Exploring the future electricity price in the Netherlands

A System Dynamics modeling approach to explore the development of electricity prices from 2015 to 2030 within a more and more sustainable environment

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MSc System Engineering, Policy Analysis & Management – Energy & Industry Domain

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Information
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Abstract

To limit global warming, greenhouse gases need to substantially be reduced in all sectors of the economy (IPCC, 2014). The Netherlands has translated this to ambitious goals towards a more sustainable environment. It aims to reach a 40% CO2 emission reduction compared to 1990 and have 27% of the total generated energy be produced through renewable energy by 2030. The large required adoption of renewable energy sources – like wind energy – evoke concerns by stakeholders of the Dutch electricity systems. The influence of a large capacity of renewable electricity production on the electricity system and on the electricity prices towards 2030, is uncertain. Besides it is unclear whether these targets are even within reach as these unknowns negatively influence the investment environment.

How will the changing energy production mix interplay with the future electricity price of 2030 in the Netherlands?

Answers to this research question can help energy utility companies and external financiers by providing insights in the future Dutch electricity system and in the future electricity prices, and thereby supporting them in making investment decisions. The results of this research might be of interest for policymakers, as the insights of the future Dutch electricity system can support them in the design of future policies.

Using literature on the Dutch electricity system design, a translation is made to implement the system in a System Dynamics model – using Vensim software. Following a System Dynamics validation process and by comparing the model output with historical data, a foundation has been created to execute simulations. A Monte Carlo Analysis has been performed in order to deal with uncertainties of external forces and megatrends that influence the electricity system towards 2030. To explore the strengths and weaknesses of the designed System Dynamics model, it is compared with existing electricity system simulation models.

The simulation model shows that the energy production mix will become more sustainable with more wind electricity production capacity and a decline of carbon intensive electricity production capacity. Due to the large adoption of wind energy capacity, the electricity prices will become more volatile towards 2030 – as the unpredictable wind speed will have more effect on the total available electricity supply when the installed capacity of wind becomes larger. The increased volatility negatively influences the stability of the electricity system and therefore more import and export capacity is needed to maintain stability.

The interpretation of the results has led to several recommendations to various stakeholders of the Dutch electricity system. The Transmission System Operator might need to extend the interconnector capacity to neighbor countries to increase its import and export capabilities when the electricity system is subjected to a shortage or surplus of electricity supply. Policymakers should closely monitor the development of the CO2-price, this factor determines to a large extent the adoption of wind energy capacity.

Every study is subjected to limitations. The limitations of this study and System Dynamics model consist of the absence of significant literature supporting the expected development of external forces towards 2030, the model consists of a simplified investment process, no simulations are performed on electricity (prices) of neighbor countries and wind energy capacity is the only renewable energy source that has been taken into account.

This research contributes to science by designing the Dutch electricity system in a System Dynamics model. For different stakeholders it provides insights in the development of the Dutch electricity system towards 2030. To KPMG the System Dynamics process shows to be an interesting analytics tool.

Acknowledgements

This thesis research marks the end of an educational and enjoyable time as a student at the Delft University of Technology. Writing this thesis was the last hurdle to be taken to obtain a MSc. Degree in Systems Engineering, Policy Analysis and Management.
Since “Energy” was one of the first words I (tried) to pronounce as a baby when passing a wind mill, it is not peculiar that this thesis research is about “energy”. During the process of my research I have developed an increasing interest for data analytics and the world behind data scientists. An interest that I could enthusiastically share with my colleagues at KPMG, where I got the opportunity to write my thesis.

I would like to thank Marina van Geenhuizen, Els van Daalen, Laurens de Vries and Pieter Bots for being part of my graduation committee. I appreciate your help on guiding me through the sometimes challenging process of scientific research. A special thanks to Els van Daalen for her weekly feedback and guidance.

Moreover I want to thank my colleagues at KPMG who were always open for a discussion. Having so much scientific experience in one office helped me to stay focused in my research and challenged me to constantly go for the extra mile. First of all, I especially want to thank Sander Klous for his trust in me and for giving me the opportunity to perform a research in such an interesting environment. Last but not least, I would like to thank Martijn Gosselink for his intensive guidance through the research project. I greatly enjoyed our feedback moments, the discussions we had and the input I got from you. It helped me to get to this result.

Finally I would like to thank my family, friends and my girlfriend Saskia for their support and motivation during this process. A special thanks to my parents for their support in general and for giving me the opportunity to go to college. I appreciate that a lot.

Justin Groot

May 23rd, 2015

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1. Introduction

The impacts that global warming and climate change will have on human societies are enormous and should be avoided (The World Bank, 2012). To limit global warming, greenhouse gases need to substantially be reduced in all sectors of the economy (IPCC, 2013).
The Netherlands has translated this advice to ambitious goals towards a more sustainable environment. It aims to a reach 40% CO2 emission reduction compared to 1990 and have 27% of the total generated energy be produced through renewable energy by 2030 (Ministerie van infrastrucutuur en Milieu, 2014).

1.1 Problem orientation

The European Union as well as the Dutch government have implemented several policy measurements to stimulate sustainable development. Yet, these policies have not led to the desired effect in both the renewable energy production adoption and the carbon emission reduction. The complex environment, that the policymakers of the EU and the Netherlands try to influence, makes it challenging to design policies that result in the desired effects. Besides, factors – like economic growth and Gross Domestic Product (GDP) – influencing the system, could potentially disarm policies when these factors evolve unexpectedly.

An important policy measure that was implemented by the European Union in 2005 is the Emission Trading Scheme, which should give European organizations the incentive to reduce Carbon emissions (European Commission, 2014c). However, due to the economic crisis, the demand of energy turned out lower than expected in the EU. This has led to a surplus of CO2-certificates, resulting in the tumbling of CO2 prices and thereby a low financial incentive for European organizations to reduce carbon emissions. A counter measure by the EU therefore is to reduce the supply of CO2-certificates faster than planned to push up the carbon emission prices and increase the investment incentive in renewable energy. The European Commission calculated that the price per ton CO2 should reach €100 to €370 in order to achieve the desired effect of CO2 reduction, compared to a price of €6.67 per ton CO2 in December 2013 (see Figure 1.1) (European Commission, 2014b).

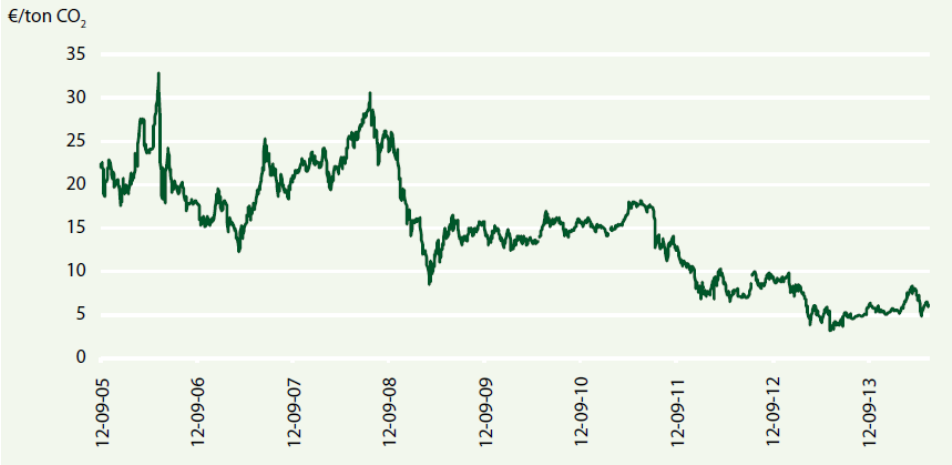

Figure 1.1 Carbon Emission Price per ton – EU Emission Trading Scheme (Simons, 2014)

Another example is the SDE+ subsidy policy measure in the Netherlands to provide financial incentives to invest in renewable energy production. For the year 2015 the government has reserved the same amount as in 2014 – 3.5 billion euro – to stimulate sustainable investments (Rijksdienst voor Ondernemend Nederland, 2014). As can be seen from Figure 1.2, by 2013 10% of the total electricity usage was produced by renewable energy. The last four years the renewable energy production has been relatively stable, which could indicate that the policy measures have led to better results before 2010 than after 2010. Even though the demand for electricity has been relatively stable between these years as well. Adjustments to these policies might be necessary to achieve the desired sustainability targets of 2030.

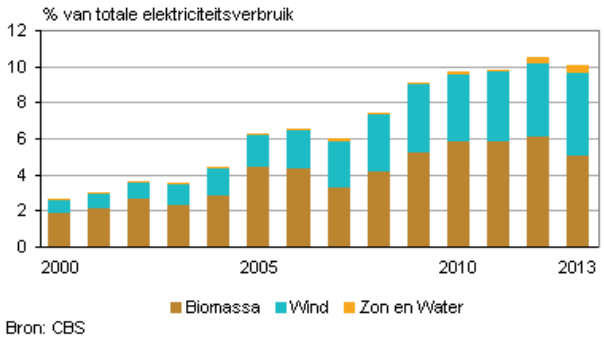

Figure 1.2 Renewable energy adoption in The Netherlands – (Simons, 2014)

Figure 1.3 underlines once more that the power industry in the EU has one of the greatest challenges ahead as it should target to reach a minimum CO2-emisssion reduction of 54% by 2030 and a minimum CO2-emission reduction of 93% by 2050 compared to levels in 1990. Improving the financial feasibility of renewable energy investments, wherein electricity prices play an important role, could contribute to achieving these targets. Stable future energy prices will decrease uncertainty and thus improve investments resulting in a higher adoption of renewable sources and a stronger carbon emission reduction.

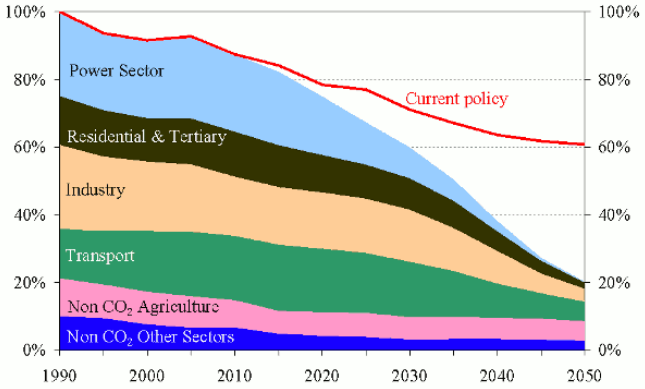

Figure 1.3 Necessary reduction of Greenhouse Gases (GHG) per industry in the EU (European Commission, 2014b)

Looking at the desired increase of wind energy production sources by the Dutch government, the opposite is currently happening. This is because the energy production from Renewable Energy Sources (RES) like wind and solar fluctuate due to weather conditions and therefore the production of electricity is less controllable for energy utility companies than traditional electricity production sources. Periods with high RES output and low demand lead to a surplus of electricity, possibly resulting in negative electricity prices. Since energy prices should naturally cover the investment and operational costs of energy production companies, negative prices will hold back further investments in RES, and thus wind energy sources, and jeopardize a sustainable future.

However, the sustainability challenge is not a puzzle focused on electricity prices only, the challenge is part of a larger socio-technical system where political, social, economic, environmental and technological issues are all influential. These effects should be taken into account when looking at the future investment environment in renewable energy.

1.2 Problem Definition

The sustainability targets of the Dutch government have been translated to policies stimulating sustainable development and are demotivating carbon intensive electricity production. This has led to a growth of Wind energy production reaching a total of 2852 MW in 2014 in the Netherlands (CBS, 2014). It is expected that the increase of wind energy adoption will continue the coming years as the Dutch government targets an installed capacity of 6000 MW in wind energy on land and approximately 2500 MW in sea by 2020 (Van Zuijlen et al., 2014).

Increasing the installed capacity of wind energy will help to de-carbonize the Dutch electricity sector and thereby become more sustainable. Whether the desired development of wind energy production is realistic is debatable though. This because the desired increase of wind energy increases the volatility of electricity production and thus the volatility of electricity prices, which subsequently increases the risk for investing in wind energy. The increase of investment risk could thus harm the desired development of installed wind energy capacity (Joskow, 2006).

For Dutch policymakers it is therefore of great importance to know what the effects of wind energy have on the investment environment (i.e. electricity prices) when wind energy capacity increases. Although as stated earlier, the sustainability challenge of the government is not only focused on electricity prices, political, social, economic, environmental and technological effects should be taken into account as well. Besides Dutch policymakers, it is important for investors – focusing on wind energy – to know how the future electricity system will behave taking into account the goals of the Dutch government, socio-technical aspects and trends towards the future.

1.3 Research Goal

The initial goal is to conceptualize the electricity market of the Netherlands as a system with the focus on providing an approximation of the future electricity prices and the development – e.g. investment decisions – in the energy production mix. The conceptualization of system includes the external forces, megatrends and possible policies influencing the electricity system and electricity prices. Information on which and how factors influence the supply and demand of electricity will be based on literature reviews of the electricity market. This conceptualized system will be converted into a simulation model. Which simulation modeling technique will be used for this research is described in chapter 2.3.

Through the simulation model, different future scenarios will be analyzed. The results of these analyses should lead to an approximation of future electricity price development in the Netherlands towards 2030. This information could be useful to policymakers and investors focusing on renewable energy and developing the energy production mix.

Energy storage might be the solution to volatile electricity prices and an instable electricity system (Dunn et al., 2011), though the technological development is rather complex and uncertain. Therefore, this technical development has been kept out of the research scope of detailed analysis – also due to the limited time of the research – however on this technical development and its effects on the Dutch electricity system will be touch upon briefly in chapter 4 – Quantitative Representation of the Dutch Electricity System – and chapter 6 – Modeling results.

1.4 Research Question

The main research question is as follows:

How will the changing energy production mix interplay with the future electricity price towards 2030 in the Netherlands?

This question can be divided into five sub-questions:

1. **What does the system domain of electricity prices of the Netherlands in 2030 look like?**
   Answering this sub-question provides insights in what the system, that determines the electricity prices, looks like. The development process of translating this system domain into a simulation model will be investigated.
2. **Which external forces mainly influence the behavior of the system domain of future electricity prices in the Netherlands?**
   This sub-question will provide insight in which external forces should be taken into account that might affect the electricity prices towards 2030.
3. **What kinds of policies guide the electricity system to a more sustainable future?**
   An answer to this sub-question provides insight in the policies influencing the energy production mix in the Netherlands. Both policies from the European Union as well as policies designed by policymakers in the Netherlands could affect the Dutch electricity system.
4. **What are possible developments of the Dutch electricity system towards 2030, taking into account uncertainty factors?**
   An answer to this sub-question provides insights in the modeling results of the simulation model on the Dutch electricity system towards 2030. The simulation model should take into account uncertainty factors of external forces in order to model towards 2030.
5. **How does the System Dynamics model contribute to research on future electricity prices compared to existing electricity price simulation models?**
   An answer to this sub-question provides insights in alternative electricity market simulation models and will compare those models with the electricity market System Dynamics model. Thereby the strengths and weaknesses of the System Dynamics model could be identified, leading to an advice to further improve the Dutch electricity market System Dynamics model in the future.

