources 20%

Table F.21 LOLE experiment 2

Lost load hours		
€10/tonnen CO ₂	€30/tonnen CO ₂	€50/tonnen CO ₂
3	2	0

Table F.22 Import export experiment 2

Import & export		
Scenario	Germany>Netherlands	Netherlands>Germany
€10/tonne	31.950.896	17.408
€20/tonne	26.793.238	31.744
€30/tonne	18.309.382	989.184

Table F.23 Electricity price summary

CO ₂ scenario	Indicator	Base	Experiment 1	Experiment 2
€10/tonne	Average Price	48,73	47,78	44,65
	Volatility	96,83	58,53	58,30
€30/tonne	Average Price	58,53	56,86	55,16
	Volatility	86,21	49,53	49,02
€50/tonne	Average Price	66,42	67,15	70,57
	Volatility	41,19	39,48	25,53

Investment NL and GE

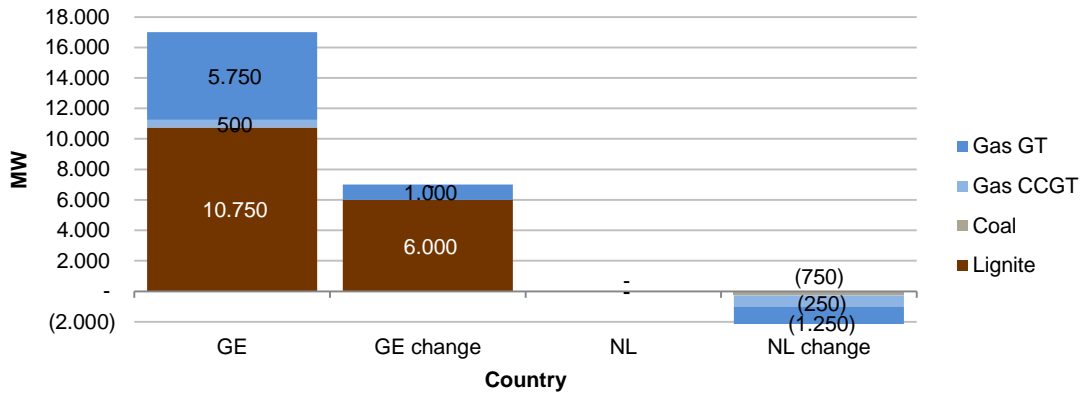


Figure F.3 Investment €10/tonne CO₂ experiment 2

Investment NL and GE

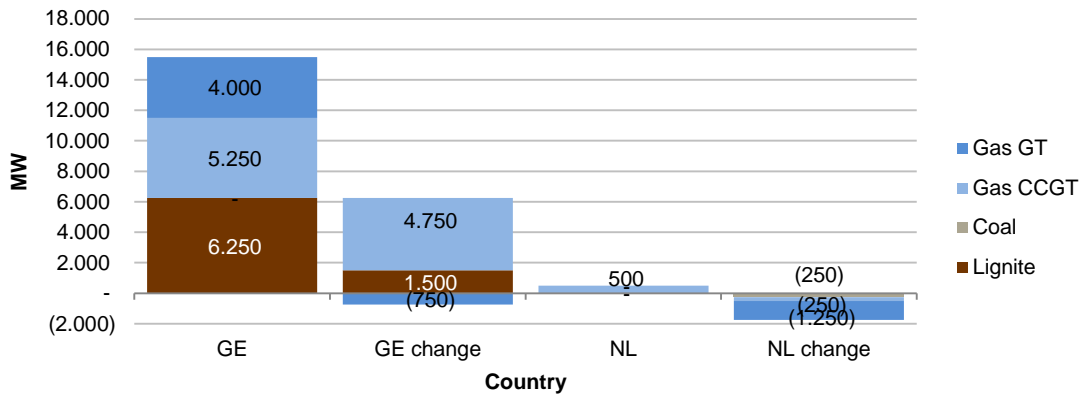


Figure F.4 Investment €30/tonne CO₂ experiment 2

Investment NL and GE

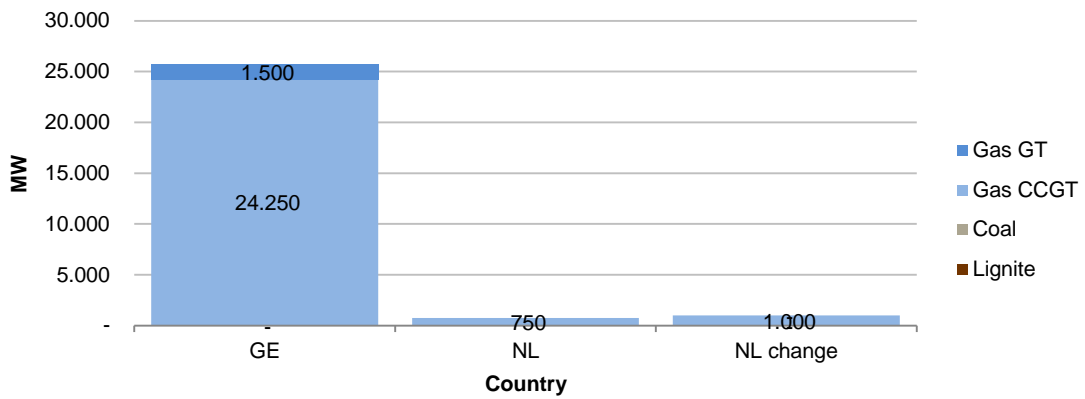


Figure F.5 Investment €50/tonne CO₂ experiment 2