1.5 Thesis outline

The structure of the thesis report is as following. Chapter 2 describes the research methodology. In chapter 3 and 4 an analysis of the Dutch electricity system is performed. This results in a conceptual model which contains the core system (domain) of the electricity system and the external forces and policies influencing this system. After this conceptual model has been implemented in the simulation software, the model will be tested – described chapter 5 on Validation. Chapter 6 provides the modeling results and the analysis done on the simulation output. Subsequently, the designed model is compared with alternative electricity system models to indicate the strengths and weaknesses of the model. In chapter 8 the conclusions and recommendations of the research are described.

Part I - Methodology

2. Methodology

2.1 Conceptualizing the Dutch electricity market

Foote has given a definition of complex systems that fits the system of an investment environment in renewable energy and future energy prices (Foote, 2007). He defined it as follows:

Complex systems describe phenomena, structures, aggregates, organisms, or problems that share some common theme:

1. *They are inherently complicated or intricate;*
2. *They are rarely completely deterministic;*
3. *Mathematical models of the system are usually complex and involve non-linear, ill-posed, or chaotic behavior;*
4. *The systems are predisposed to unexpected outcomes (so-called emergent behavior).*

Complex systems are exposed to dynamical changes within the system that could influence other parts of the system unexpectedly. Therefore, actions (i.e. policy implementations) that are taken by policymakers should be monitored constantly in order to measure whether the policies have led to the desired effect. Walker (2000) has proposed a *Policy Approach Framework* (Figure 2.1) which identifies the most important elements of the policy analysis process. Applying this framework, helps to understand the current situation concerning policies influencing the (future) energy prices. Next to that, it could help to identify future policies scenarios and the future feasibility of investments in renewable energy in the Netherlands.
The approach exists of four main aspects:

System domain for Policies

The system domain applicable in this research situation is the energy market wherein energy prices arise from supply and demand. The development of energy production systems are part of the system domain as this factor influences the supply of energy. The boundary of the system domain is the Dutch energy market – APX power exchange. In chapter 3.2 the system domain will be described more extensively.

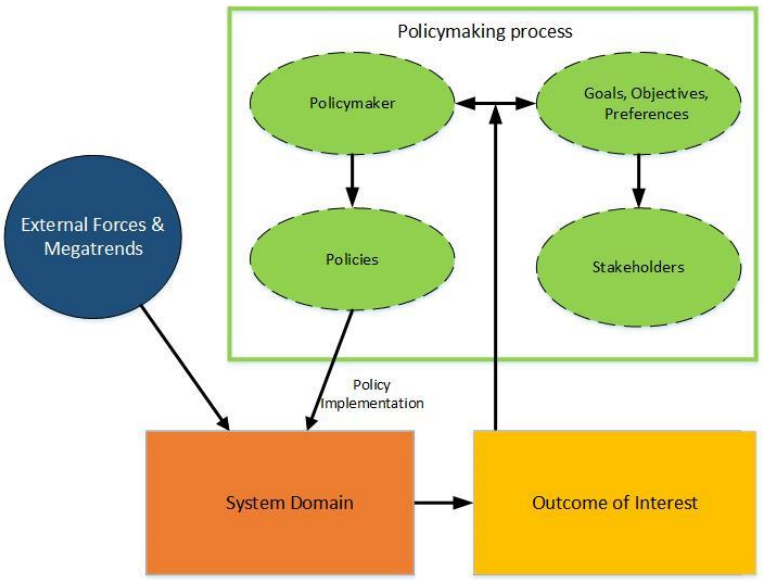

Figure 2.1 Elements in the Policy Approach Framework (adapted from Walker, 2000)

Outcomes of Interest

The goal for the Dutch government is to reach its set sustainability targets – to reduce 40% CO2-emissions compared to 1990 by 2030 and 27% of the energy supply should be produced sustainably. These targets should be reached without compromising the living standards and qualities for the citizens in the Netherlands (Ministerie van infrastrucutuur en Milieu, 2014).

Besides, the Dutch government should take the development of the electricity prices into account as this influences the investment environment and thus the development of the electricity production mix towards renewable sources.

External Forces

Besides short term factors – economic, technical or demographical – megatrends should be taken into account. This because megatrends – like population growth and wealth – are expected to influence the system domain over the longer term (KPMG, 2012).

Policymaking Process

The process of policymaking takes into account the stakeholders that have direct and indirect influence on the policies (e.g. the Dutch government and European Union, energy production companies, citizens of the Netherlands). Based on the goals, objectives and preferences of these stakeholders, new policies are built or old policies are adjusted by policymakers.

2.2 Overview of the study area

2.2.1 Electricity Market Design

In Figure 2.2, the design of the Dutch electricity system is shown. Since July 2004, this electricity market

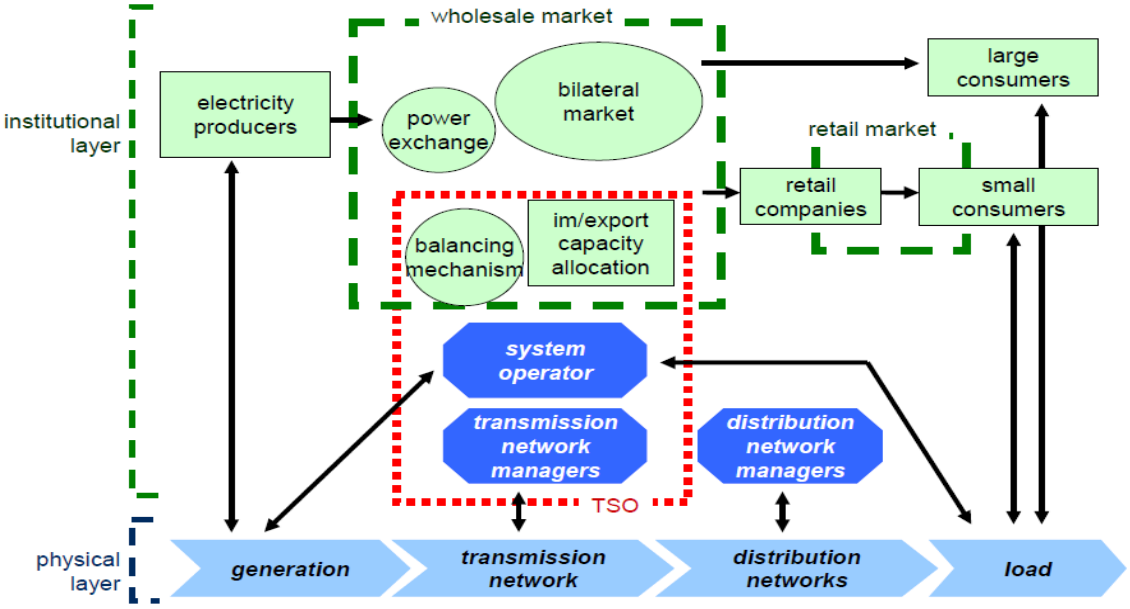

Figure 2.2 Schematic overview of the electricity system design (de Vries et al., 2010)

has been liberalized and competition in the generation of electricity has been introduced. Based on the electricity supply by the producers and the electricity demand of consumers, the price of electricity is determined in the hourly power exchange (APX). Next to hourly electricity prices on the APX spot market, electricity
producers close long-term contracts (mostly quarterly or yearly) with larger customers through the bilateral market (APX Group, 2015). This research will use the determination of electricity prices through supply and demand, since this method is not prone to social aspects – like negotiations – while long-term electricity contracts are. Besides that, the power exchange provides open data on the electricity prices while prices of long term electricity contracts are not available.

A Transmission System Operator (TSO) is responsible for the transportation of the electricity to the users and the stability of the electricity grid. The Dutch TSO – TenneT – is responsible for balancing mechanisms to stabilize the grid. Next to that, TenneT is the owner of the interconnectors between the Dutch and foreign electricity system. Through these interconnectors, import and export of electricity takes place (TenneT Holding B.V., 2014b).
A Distribution System Operator (DSO) is responsible for the stability of the local electricity network and transports the electricity form the high voltage network, through their lower voltage network, to the customers.
Both the TSO and DSO are government owned but the electricity that these organization transport are generated by energy utility companies, that are a part of an open market where competition determines the price of electricity – in the APX market.

Figure 2.4 indicates that the amount of electricity that is traded in the power exchange – short term market – is increasing. In 2013 more than half of the energy was traded through the short term market,

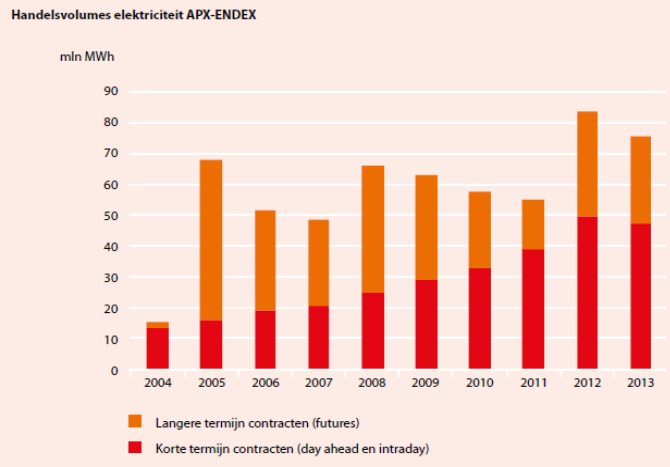

Figure 2.4 Short term (red) versus Long term (orange) (Energie-Nederland, 2014)

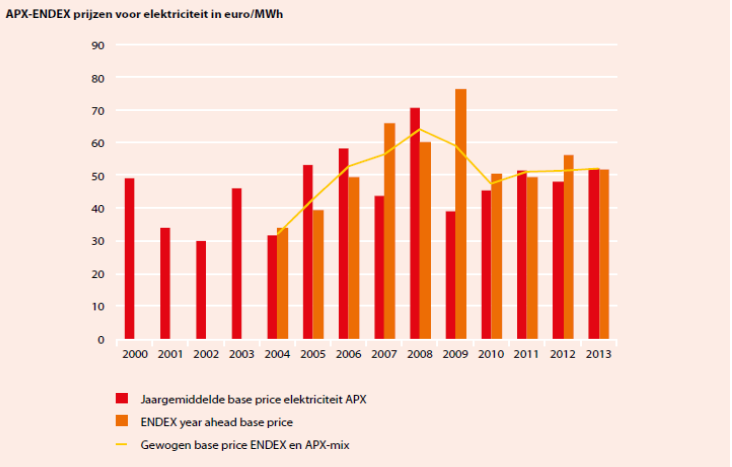

Figure 2.3 Average electricity prices short term (red) versus long term (orange) (Energie-Nederland, 2014)

while in 2005 about 20% got traded through the short term market.
The average electricity prices in the short term market and long term market are not the same, but Figure 2.3 shows that the difference of electricity prices between the two markets have been relatively small the last 5 years. A possible explanation for this is that the open data on the short term market has led to more transparency on hourly electricity prices and therefore have led to fairly equal long term electricity prices.

2.2.2 Power Exchange in the Netherlands

The change in supply of electricity, generated by the energy production companies, and the variation in demand of customers affect the electricity price.
Figure 2.5 represents the APX power exchange where the electricity price is determined through the supply and demand of electricity. The supply curve shows how much electricity is available and how much is produced by the different generation methods. Every generation method has a different cost price and the electricity producers determine on an hourly basis for how much they would like to sell their generated electricity per generation method. Normally, the hourly bids will be close to the marginal cost – the cost of producing an extra unit – per generation method. As can be

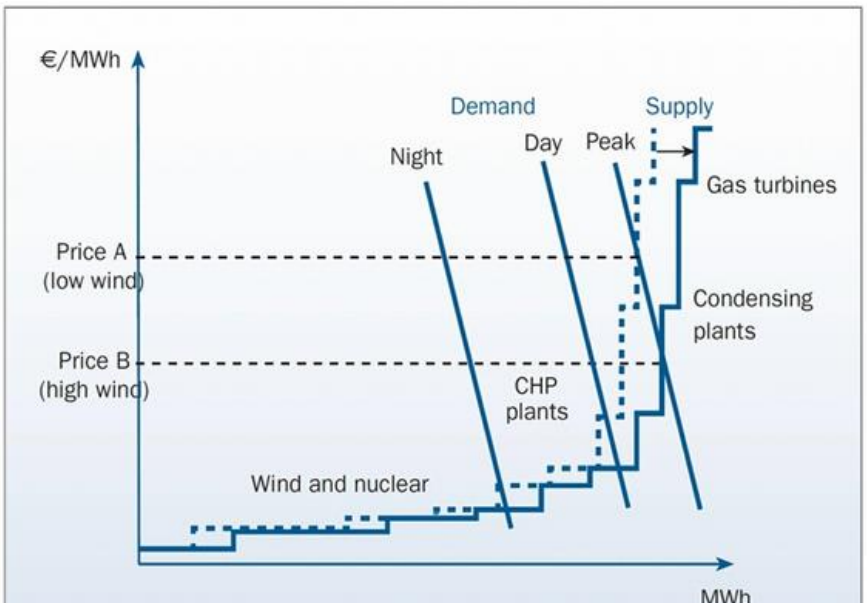

Figure 2.5 Merit Order – determination of electricity prices through supply and demand (Peak Oil, 2011)

seen in Figure 2.5, wind (and other renewables) and nuclear have the lowest marginal cost, while gas turbines have the highest marginal cost.

The electricity demand depends on the time of the day. Generally, there are peaks in demand during the morning and the evening and at night the electricity demand is fairly low. The angled demand curve indicates the price elasticity of electricity, the higher the price the lower the demand.
The electricity price is determined through the intersection of supply and demand. The intersection indicates the market price in a certain time period – the market clearing price.
From Figure 2.5 it can be seen that the change in the electricity generation will influence the electricity price. When more wind is available, the supply curve will move to the right and the market clearing price will become lower – see price A (low wind) and price B (high wind), during peak hours

2.2.3 System overview

In Figure 2.6 a schematic overview of the simulation model to explore the (future) electricity prices is given.

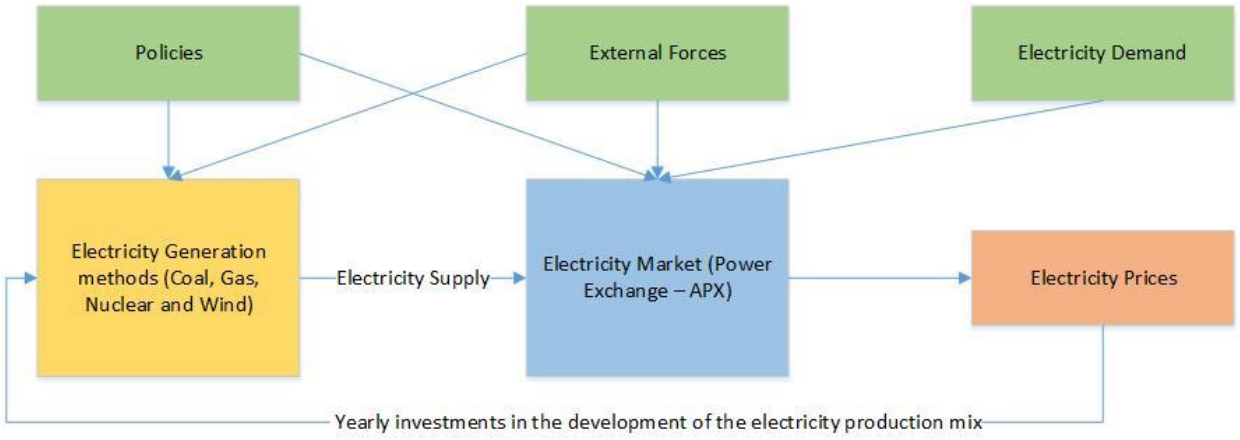

Figure 2.6 Schematic overview of the foreseen model

As stated earlier, the electricity prices influence the investment environment, since higher electricity prices provide more room to invest in the development of the production mix. This feedback loop – *Yearly investments in the development of the electricity production mix* – will play an important role in the long-term development, because further development of the production mix could increase the volatility of the electricity prices over the long term (e.g. towards 2030).

Research Approach

As stated earlier, the Dutch electricity system is a complex system. In order to analyze the system, the policy analysis approach of Walker (2000) shall be used to conceptualize the entire system. This approach takes the important elements influencing the behavior of the system into account. The four elements – shown in Figure 2.1 – will be identified based on literature.

System domain

The components of the system domain will be identified through literature. An important literature review of the Karlsruhe Institute of Technology will be used (Teufel, Miller, & Genoese, 2013).
In chapter 3 the approach in conceptualizing the Dutch electricity system is provided. A schematic overview of the conceptualized model will be given in that chapter.

Outcomes of Interest

There are two interest groups with different outcomes of interests. Firstly, the outcome that interest the Dutch government is to achieve the set sustainability target of reducing the CO2-emissions with 40% - compared to the emission level in 1990 – by 2030 and have adopted 27% of the entire production mix as renewable energy sources (European Commission, 2014a). The Dutch Government's main interest is the development of the electricity production mix and thereby reducing CO2 emissions. Therefore, the government will focus on designing policies that positively influence these factors. The iterative improvements of policies – based on the outcome of interest (e.g. CO2 reduction levels and renewable energy adoption) – will loop back into the System Dynamics model.

Secondly, the outcome that interests investors and energy production companies is the future electricity price development (e.g. uncertainty in the electricity market). Only when investments are feasible, they will invest in renewable energy and thereby help the Dutch government to achieve the set sustainability goals. Therefore, the main focus will be on the investors or energy production companies and the (future) electricity prices as these eventually determine whether the renewable energy sources get adopted – with input from the Dutch government through policies.

External forces

The electricity system is vulnerable to changes in behavior of external forces. Therefore the expected development of these forces towards 2030 need to be taken into account.

KPMG Sustainability group has done research into the field of the long-term effects. Based on the research, the company has identified ten megatrends that will influence the world in 2030/2050 (KPMG, 2012). The megatrends that may influence the electricity system are:

- Climate Change
- Material Resource Scarcity
- Wealth
- Ecosystem Decline
- Energy & Fuel
- Population growth
- Urbanization

The exact meaning of the individual megatrends, and to what extent the megatrends are influencing the electricity system and future electricity prices will be explained in chapter 3.

Policies

The Dutch government is constantly designing and adjusting policies to influence the electricity system in the right direction – towards reducing CO2-emissions. The effects of the already implemented policies have just led to a stabilization of the CO2-emissions. In order to decrease emissions further, the government focuses on stimulating development of a more sustainable energy production mix and discouraging CO2-emissions. The simulation model can be used to eventually test what kind of effects the different policies have when focusing on reduction of CO2-emissions, both on the demand and supply side.

2.3 System Dynamics

System Dynamics (SD) – introduced by Jay Forrester in the 1960s – is a well-established simulation modeling methodology for visualizing, understanding and analyzing complex dynamic feedback systems (Forrester, 1969). Elaborating on systems thinking, the methodology is able to analyze the cause-and-effect relationship among elements in subsystems and between subsystems within a dynamical system, based on computer simulation modeling. This is used to quantitatively analyze the structure of an information feedback system and the dynamic relation between structure and behavior of a system.
SD can reflect on the incorporated individual subsystems within a general framework and analyze their interactions. As policy responses are taken into account as well, the method can provide an holistic understanding of the entire dynamical complex system.

System Dynamics has been used in many areas, including:

- Urban Industrial Systems (Forrester, 1969; Forrester, 1971)
- Ecological systems (Kerem & Barlas, 2001)
- Environmental management and policy assessment (Dyson & Chang, 2005)
- Greenhouse Gas (GHG) mitigation (Anand, Dahiya, Talyan, & Vrat, 2005; Kunsch & Springael, 2008)
- Development of the energy industry (Bunn & Larsen, 1992)

The goal of this research is to explore the future electricity prices of The Netherlands towards 2030. A way to deal with uncertainties towards 2030 is to use Monte Carlo analysis – which is included in the System Dynamics Software. Hereby every external force in the System Dynamics model is simulated based on scenarios and a certain variation. Through this analysis, the resulting effect of a slight change of an external force on the electricity system can be tested.
Ford has been using System Dynamics to analyze many aspects of the electric power industry. His literature review on this subject – *System Dynamics and the Electric Power Industry* – is used as important literature throughout the thesis (Ford, 1997). Next to that, the System Dynamics model on the world's energy system of Davis and Simonovic (2009) is used as input.

Other simulation methods are not considered in this thesis, as a System Dynamics model of the Dutch electricity system is a way to analyze the macroscopic behavior of the system. One of the targets of this thesis research is to analyze megatrends – i.e. external forces that evolve over the longer term. As long term trends are analyzed, in combination with the analysis of a large complex system – The Dutch electricity system – a macroscopic analysis should be performed. The fact that System Dynamics provides insight – in a visualized way – in the system taking into account the dynamics of external influences makes it an interesting analytical tool. In this way different stakeholders are able to understand the System Dynamics model.
At the end of the research, the System Dynamics model will be compared with existing simulation models that could analyze future electricity prices of an electricity system as well. Thereby the strengths and weaknesses of the designed System Dynamics model can be defined, which can lead to recommendations to improve the model in future research.

2.3.1. System Dynamics: How it works

"System Dynamics is an approach to understanding nonlinear behavior of complex systems over time using stocks and flows, internal feedback loops and time delays" (MIT, 1997). Thereby it assumes that the complexity of the system originates from internal causal structures (Meadows & Robinson, 1985).

System Dynamics exists of three main concepts; feedback loops and stocks and flows. A feedback loop is a circular causal path of variables, where variables affect previous variables. An example is a population feedback loop, where an increase of births per year leads to an increase of the population, leading to more births per year – Figure 2.7. The causality of this feedback loop is positive as the variables in the feedback loop amplify each variable. If the feedback loop contains a negative causality it represents a negative feedback loop. In a negative feedback loop, an increase of a variable – like death rate – leads to a decrease of the population.

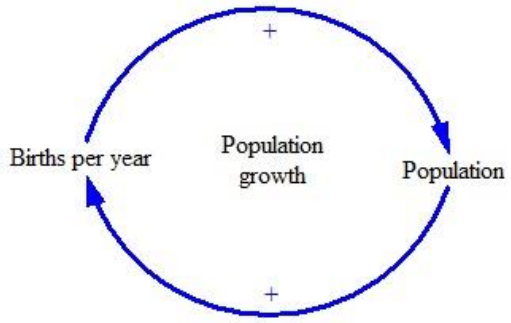

Figure 2.7 Population Feedback Loop

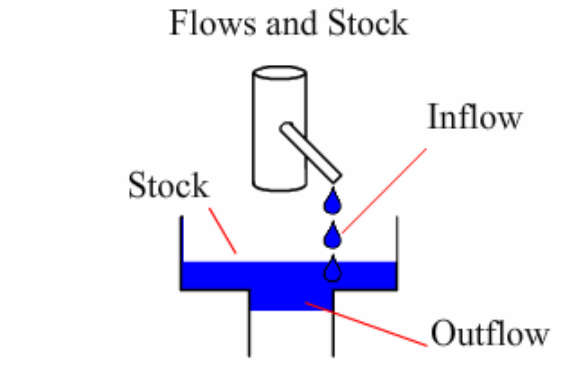

Figure 2.8 Stock and Flow Diagram

Figure 2.8 schematically provides an overview of a stock and flow diagram. A starting stock value represents the water level when time is zero. Depending on the inflow and outflow value, the stock will increase or decrease.

The representation of the Dutch electricity system could be modelled by building an extensive network of variables – containing stock variables like installed capacity per generation method and flow variables like the adoption of new production capacity of a certain generation method.

An important note – made by Sterman – is that all models are wrong since it is a simplification of reality (Sterman, 2000). However, it does not mean that models are useless, as it provides an approach to understanding the behavior of the real world. Based on historical data, the usefulness of a model could be determined. A part of the validation process is to compare historical behavior of the system with modeling data. The closer the output of the model to historical data, the better the representation of reality (in the past). Though, this does not guarantee a good representation of reality in the future, but it increases trust when the historical behavior is represented well. Another way to test the model is to assess the behavior of the model under extreme conditions. If the model behaves as expected during these circumstances, the confidence level of the mode would rise.

Due to validation purposes, the System Dynamics model of the Dutch electricity system will start in 2005. The model will exist of starting values from 2005 and output data after 2005 will be based on simulations of the model. The simulation data from 2005 to 2014, will then be compared to historical data in the validation process – Chapter 5. Once the model has been tested, simulations towards 2030 can be done. This data shall be used to identify a conclusion on the future electricity price towards 2030 in the Netherlands.

Part II–Conceptualization of the Dutch Electricity System

The simulation modeling process that describes the identification of a system and that describes how to implement the conceptualized model in System Dynamics will be used to conceptualize and to model the Dutch electricity system (Waveren et al., 2000). The simulation modeling process consists of a qualitative analysis, which results in an identification the important variables of a system and the relations between those variables. Also, the simulation modeling process has a quantitative analysis that determines which input data is required, which analysis data is needed and what the mathematical relations between the variables of the system are. Both aspects combined – qualitative and quantitative analysis – lead to a conceptual model design of the Dutch electricity system. The qualitative analysis leading to the conceptual system design is given in chapter 3. The quantitative part will be described in chapter 4. The information gathered from chapter 3 and 4 functions as input the foreseen System Dynamics model. Important parts of the System Dynamics model are provided in chapter 4. The details on the qualitative and quantitative aspects of the conceptualized model are given in appendix A, B, C and D.
The main literature used for forming a conceptual model of the Dutch Electricity system is from Davies and Simonovic (2009) – found through the literature review of the Karlsruhe Institute of Technology. In their report *Energy sector for the integrated System Dynamics Model for analyzing behavior of the social-economic-climate model,* they provide an SD-model on the worldwide energy system.

3. Qualitative Representation of the Dutch Electricity System

As described in chapter 2, the three aspects of the SD-model are the system domain, the external forces and policies influencing the system domain. The components of the system domain will be defined through the electricity market design of De Vries et al. – which was shown in Figure 2.2 (2010). Through literature research the external forces and policies influencing the electricity system are defined.
Each component of the electricity system model is described in a separate section.

3.1 Model Assumptions

Before conceptualizing the Dutch electricity system, the most important assumptions of the foreseen System Dynamics model are provided. Within these boundaries the simulation model will be built and simulated.

Generation methods in the Dutch electricity system

To reduce complexity it is also assumed that the generation capacity for electricity in the Netherlands only consists of four generation methods. To reduce complexity the different generation technologies for gas electricity production have for example not been taken into account. Various gas electricity generation technologies exist, which differ in efficiency and characteristics. An open-cycle gas turbine is for example more expensive in LCOE then Combined Cycle electricity production. To reduce complexity, gas electricity production has been generalized. The determined direction coefficient to create a difference in marginal cost between produce MWs of the same generation methods, has a positive influence on this assumption. This because the difference in marginal cost of different generation technologies have been taking into account. Solar electricity production is a sustainable source that has not been taken into account. First of all the research is focused on wind energy, but for simulating the electricity system solar electricity should be taken into account. However, it is assumed that solar electricity production is done off grid - decentralized. In this way, this assumption could be justified.

Import and Export of electricity is always possible

The system boundaries of this research were chosen to be the geographical boundaries of the Netherlands. However, electricity systems (of different countries) are connected to each other. The different electricity systems work together to stabilize the electricity grids. A surplus in one electricity system could help to solve a shortage in another system. More realistically, the electricity systems of neighbor countries of the Netherlands would be simulated as well to determine the available electricity for export or the required electricity import. Besides, simulations of electricity systems of neighbor countries would determine the electricity prices in the different countries - which influence each other's electricity prices. However, simulating these neighbor countries' electricity systems would make the model too complex for this research as the size of the SD-model would double when adding another electricity system. To reduce complexity, it is assumed that electricity is always available to import and electricity could always be exported when a surplus occurs.

Taking into account the lower electricity prices in Germany

As the electricity system of neighbor countries is not simulated in the model, electricity prices of neighbor countries are not determined as well. Data on electricity prices of different countries show that the electricity price in Germany is structurally about 20% lower than in the Netherlands (explained in Appendix B.3.). This means - as it is assumed that export and import electricity are always available - that it would lower the Dutch electricity prices with 20% as well. This because electricity prices from Germany compete well with the generation capacity in the Netherlands. Obviously, in the real world, this is much more complex since the amount of available electricity for import and the number of times this is available plays an important role. Since no simulations of the neighbor countries' electricity systems are made, the real influence of electricity import cannot be determined. Therefore it is assumed that using an import factor over the electricity prices would be a simplified and well-working substitution. However, research needs to be done to check this assumption.

3.2. System Domain

This section explains every component of the core system domain in more detail, focusing on the role of the component within the system domain. It starts with the power exchange as most components – electricity demand and electricity supply – influence this subsystem. The electricity supply arises from the

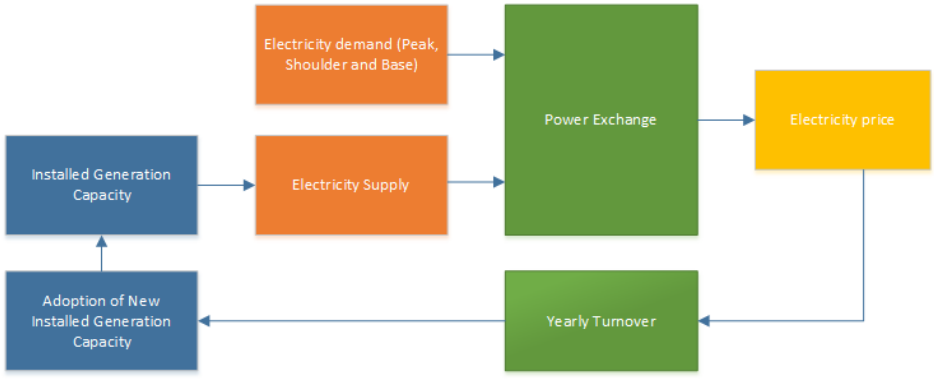

Figure 3.1 Schematic overview components of the Conceptualized Model

installed capacity of generation capacity. The power exchange determines the electricity prices, which influences the yearly turnover and the available investment budget to adopt new generation capacity.

In the table below, the definitions of the components – shown in Figure 3 – are given.

Subsystems of the Dutch electricity system	Definition
The Power Exchange	Determines the hourly electricity price through demand and supply (€/MWh)
Electricity Demand	The desired hourly electricity volume (MWh)
Electricity supply	The hourly available electricity (produced and imported) (MWh)
Installed Capacity	Electricity Generation Capacity (MW)
Yearly Turnover	Sold electricity times electricity price (€)
Adoption of Installed Capacity	Made investments in new generation capacity (MW)

The Power Exchange

The basis of the system domain is the power exchange that determines the electricity price based on the supply, demand and the marginal cost of the different generation methods considered in this research (coal, gas, nuclear and wind).

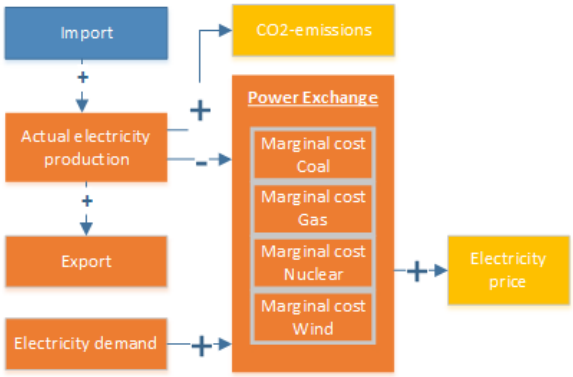

Figure 3.2 Conceptualized Model – Power Exchange

The electricity prices are determined through the merit order – explained in chapter 2.2.2. The hourly prices fluctuate through changes in supply and demand. Next to that, coal, gas and uranium prices influence the marginal cost, as well as the cost of CO2-emissions determined through the European Emissions Trading System. These external forces influencing the electricity price will be touched upon in chapter 3.2.

When supply increases, electricity prices go down in general. If demand increases, prices go up. The more electricity produced by coal and gas power plants, the higher the CO2-emissions.

Electricity produced in neighbor countries and then exported to the Netherlands, does not affect the total CO2-emissions of the Netherlands. The electricity produced in the Netherlands and then exported to neighbor countries does affect the CO2-emissions of the Netherlands. Therefore, export to neighbor countries is part of the system domain and import is an external force.

Electricity prices in neighbor countries could influence the Dutch electricity price, but this falls out of scope in the SD-model of this thesis.

How the electricity price will be determined in the model will be explained in the quantitative part – in chapter 4.

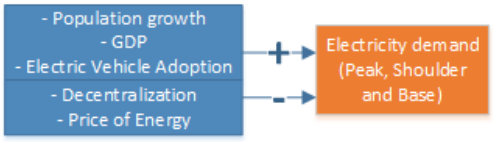

Figure 3.3 Conceptualized Model – Electricity Demand

Electricity Demand

Electricity demand fluctuates constantly. In order to take these hourly fluctuations of electricity demand into account, while modeling on a yearly basis, the different demands over the year are split up into phases. Chapter 4 will elaborate on

the Load Duration Curve – hourly demand per year – and why and how the different demand phases are added to the System Dynamics model.

Figure 3.3 shows that the electricity demand is only dependent on external forces. This means that the fluctuations of the electricity demand is caused by the dynamics of external forces. The meaning of these external forces and how they influence the electricity demand will be explained in chapter 3.3.

Actual Electricity Supply

The actual electricity production is dependent on the generation efficiencies of the generation methods, the desired amount of electricity supply every day and on the actual wind energy generation – dependent on the availability of wind – which varies constantly. In chapter 3.3 these external forces are discussed in more detail.

In this research four different generation methods are taken into account; Gas, Coal, Nuclear and Wind. All generation methods have different characteristics and thus for each method will be dealt with differently in the SD-model. Nuclear and Coal production capacity are inflexible sources that cannot be turned on and off quickly. Next to that, the investment costs are relatively high but the variable cost are relatively low. Therefore, it is financially most interesting for energy utility companies to have those plants running most of the time to cover the high fixed cost.

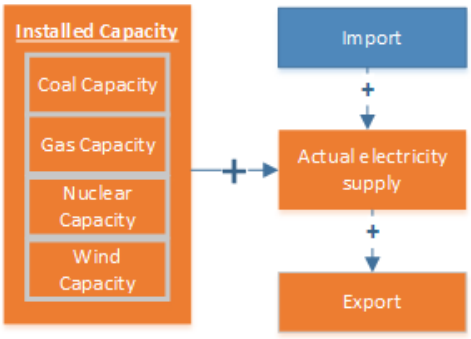

Figure 3.4 Conceptualized Model – Electricity Supply

Gas production capacity is a flexible source that can be switched on and off quick and efficiently. The investment cost are relatively low but the variable cost are high. Therefore gas production capacity is used when electricity demand is high and when shortages of electricity need to be covered.

Wind electricity production is dependent on the availability of wind. As this is unpredictable, the supply of wind electricity is also unpredictable. During times with a high availability of wind, the electricity production through gas power plants will be ramped down. When there is low availability of wind, gas production will be ramped up.

The investment cost in wind production capacity are relatively high, but the variable costs are close to zero.

Export and import are taken into account in the model, however it is assumed that only electricity is imported or exported when there is a shortage or surplus of electricity in the market. In chapter 3.2 the import and export variables are discussed in more detail. Explicit focus is put on the cost of imported and exported electricity. The model describes whether electricity is transferred from or to neighbor countries of the Netherlands.

Installed Capacity

The mix of installed production capacity changes over time. Old, unreliable power plants are demolished, new installed capacity is constructed to replace demolished power plants and to cope with increasing electricity demand. The section 'Adoption

Figure 3.5 Conceptualized Model – Electricity Supply

of Installed Capacity' will elaborate more on the development of installed capacity.
The installed capacity affects the actual electricity supply – e.g. more installed capacity enables generation of more electricity and thereby lowering the price. An important factor in determining which generation method and how much of its installed capacity will deliver electricity is the marginal cost – the cost for producing an extra megawatt. The lower the marginal cost of a generation method, the more preference it has over other generation methods in the power exchange. Therefore, it is of great importance that energy utility companies renew their installed capacity once older power plants lose advantage over technologically-developed power plants with lower marginal cost.
The marginal cost of wind electricity are the lowest, followed by Nuclear, then Coal and finally gas electricity. Installed capacity in neighbor countries is important to take into account in the model as well, since those electricity prices also influence the electricity prices in the Netherlands through import. Germany has a large volume of renewable energy source and thereby the electricity price is relatively low when wind and solar are available. When there is a high availability of wind and solar, a surplus of electricity will most likely occur resulting in more export of cheaper electricity to the Netherlands.

Yearly Turnover and investment budget

The yearly turnover of all the energy utility companies in the Netherlands, is calculated by multiplying the hourly price of electricity – which is an output of the power exchange – with the number of hours per year.
As the fluctuations of electricity demand will be taken into account by dividing the demand into phases (explained in the next chapter), the power exchange results in different hourly electricity prices for these phases. These prices are multiplied by the number of hours in a certain phase. The sum of these multiplications will lead to the yearly turnover for the Dutch energy utility companies. As shown in Figure 3.6, an increase of electricity price leads to a higher revenue.

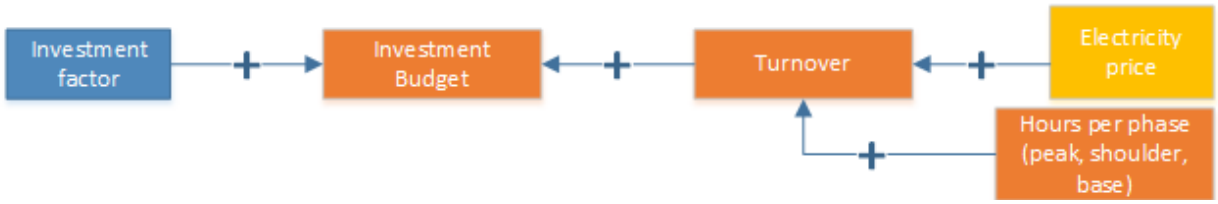

Figure 3.6 Yearly Turnover and Investment Budget

A percentage of the total revenues will form the available investment budget, which will partly be used to adopt new power plants or wind parks. A high electricity price will lead to a higher revenue, a higher revenue leads to a higher investment budget and a higher investment budget leads to more development or improvements of the electricity production mix.
An alternative to determine this investment budget is through taking a percentage of the calculated profit of the Dutch electricity system. The profit is then calculated by subtracting the fixed and variable costs from the revenue. The advantage of this approach is that the cost of power plants not generating electricity – due to their high marginal cost – are taken into account in the model.

A third way energy utility companies obtain investment budget is through loans from banks or investors. This method is left out initially to study how the model behaves without external financing. If the validation process it turns out external financing is needed for a correct simulation, this will be added to the model.

Which of the two methods to determine the investment budget works best will be determined during the validation process in chapter 5. External financing could be added if necessary.

Adoption of Installed Capacity

Investments in new generation capacity fall under the Adoption of Installed Capacity. Development of the installed capacity is in the first place needed to replace power plants that are to be destructed due to financial infeasibility or unreliability after the power plants' life time. Other reasons are for example to respond to expected electricity demand increase or to development more cost competitive power plants. Financial factors play an important role in determining which and to what extent generation methods to adopt. In the System Dynamics model the four generation methods will be compared – from the financial perspective – through the Levelized Cost of Electricity (LCOE). In chapter 4, this method for comparison will be further explained.

Another factor is the affinity with each of the generation methods. This is important for allocating the investment budget for the generation methods. The carbon intensity is a vital aspect for the affinity factor influencing an investment decision. Also, this factor will be addressed more extensively in the next chapter.

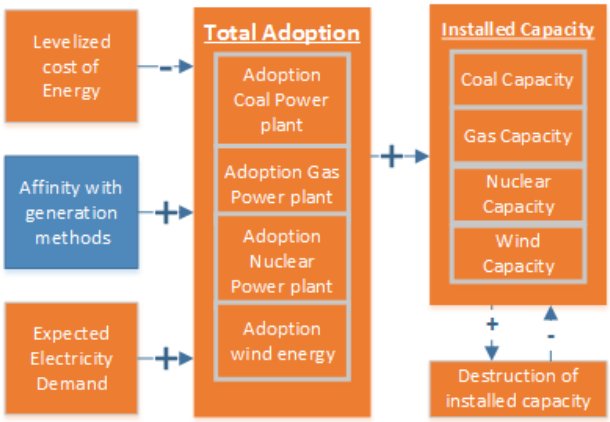

Figure 3.7 Installed Capacity Dynamics

In addition to the financial and affinity factor, adoption of new generation capacity is based on the expected electricity demand.

Figure 3.7 provides an schematic overview of the dynamics of installed capacity. The adoption of new capacity depends on the cost and the affinity with a generation method. If the LCOE of a generation method decreases, it is more likely it will be adopted. The causal relation between affinity and adoption is positive, if the affinity increases the adoption increases. Similarly a positive causal relation exists between the adoption and destruction of capacity, thereby influencing the total installed capacity.

Complete Conceptual Model

Figure 3.8 provides an overview of the complete conceptual model, including the external forces (blue) and the policies (green). The orange components have been discussed in chapter 3.1. In the next section (chapter 3.2), external forces and policies influencing the system domain are discussed. Chapter 4 describes the relations between the variables quantitatively and provides insight on how the conceptual model is eventually implemented in System Dynamics.

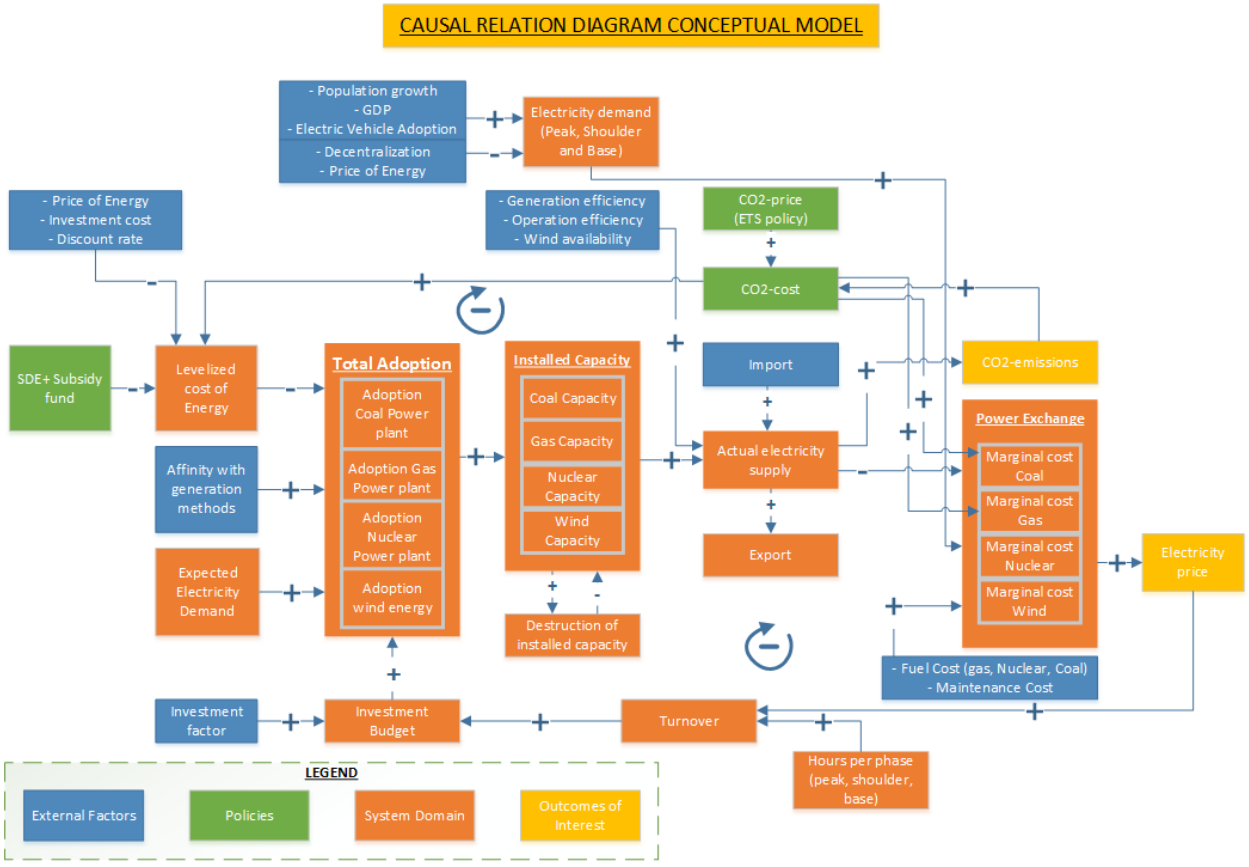

Figure 3.8 Complete Conceptual Model of the Dutch electricity System

3.2 External Forces and Policies

This section provides information on the external forces and policies that interrelate with the components of the system domain. Based on literature, assumptions of the development of the external forces and policies have been made. How the assumed scenarios develop towards 2030 is shown in Appendix E.
The external forces and policies that are discussed in this section are the following:

The Power Exchange
- Fuel Cost (Gas, Nuclear and Coal)
- Maintenance Cost

Electricity Demand
- Gross Domestic Product (GDP)
- Price of Energy
- Population Growth
- Decentralization
- Electric Vehicle Adoption

Actual Electricity Supply
- Generation Efficiency
- Operation Efficiency
- Wind availability
- Import of Electricity from Neighbor Countries

Adoption of Installed Capacity
- Affinity with generation methods
- Levelized Cost of Electricity (LCOE)
- GDP
- Future Energy prices (Gas, Coal, Uranium)

Yearly revenue and Investment budget
- Investment Factor

Policies Influencing the Dutch Electricity System
- SDE+ Subsidy Fund (Dutch Government)
- European Trading Scheme (CO2-price)

3.2.1 External Forces

The Power Exchange

The power exchange is a representation of the APX electricity market – shown in chapter 2.2.2. The merit order represents the actual supplied electricity to the power exchange and for which price each MW could be sold. Generally, the selling prices will be close – if not exactly – to the marginal cost of the generation method that produced one megawatt electricity. The marginal cost of wind electricity is the lowest, followed by Nuclear, then Coal and the highest marginal cost are that of Gas power plants.
The marginal cost of the generation methods is determined by two external factors. The fuel cost for the production of an extra megawatt and the variable maintenance cost per megawatt. Maintenance cost is an external variable that is relatively stable. On the other hand, the fuel cost (i.e. gas, coal and uranium) could fluctuate heavily.
As the fuel cost have a high impact on the marginal cost, it has a tight connection with the electricity prices.
Another external force that influences the marginal cost, and thus the power exchange, is the price for CO2. This is a policy measure – Emission Trading System (ETS) – and will be explained in the next section.

Electricity Demand

Gross Domestic Product (GDP)

The electricity demand depends on the customers of the energy utility companies, which are large consumers (i.e. companies, factories) and small consumers (i.e. households). During periods of higher economic activity, large consumers demand more electricity as they produce more (Seng Leung et al., 2005). Besides, households have more money to spend during economic prosperity and will use more electricity. Therefore, the Gross Domestic Product (GDP) of The Netherlands is added as an external force influencing the electricity demand.

The effect of energy price increase influences the electricity demand as well. Demand decreases when oil, gas-, coal- and nuclear-prices increases, as the marginal cost of each generation method – except Renewable Energy Sources – goes up and thus the electricity price goes up. Next to that, the amount of money that households and company could spend decreases when energy prices go up.

Population

According to de Vries & Janssen the electricity demand is highly dependent on the size of the population (De Vries et al., 2002). Population growth is determined as one of the important megatrends to 2030 (KPMG, 2012), which makes this external force an variable to take into account for modeling the SD-model to 2030.

Decentralization

Decentralization is another trend and means that companies and household are becoming more and more prosumers – producers and consumers of electricity at the same time. This negatively influences the electricity demanded from the central grid. Next to that, the electricity generated and consumed locally does not affect the power exchange.

Electric Vehicles

One of the promising ways for the Dutch government to reduce carbon emissions is to stimulate electric vehicle (EV) adoption. The Dutch government has set targets to have adopted 1 million Electric Vehicles by 2025. Reaching this target will affect the electricity system, as electricity demand will thereby increase – even though a part of the electricity will be generated on a decentralized basis. Having adopted 1 million EV's implies the need for a large electricity storage capability as well, which could support the electricity system on the supply side. Though, due to the complexity of (the development of) energy storage, this positive factor will fall out of scope and should be researched in future research.

Assuming that by 2025 1 million EV's would have been adopted (Rijksoverheid, 2014), with a battery capacity of 85 kW (Tesla, 2015) – just like the Tesla S model nowadays – it would translate to a maximum daily storage capacity of 85 GW. Compared with an average daily electricity demand of 280 GWh – based on yearly electricity demand data of 2015 – this is about 30% of the daily electricity demand.

EV adoption is a random example, but it symbolizes unknown technology developments that could be developed the upcoming 15 years.

Actual electricity supply

The actual available electricity supply is dependent on the available generation capacity and the amount of electricity that is imported from neighbor countries.

The available generation capacity is determined based on three external forces:

- The capacity factor – the generation efficiency of a power plant or wind mill.
- The operation efficiency – the number of hours per year the power plant or wind mill could run.
- Wind availability – the more wind, the more electricity generation.

The next chapter will provide the different generation efficiencies of the generation methods.

Wind availability

The wind availability only influences the wind electricity production and has an effect on the capacity factor of installed wind capacity. From a technical perspective, this factor is not constant over time – contrarily to the Coal, Gas and Nuclear electricity production.

Figure 3.9 provides a typical wind pattern in IJmuiden – a coastal town in the Netherlands. This graph shows the volatility of wind speed and thus the high volatility of wind energy production. These wind patterns are taken into account in the System Dynamics model.

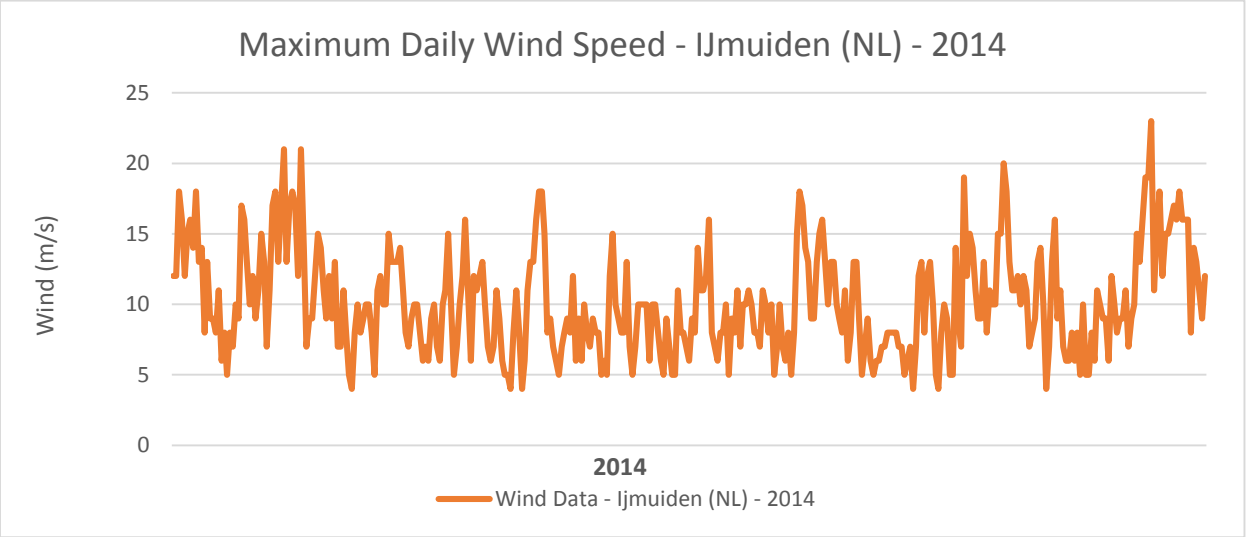

Figure 3.9 Wind pattern example in IJmuiden - The Netherlands (KNMI, 2015)

The volatility shown in Figure 3.9 will be taken into account in the System Dynamics model. 10 years of historical wind data show that the average wind speed is 7.2 m/s. Next to that, it indicates that the wind around IJmuiden follows a normal distribution. The standard deviation is 3.7 m/s. Through a Monte Carlo analysis and this normal distribution, the volatility of wind electricity production can be taken into account.

In times of low wind availability, other generation methods should absorb the shortage of wind energy production in order to meet the demand of electricity. Contrarily, in times of high wind availability, other generation methods should ramp down production in order to prevent an abundance of electricity in the market leading to lower electricity prices.

Electricity Import

Another external force which influences the actual electricity supply is the import of electricity from other countries through the interconnector network – which is owned by TenneT. Import shall is only done to meet the electricity demand when the Dutch installed capacity cannot generate sufficient electricity. The import variable is left out of the system domain – but is added to the model as an external force – as the

System Dynamics model would otherwise become too complex for this research – looking from a time perspective.
The output of the allocation function in the System Dynamics model are values given to each generation method, meaning how much each method delivers to the power exchange. In this way the different steps in the merit order are determined.

Adoption of Installed Capacity

The installed capacity depends on the preferences of generation methods and the investments made in the development of capacity. Next to the preferences and investments, the market determines to a large stake which investments should be made – as only the most competitive installed power plants will survive in the market.

Factors influencing the installed capacity are the adoption of new capacity or the destruction of power plants or wind parks, which are part of the System Domain and do not count as external forces.
The external forces that do influence the installed capacity are:

- The construction times (in year) of new generation methods
- The life time of a certain generation method
- The decision of the energy utility company to destruct the power plant or shut it down for a while – when there is over capacity and thus a low financial feasibility.

The exact numbers that will be used for these aspects in the System Dynamics model are discussed in the next chapter.

Affinity with generation methods

The adoption of new generation capacity is prone to the affinity an energy utility company (or an investment company) has with a certain generation method. The affinity consists of non-financial factors, like the CO2-intensity of a generation method. Although the affinity factor cannot contain all the social aspects influencing an investment decision – because social factors are too complex – an attempt will be made to merge it into one (affinity) factor. This factor shall be tested in the validation phase to make sure that the affinity factor is set correctly.
The affinity factor is not a fixed variable that influences the model the same each year – it is time dependent. For example, after the nuclear disaster of Fukushima in Japan on the 11th of March 2011, the affinity for nuclear energy decreased significantly (Corradini, 2011). The German government decided to phase out all nuclear power plants, even though about 25% of its electricity was obtained through nuclear energy in March 2011. Estimations of the German government show that approximately one trillion euro is needed to finance this transition (World Nuclear Association, 2014).

Levelized Cost of Electricity (LCOE)

The external forces influencing the adoption of capacity on the cost side – how much and which generation methods – is determined through the Levelized Cost of Electricity (LCOE).
The LCOE is a method to financially compare the different generation methods with each other.

The LCOE is determined through the cost of energy (Gas, Coal or Uranium), required to generate one megawatt electricity. Besides, the investment cost and discount rate are taken into account. The formula

of the LCOE is not added to the SD-model, but through literature the LCOE's of the different generation methods have been determined.

GDP and (future) energy prices

Other external forces influencing the investment environment are the economy and the (future) energy prices (i.e. oil, gas, coal and uranium) (Department of Energy & Climate Change, 2013)
Within an uptrend economy, more investments are made compared to investments in a downtrend economy. Therefore, the System Dynamics model for investment decisions is connected to the GDP of the Netherlands.
The (future) energy prices are analyzed for an investment decision, since it influences the (future) marginal cost of generation methods. A possible rise of marginal cost could negatively influence the competitiveness of a generation methods when other methods are not exposed to a rise in cost.

The last important variable – which is not an external force, but it influences the adoption – is the expected future electricity demand. When the installed capacity is sufficient to deliver the demanded electricity (e.g. overcapacity in the electricity market), then it is less likely that energy utility companies would invest in new capacity. Though, when there is a shortage of installed capacity, more investments in capacity development will be made.

Yearly Turnover and investment budget

An external force that positively influences the yearly turnover is the earnings from exporting electricity. It is assumed that all the electricity that is not been sold internally through the power exchange, will be exported to other countries.
Another external force is the Investment Percentage, which determines the Investment Budget based on the yearly turnover (or profit – depending on what turns out to be best in the validation). Through literature and by comparing the investments in the model with historical data, the Investment Percentage will be determined.

A higher investment budget will lead to a higher ability to develop the installed capacity to a more sustainable production mix.
When the investment budget is not sufficient, the model will show a lack of renewable energy source adoption. This could indicate that the Dutch government should support the electricity system – through policy making – stronger.

3.2.2 Policies

SDE+ Subsidy Fund – Subsidy Renewable Energy

The SDE+ (Stimuleringsregeling Duurzame Energieproductie – to stimulate policy Sustainable Energy generation) subsidy is a policy designed by the Dutch government to stimulate renewable energy sources. It started on the 1st of January 2008. The predecessor of the SDE+ subsidy is the MEP (mileukwaliteit elektriciteitsproductie – Environmental quality electricity generation), but the policy was stopped in 2006 since the subsidy did not provide the right investment incentive (Rijksdienst voor Ondernemend Nederland, 2014). As the foreseen SD-model starts in 2005, the MEP subsidy has not influenced the adoption of wind energy much and therefore this policy is not taken into account. This means that the

subsidy policy from 2005 to 2007 will be inactive in the SD-model. From 2008 on, the subsidy is active and leads to a lower LCOE of wind and therefore a higher adoption of wind energy capacity.
The assumption of not taken the MEP subsidy into account, will be tested in the validation phase. If from the validation could be concluded that MEP subsidy did have effect, then it could be added later on anyway.

Emission Trading Scheme (ETS)

The European Union Emissions Trading Scheme ((EU) ETS), was launched in 2005 to combat climate change and reduce CO2 emissions. It is the first large greenhouse gas emissions trading scheme in the world, and it is currently the largest (Ellerman & Buchner, 2007). Since 2013, the ETS covers more than 11,000 factories, power stations, and other installations having a net heat excess of 20 MW in 31 countries (all 28 EU member states and Iceland, Norway, and Liechtenstein).
The ETS functions like a 'cap and trade' principle. The total amount of greenhouse gases that are allowed to be emitted by all participating installations are set as cap (European Commission, 2014c). Based on the cap, CO2 allowances for emissions are auctioned off or allocated for free, and can be traded. All installations must monitor their CO2 emissions and report their CO2 emissions, and should assure that they hand in enough allowances to cover their emissions. If the installation's emissions exceeds the permitted allowances, it must purchase allowances from others to cover the emissions. Contrarily, if the installation performed well and kept emissions below the permitted allowances, then the installation can sell its allowances.
The idea of this system is to find the most cost-effective way to reduce emissions without significant governmental intervention.
Currently, the third trading period of allowances is in progress, which runs between January 2013 to December 2020. Compared to the first trading period (2005 – 2007), the available allowances for 2020 have been reduced by 21%. The price per CO2 allowance has been lower than intended. This is caused by the surplus of allowances which is mostly due to the economic crisis that led to lower CO2 emissions.
On the 4th of January, CO2 allowances for 2013 traded on the London's ICE Future Europe exchange for between €6.22 and €6.40 per allowance – one allowance permits one ton of CO2 emissions. The minimum price per allowance – €2.65 – was reached on the 24th of April in 2014. Currently, the price €6.82 – on the 3th of March 2015. Figure 3.10 shows the CO2 allowance price of the period 2012 to 2014.

Figure 3.10 CO2 allowance price - London's ICE Future Europe Exchange (EEX, 2015)

Through historical data and literature on future scenarios on the expected development of CO2 prices, a scenario on CO2 prices towards 2030 will be added to the model. For the Monte Carlo analysis an uncertainty factor will be added to this scenario in order to (partly) deal with uncertainties towards 2030. How the CO2 prices are taken into account in the System Dynamics model is explained in the next chapter.

Uncertainty factors of External Forces and Policies

To model the external forces and policies towards 2030, uncertainty factors should be taken into account for the assumed scenarios of the external forces and policies as it is uncertain how these variables will development and as they could deviate from the assumed scenarios. The assumed scenarios are based on literature research, however limited literature is available on the uncertainty factors of these determined scenarios in the research. Therefore an assumption has been made on the uncertainty factors, which has been set at 10% variation of all external forces and policies following a random uniform distribution. Expect for the wind speed variation, which has been determined through calculations based on 10 years of historical wind data.

Assuming that all external forces and policies have an uncertainty factor of 10% is a limitation to this research and future research is required to determine more realistic uncertainty factors, but for this research it is just not known. Even a brief research on the individual uncertainty factors has not been done in this research, as it is also not known how certain external forces or policies influence each other. Certain external forces and policies could strengthen or weaken each other, leading to incorrect uncertainty factors as only the individual uncertainty factors of each external forces has been studied. Therefore it is assumed that all uncertainty factors – expect for the wind speed variation – are the same. In this way, incorrect assumptions due to interrelated influences of external forces are not made since all uncertainty factors are the same.

4. Quantitative Representation of the Dutch Electricity System

This chapter describes the available data and quantitative analysis on the Dutch electricity system, which is used as input for developing the electricity market System Dynamics model. The quantitative analysis is based on the information gathered in the qualitative analysis in chapter 3.
The SD-model is split up into six components. The data and mathematical relations of the external forces and policies influencing each of these components are shown. In this part an overview is given on which data is used as input data and which data is used to validate the System Dynamics model.
Based on the information gathered in chapter 3 and 4 – that has led to the conceptual model of the Dutch electricity system – the model can be implemented in System Dynamics Software to support the mathematical relations, the main parts of the SD-model and the formulas behind the model will be discussed.
In chapter 5, the System Dynamics model is tested based on the data provided in this chapter.

4.1 Quantification of the System Dynamics model

In order to quantitatively describe the foreseen System Dynamics model, it will be divided into six parts. The external forces and policies connected to the parts will be taken into account. This is because they are part of the formulas describing the mathematical relations between the variables. The conceptual model will be divided in the following six parts:

- The Power Exchange
- The electricity demand
- The electricity supply
- The installed capacity
- Yearly turnover
- Adoption of installed capacity

4.1.1 The Power Exchange

The specific data on hourly electricity prices is not available for this thesis as the data is foreclosed. Though, the average yearly electricity prices are available and shown in Figure 4.1. The hourly electricity prices may fluctuate from the data given in Figure 4.1, but it gives an indication on the macroscopic trend of the average yearly electricity prices of the power exchange.

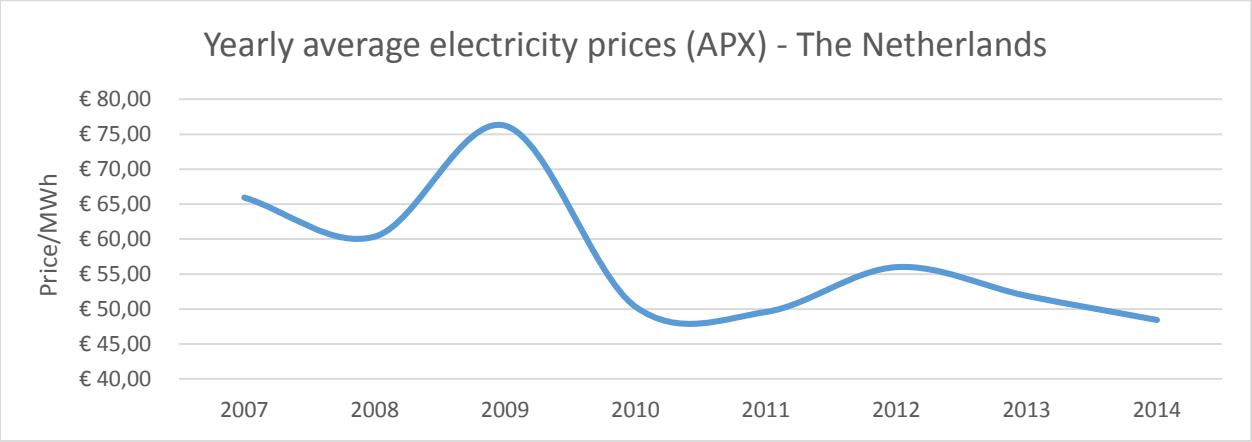

Figure 4.1 Yearly average electricity prices (APX) - The Netherlands (Letter Henk Kamp, Minister Economic Affairs, 2013)

The formula behind the determination of the hourly electricity prices is based on an IF-function – called the IF THEN ELSE function in Vensim. This is necessary since the generation methods with the lowest

marginal cost get priority. Also, every step in the merit order needs to be calculated separately. Thereafter, the different steps can be combined into one aggregated electricity graph. Below the formulas behind the electricity price determination System Dynamics model are given.

$$Merit\ Order\ [step\ 1: Wind] = IF\ THEN\ ELSE(ED > EP[Wind], 0, MC[Wind])$$

$$Merit\ Order\ [step\ 2: Nuclear] = IF\ THEN\ ELSE(ED > (EP[Wind] + EP[Nuclear], 0, MC[Nuclear])$$

$$Merit\ Order\ [step\ 3: Coal] = IF\ THEN\ ELSE(ED > (EP[Wind] + EP[Nuclear] + EP[Coal], 0, MC[Coal])$$

$$Merit\ Order\ [step\ 4: Gas] = IF\ THEN\ ELSE(ED > (EP[Wind] + EP[Nuclear] + EP[Coal] + EP[Gas]), Cost\ of\ Import, MC[Gas])$$

ED[y] = Electricity Demand (MW)
EP[y,x] = Actual Electricity Production (MW)
Y=electricity demand phase (Base, Shoulder, Peak)
MC[x] = Marginal Cost per Generation Method (Euro/MW)
X = Generation Method

The formulas are set up in such a way that when the demand can be matched through a certain generation method, the marginal cost of the generation method will become the electricity price. The four steps represent the four steps of generation methods in the merit order, with wind as the first and gas as the last (Figure 4.2). For example in the first step; when the electricity demand is smaller than the electricity production of wind – so all the electricity could be delivered by wind electricity production – then the marginal cost of wind becomes the electricity price. If the electricity demand is larger than the electricity production of wind, then the marginal cost of wind does not determine the electricity price and the next step (of nuclear) needs to be taken. The output of the formula in step 1 will be zero, expect for the fourth formula. When gas cannot supply all the electricity that is demand, electricity should be imported. It is assumed that the price of import equals the electricity price in the Netherlands. Later in this section more information on this is provided.

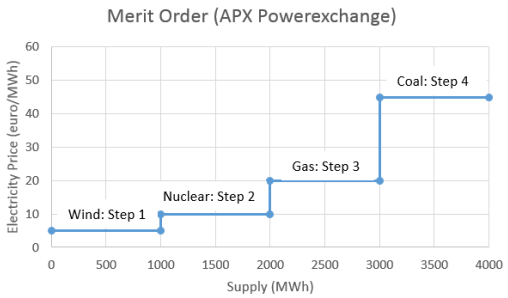

Figure 4.2 Merit Order Steps in the Power exchange

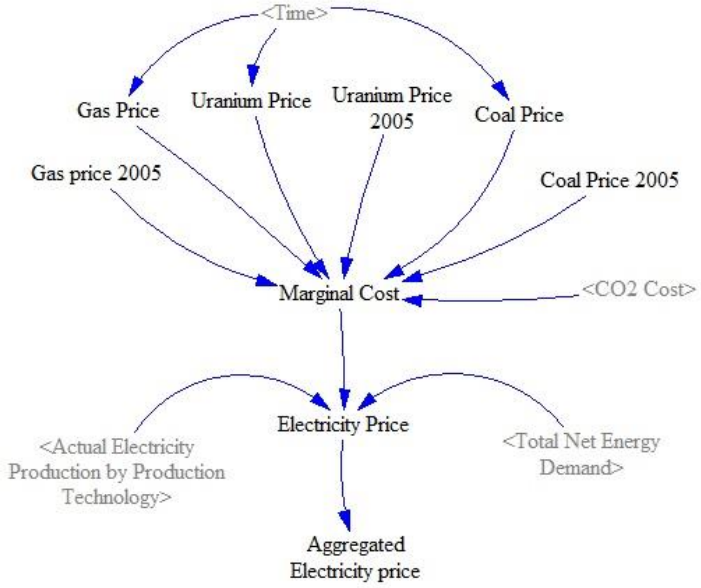

Figure 4.4 Electricity Price System Dynamics model

The determined electricity price will be the hourly market price that has to be paid for one megawatt.

In the electricity price formula it is assumed that the marginal costs per generation method are all the same. In the real world

this is not the case. Not all power plants have the same marginal cost and thus cheaper power plants will be bid first in the merit order and more expensive power plants are bid last. To deal with this, a direction coefficient of the possible increase of marginal cost between the cheapest and the most expensive power plant has been determined per generation method. The calculation of this marginal cost direction coefficient is shown in Appendix B.3.

The development of the marginal cost of the generation methods is an important factor determining the electricity price. Therefore the development of the marginal cost will be modelled in the power exchange component of the System Dynamics model. The energy prices (Gas, Coal and Uranium) will develop according to the scenario sketched in the trends report of the European Commission – see Figure 4.5.

The uncertainty factor that needs to be used in the simulations will be determined during the validation of the SD-model. The growth of marginal cost is calculated based on a percentage growth computed by dividing the yearly energy price by the energy price in 2005. For the calculation of the future marginal cost, the energy price scenarios of Figure 4.5 have been taken into account.

Next to the energy prices, the development of the CO2-cost influences the electricity price as well (see formula of the Marginal cost below).

$$Marginal\ Cost = Fuel\ Cost + Variable\ Maintenance\ Cost + CO2\ Cost$$

In a report of the European Commission – *EU ETS emission Trading Scheme (ETS): Response to consultation on the auction time profile* (Neuhoff & Schopp, 2012) – a scenario is sketched where the CO2 price will be

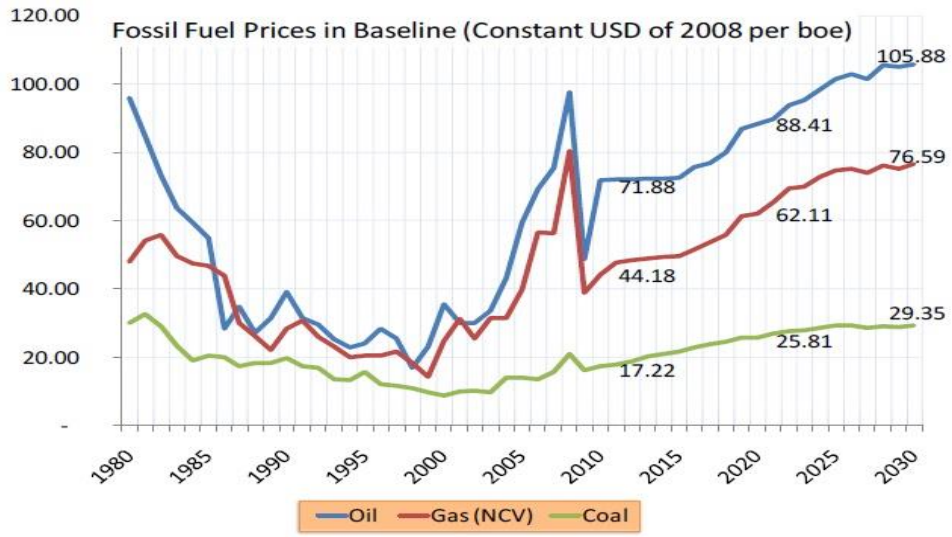

Figure 4.5 Expected development energy prices (Neuhoff & Schopp, 2012)

46 €/tCO2 in 2020 and 186 €/tCO2 in 2030. In the validation phase, the uncertainty to these prices will be determined. As stated earlier, when the installed generation capacity cannot cover the electricity demand, electricity import will take place. The import of electricity has added to the electricity price formula, but it is assumed that the imported electricity does not influence the electricity price directly.

To deal with cheaper electricity prices from – for example – Germany, a factor on the price of imported electricity has been determined through the average electricity prices of neighbor countries and the Netherlands. This graph with this data of average electricity prices of neighbor countries is shown in Figure 5.3. In Appendix B.3. a more detailed explanation is provided on the determination of the factor on the price of imported electricity.

4.1.2 Electricity Demand

The Volatility of Electricity Demand

Figure 4.6 shows the hourly fluctuation of electricity demand over one week – randomly chosen. During workdays of the week the pattern is clearly different than in the weekends. Also the demand between night time and day time differs highly, with a clear peak in the evening. Besides the variation in demand on a daily basis, electricity demand fluctuates per week, month or season as well, which makes it hard to predict electricity demand.

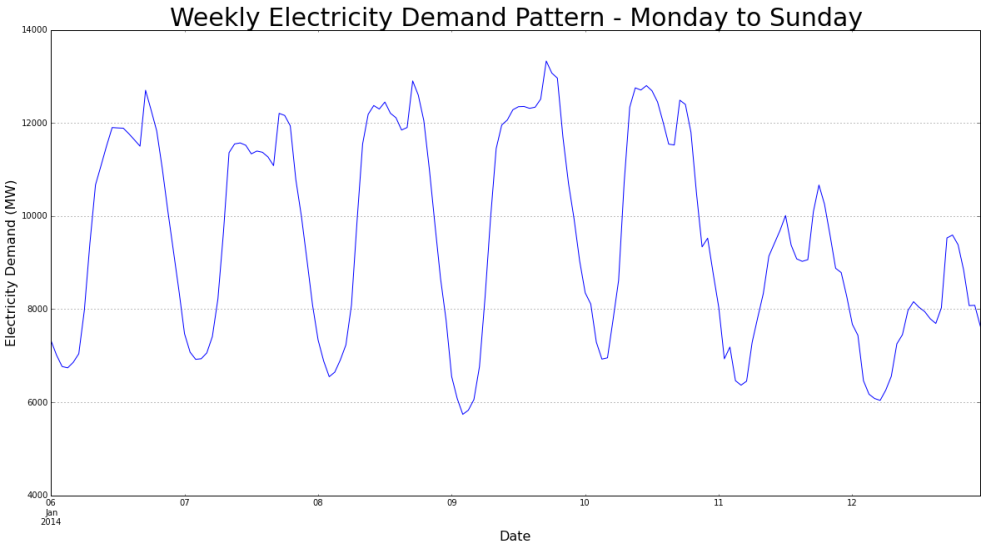

Figure 4.6 Weekly Electricity Demand Pattern

The fluctuations in demand, supply and electricity prices can be translated to investment risks. The higher the volatility of demand, supply and electricity prices, the higher the investment risk is. The modeling output of these factors are therefore important to analyze as these factors provide insights in the investment environment of the Dutch electricity system.

With an expected increase of renewable energy source adoption in the upcoming years, analyzing the investment environment becomes more and more important for the stakeholders of the Dutch electricity system. This because more wind energy production leads to a higher volatility of electricity supply and thus higher investment risks (Ketterer, 2012). Due to the relation of more wind energy production and higher investment risks, the development of wind production could eventually slow down investments in capacity development and thus jeopardize the achievement of sustainability targets for 2030.

To build a simulation model that takes these short term fluctuations into account, while modeling on a yearly basis, the load duration curve is introduced to parametrize the electricity demand.

The load duration curve represents the hourly electricity demands of an entire year, ranked from highest to lowest demand (Figure 4.8) (TenneT Holding B.V., 2015).

The deviating electricity demand from the average electricity demand have the most influence on the volatility of the electricity price. While the average electricity demand could most of the time relatively easily be covered, it is more difficult to cover outlying electricity demands. These outlying electricity demands should therefore also be taken into account in the System Dynamics model.

The System Dynamics model simulates on a yearly basis and to prevent that the model only takes one value for electricity demand – i.e. the average electricity demand – into account, the electricity demand has been split into three phases. In this way variations in electricity demand have been taken into account in the model. Figure 4.7 provides the hourly electricity unordered. For the Load Duration Curve the demand per hour is ranked from the maximum to the minimum value. Based on this Load Duration Curve the different phases are determined – shown in Figure 4.8.

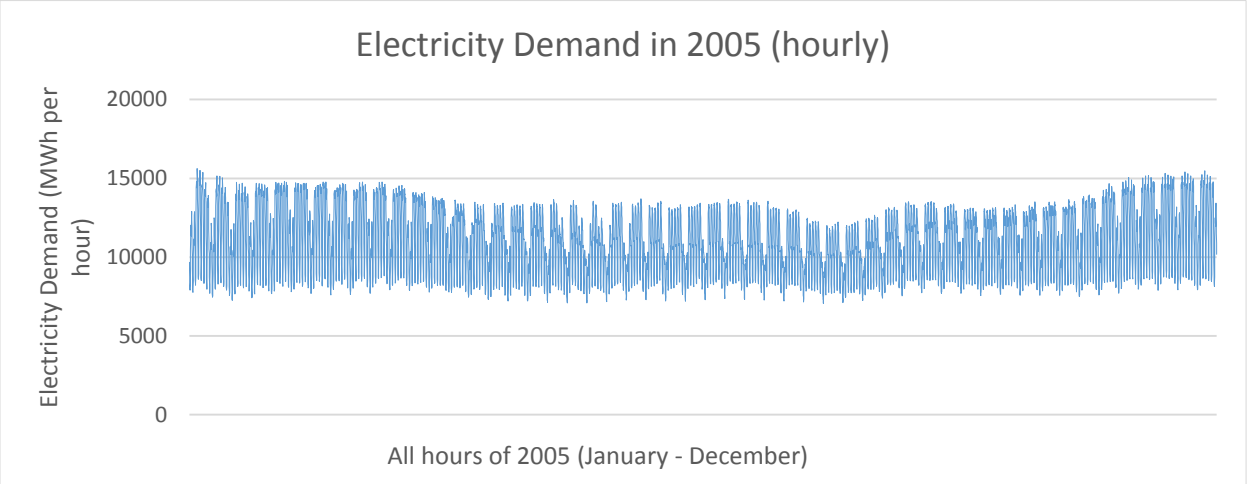

Figure 4.7 Hourly Electricity Demand in 2005 (unordered)

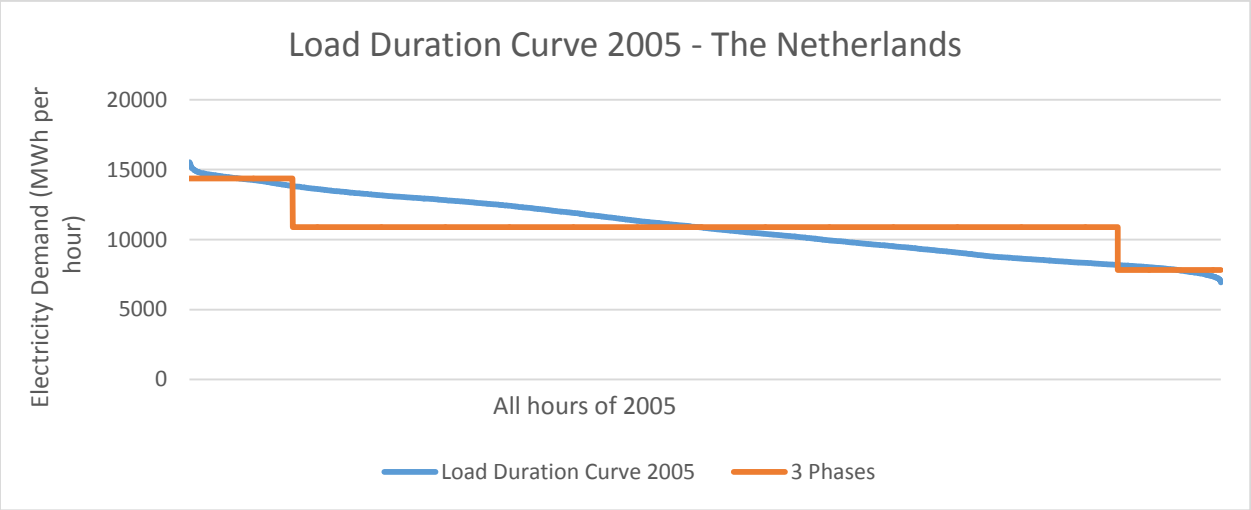

Figure 4.8 Load Duration Curve - Electricity Demand (ordered) and demand phases

One group – i.e. phase – of outlying electricity demands are above average – electricity demand in peak hours. One group of outlying electricity demands are below the average – electricity demand in base hours (mostly at night). The third phase – the shoulder – consist of the average electricity demand. The orange line in Figure 4.8 shows the three defined phases.

As the outlying electricity demands do not occur as often, it is assumed that the peak and base consist of 10% – 876 hours – of the total hours per year. The rest of the time is defined as the shoulder phase – 7008 hours.

The input values in 2005 in the system Dynamics model of the phases peak, shoulder and base are respectively 14376 MW, 10902 MW and 7829 MW. Based on the starting values and external forces influencing the electricity demand, the electricity demand towards 2030 will be determined in the model.

For this research it is decided to divide the load duration curve in three phases, as more phases would be too time consuming. For future research it would be interesting to investigate the effects of splitting the load duration curve into more phases.
The number of phases has not been varied, but the size of the three phases has been varied. A sensitivity analysis has been executed to test the effects of changing the size of phases. This sensitivity analysis is explained in Appendix G.4. In this sensitivity analysis three scenarios have been tested; the normal case: 10/80/10, the large peak and base case: 20/60/20 and the small peak and base case: 5/90/5.

Even though the phases are split up, they will be simulated at the same time and thereby exposed to the same external forces and uncertainty factor values – per Monte Carlo analysis run.

Modeling Electricity Demand

One important external force influencing the electricity demand is the Gross Domestic Product (GDP) of the Netherlands. The elasticity between the GDP and the electricity demand is determined at 0.6% – When GDP increases 1%, the electricity demand will increase 0.6%. This elasticity is determined by Naill (in 1977) (and is still used in models as the elasticity between GDP and electricity demand (Naill, 1977)).
The effect of energy price increase influences the electricity demand as well. Demand decreases when oil-, gas-, coal- and nuclear-prices increases, as the marginal cost of each generation method – except RES – goes up and thus the electricity price goes up. Next to that, the amount of money that households and company could spend decreases when energy prices go up. Naill has determined the causality between energy prices and electricity demand as -1.1%. This means that the electricity demand will decrease by 1.1% when energy prices increase with 1% (Naill, 1977).

Below, the main formula defining the electricity demand is given. An overview of the formulas leading to the variables of the Electricity Demand (ED) formula are provided in Appendix B.1.
The SMOOTH-variable is a Vensim function that averages (i.e. smoothens) the result of the division of the Average Electricity Price (AEP) over a certain period of time, provided as the right-hand argument – in this case 1 year. The effect of this smoothing function on the simulation results is not yet known, but will be tested in the validation phase. The basis of this formula has been derived from the Energy SD-model of Davies and Simonvic (2009).
As the correlation between electricity demand and GDP is 0.6 – determined by Naill (1977) – the yearly GDP is multiplied by the amount of MWh electricity demand per euro, before it is factored by 0.6. The ratio AEP(t)/AEP – indicating the yearly average electricity price change – is also multiplied with the GDP and R-value, after it is factored by the correlation of -1.1 (Naill, 1977). By calculating the absolute difference between the extra electricity demand caused by the adoption of Electric Vehicles and the decrease of electricity demand caused by decentralized electricity production, long term trends influencing the electricity demand are taken into account. Another long term trend that has been taken into account is the growth of the Dutch population, leading to a higher electricity demand.

$$ED = \left(\left(R(ED\ in\ 2005) \cdot GDP(t) \cdot SMOOTH\left(\left[{AEP(t)}/{AEP\ (2005)}\right], 1\right)\right) + (EV - D)\right) * P$$

ED = Electricity Demand (MW)	SMOOTHING-factor = 1 (year)
GDP(t) = GDP over time (€)	EV = EV electricity demand (MWh)
AEP(t) = Average Electricity Price over time (€/MW)	D = Decentralization (MW)
AEP (2005) = Average Electricity Price in 2005 (€/MW)	R(ED in 2005) = Ratio of electricity use to GDP in 2005 (Dmnl)
P = Yearly Population Growth (Percentage with respect to 2005)	

In Figure 4.9 the System Dynamics submodel with the underlying ED-formula is provided.
The System Dynamics model is based on yearly events but hourly scenarios of electricity demand and supply have been taken into account and hourly electricity prices have been calculated in the model. To eventually compute to a yearly output, the results are multiplied by 8760 hours. In order to simulate a variance of electricity demand, a Monte Carlo simulation will be executed. How many runs in Monte Carlo are required for modeling towards 2030 will be determined during the validation phase. Next to that, the Electricity Demand is divided into three phases, which leads to more fluctuations as well.

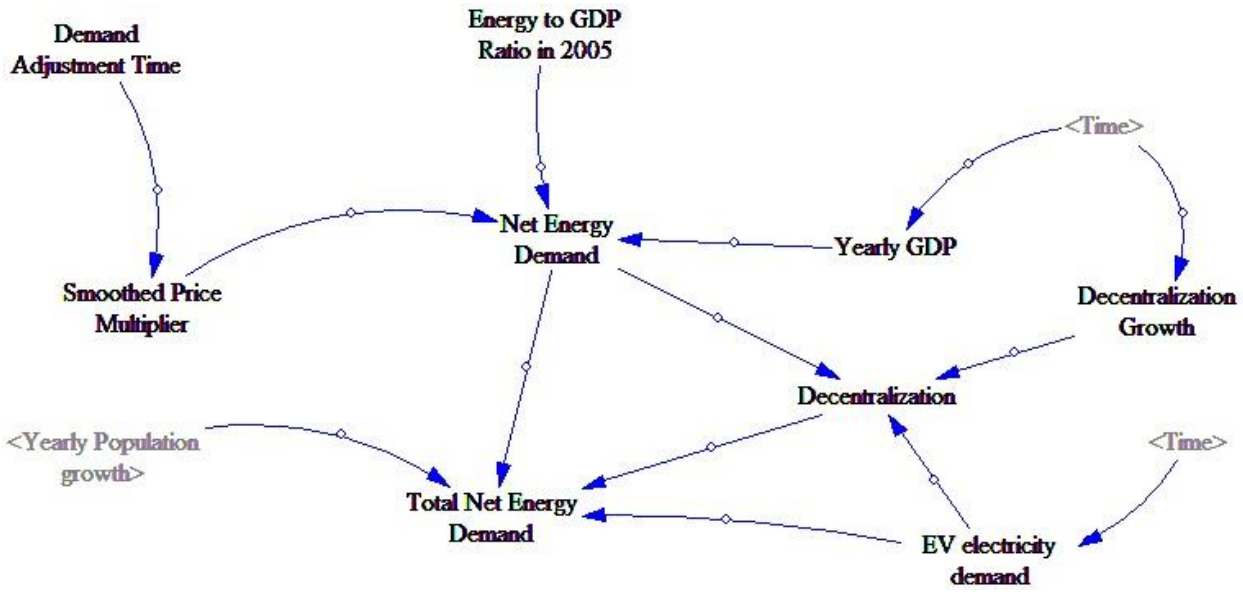

Figure 4.9 System Dynamics model - Electricity Demand

The average Electricity Price of 2005 is used as initial condition, since the simulations start in 2005. The R-value (Average ratio of electricity usage to GDP in 2005 per hour) is derived from historical data (TenneT Holding B.V., 2014a). In Appendix A.3. the calculation of this value will be shown for all three phases of the electricity demand.

The growth of population scenario is based on an estimation of the CBS and the University of Denver. It states that the expected population in the Netherlands will be 17,07 million (University of Denver, 2015). For this factor an uncertainty factor will be taken into account as well, which is determined later.
The Electric Vehicle (EV) electricity demand is based on the target of the Dutch government to have adopted 1 million EV's by 2025 (Rijksoverheid, 2014). As the adopted Electric Vehicles by 2005 in the Netherlands was basically zero, historical data support is lacking which is an issue for the validation of this specific variable.

Next to the estimation of EV electricity demand towards 2030, it is also hard to estimate with which rate decentralization will take place in the Netherlands. This because many factors influence the volume of decentralized electricity production towards 2030.
The university of Denver states in their International Futures page, that the GDP per capita in the Netherlands will grow from 827,9 billion dollar in 2015 to 1,019 trillion dollar in 2030. This scenario – with a to be determined uncertainty factor – will be taken into account in the System Dynamics model (University of Denver, 2015).

Figure 4.9 includes a variable called 'Smoothed Price Multiplier', this variable contains the development of energy prices over time. This has been calculated through a comparison of the yearly energy prices with the energy prices of 2005. The same scenario for energy price development as in Figure 4.5 of section 4.1.1 will be used in the System Dynamics model.

4.1.3 The Actual Electricity Supply

The volatility of electricity Supply

In chapter 4.1.2. the way volatility of Electricity Demand has been taken into account in the model is explained. However, the electricity demand is not the only factor that constantly fluctuates. The supply of electricity is another factor that fluctuates – especially with the increasing installed capacity of renewable energy sources – and which should be taken into account in the model.
The four generation methods that are considered in the model are Gas, Coal, Nuclear and Wind. Two important electricity production characteristics of these generation methods is that Coal and Nuclear deliver constant output and are inflexible to adjust output. The output of Wind electricity production is uncertain – as it is dependent on the wind availability which is uncertain. Next to that, the marginal cost of wind electricity production are the lowest of the four generation methods. Therefore wind electricity is competitive, though the degree of competitiveness is dependent on the availability of wind – as no available wind does not affect the electricity system, and contrarily.
The characteristics of gas electricity production is that this method is flexible to ramp up and down depending on the required electricity production. Through gas electricity production shortages of supply could be intercepted to a certain extend.

Both demand as well as supply volatility cause the electricity price dynamics. The demand side should be monitored in a way to be able to constantly determine the demanded electricity in a certain point of time. The supply side should be monitored constantly as the fluctuating supply should match the electricity demand at all times. When flexible gas electricity production is not sufficient to stabilize the electricity system, electricity from or to neighbor countries could be exported or imported. Technological developments in electricity storage are promising developments to counteract the increasing volatility – through the high adoption of renewable energy sources – and thus instable electricity system (Dunn et al., 2011). In the research approach it is stated that energy storage is kept outside the scope of this research. However, since this factor is expect to become important in the future – looking at the expected increase in volatility of electricity supply – a broad analysis on the effects of energy storage on the system is executed. The way energy storage has been added to the model is explained later in this chapter. The effects of energy storage on the electricity system are explained in the modeling results – chapter 6.

The variation of the availability of wind influences the electricity prices. Therefore, it is of great importance to simulate the variations of wind as happens in the real world. In order to research the variation of wind speed, ten years of wind speed data of IJmuiden – The Netherlands – has been researched.
It shows that the variation of wind follows a normal distribution shape (Figure 4.10). Based on this, it is decided to follow the normal distribution for wind variation.
An important note is that the fluctuations of wind speed fluctuate through simulations and are thus not part of the System Dynamics model itself – which *is* the case on the demand side. On this side, the fluctuations of wind speed are part of the model as three phases have been defined – Base, Shoulder and Peak. The chosen value for wind speed – based on the normal distribution (in graph X) – in each Monte Carlo simulation run (in total 8000 runs) is fixed for the entire time period (from 2005 to 2030).

Modeling fluctuating wind electricity production

Based on this information it is determined that the average wind speed is 7.27 m/s and the standard deviation is 3.68 m/s. When varying the wind speed according to the normal distribution in the System Dynamics model, it is decided to varying it with a maximum of one sigma. The minimum wind speed is therefore 3.59 m/s and the maximum wind speed 10.59 m/s. Wind speeds in this region occur the most.

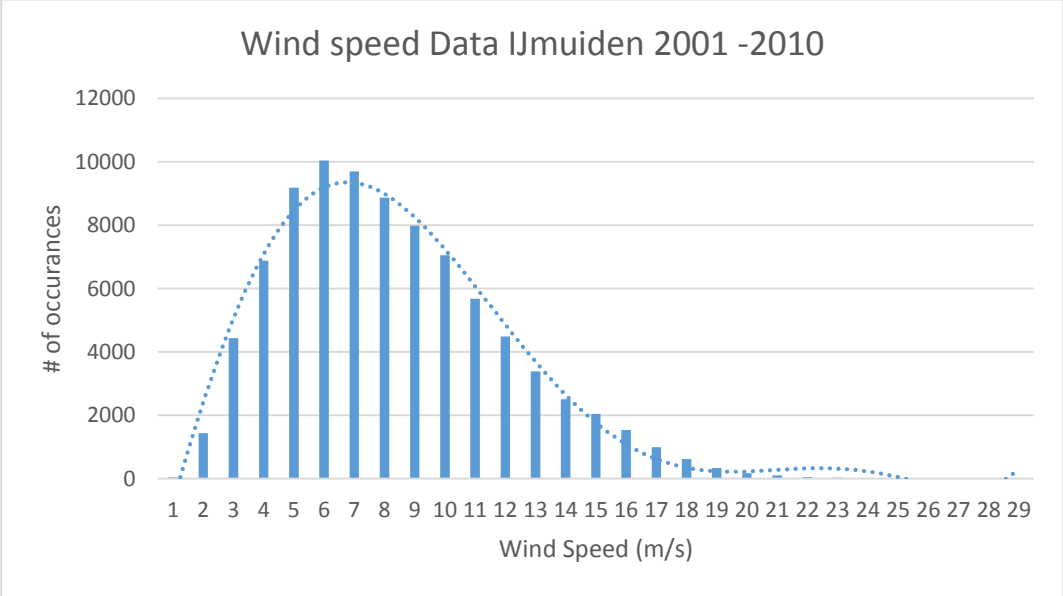

Figure 4.10 Wind Speed Data IJmuiden 2001 - 2010

The yield of wind capacity is not the same for every wind speed. A part of a model on wind turbines – from Pieter Bots – has been added to the System Dynamics model to determine the yield of wind capacity for various wind speeds (Pieter Bots, 2015). The formula that is used for this determination is shown below. The Vmin is 4 m/s, the Vpeak = 10 m/s and the Vmax = 20 m/s. Based on this formula the capacity factor of wind could be determined. As this is a factor of the actual electricity production compared with the maximum potential electricity production. Based on this formula and the average wind speed, the average capacity factor is 38.49%.

$$P_W = \begin{cases} 0 & als\ v < v_{min}\ of\ v > v_{max} \\ \left(\frac{v}{v_{piek}}\right)^3 P_{max} & als\ v_{min} < v < v_{piek} \\ P_{max} & als\ v_{piek} < v < v_{max} \end{cases}$$

Modeling Electricity supply with energy storage

The System Dynamics is built to analyze long term trends in the Dutch electricity System. Though, the level of energy storage fluctuates constantly (short term).

The effect of energy storage is that it lowers the desire to import and export electricity as excess or lack of electricity could be added to or subtracted from the storage capacity. Therefore, energy storage is connected to the import and export of electricity in the System Dynamics model. The capacity of energy storage is difficult to predict as it is highly dependent on technological development of energy storage techniques. DNV GL, Berenschot and Delft University of Technology have published a roadmap on energy storage towards 2030 in the Netherlands. However, this report does not quantify expected developments in energy storage capacity (Topsector Energie et al., 2015)). As other sources on the expected capacity development of energy storage towards 2030 in the Netherlands are lacking, an assumption is made for this research. The potential capacity of energy storage consists of the number of electricity vehicles and the potential capacity of other energy storage capacity techniques. It is assumed that by 2030 10% of the total installed capacity is the energy storage capacity from different storage techniques – which equals approximately 2,500 MW installed capacity of energy storage. As the expected number of electric vehicles by 2030 in the model are 1.35 million cars and assumed that 10% of this battery capacity is available for energy storage by 2030, this equals a storage capacity of 11,475 MW. This means that the energy storage capacity by 2030 in the Netherlands equals 13,975 MW.

As Figure 4.11 shows, the actual electricity generation varies continuously. It topped in 2010 and thereafter

it decreases. This does not imply that the total electricity consumption in the Netherlands decreased. According to TenneT – the Transmission System Operator in the Netherlands – import of electricity has increased over the years, with an import of about 21 million MWh in 2011 and 32 million MWh in 2012 (TenneT Holding B.V., 2012). The export of electricity also increased in 2011 and 2012 with respectively 11 million MWh and 15 million MWh (TenneT Holding B.V., 2012). This resulted in 7 million MWh more import of electricity and a decrease of 10 million MWh in electricity demand in 2012.

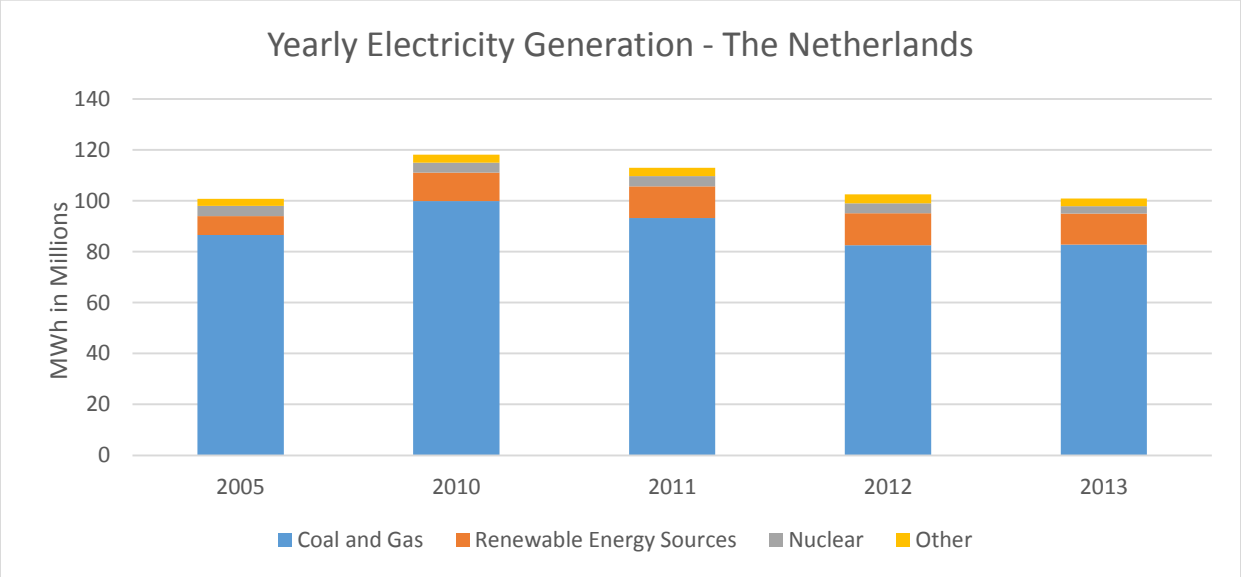

Figure 4.11 Yearly Electricity Generation - The Netherlands (CBS, 2013)

The actual electricity supply is dependent on the available installed capacity and the demanded electricity supply. When there is sufficient installed capacity to generate the demanded electricity then a decision has to be made on how much electricity every single generation method should produce. The input for this determination is based on a Forecasting-formula and a Demand Delay-formula (shown below) in Vensim – the System Dynamics software. This forecast formula provides a simple trend extrapolation forecast of the future value of a variable based on its past behavior. The Demand Delay formula is needed as input for the forecast formula. The demand delay is set at minimum – 1 year, so that the forecast could react fastest when sudden changes happen in the system. The time horizon is the number of years the trend extrapolation needs to be done. This is also kept at the minimum value – 1 year – so that the system can react fastest to changes. The [x] in the formula stands for the phase of demand – Peak, Shoulder or Base. In Appendix B.4. the FORECAST function is further explained.

$$Demand\ Forecast = FORECAST(Demand\ Delay[x], Smoothing\ time, Horizon\ for\ Demand\ Forecast)$$
$$Demand\ Delay = DELAY\ FIXED(Total\ Net\ Energy\ Demand[x], 1)$$

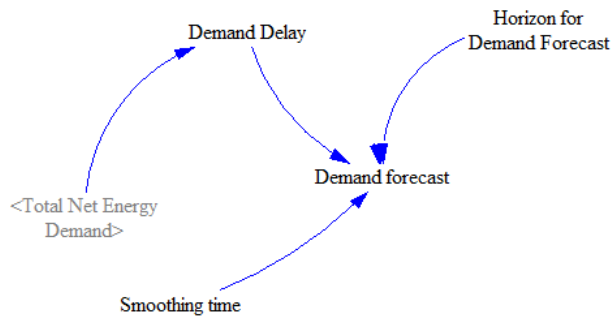

Figure 4.12 Demand Forecast in System Dynamics

Figure 4.12 provides an overview of how the forecasting formula has been added to the System Dynamics model in Vensim.

The calculated demand forecast is input for the *Electricity Production* subscript, to determine how much electricity should be generated. The division of how much each generation methods should produce is based on the generation characteristics of the generation methods and the capacity factors – average generation efficiency of the power plants. Figure 4.13 shows the capacity factor and operation efficiency used for the System Dynamics model.

	Coal	Gas	Nuclear	Wind
Capacity Factor	85%	87%	90%	38.5%

Figure 4.13 Capacity Factor per generation method
(Energy Infromation Administration, 2014)

As stated, the generation characteristics are important for dividing the volume of electricity each generation methods should produce. The division is based on the four steps of the merit order, which has the sequence Wind – Nuclear – Coal – Gas. Wind electricity production is relatively cheap. Wind electricity production is a complex aspect for the electricity system as it fluctuates based on the available wind speed. This fluctuations will be taken into account in the SD-model as well. The exact fluctuations will be determined in the validation phase – chapter 5.

Nuclear and Coal electricity production are relatively fixed, as the power plants are inflexible and cannot be ramped up and down quickly. As gas electricity production is relatively flexible, this electricity will be used to fill up the gaps if more electricity is demanded than produced by wind, nuclear and coal. When wind speeds are low more gas power plants are turned on to cover for the low wind electricity production. With high wind speeds, less (or no) electricity will be produced through gas power plants.

Another external force which influences the actual electricity supply is the import of electricity from other countries through the interconnector network – which is owned by TenneT, the Dutch Transmission System Operator. Import shall only be done to meet the electricity demand when the Dutch installed capacity cannot generate sufficient electricity. Import is left out from the system domain, but it is added as an external force in the model. If import would have been part of the system domain, it would become too complex for this research.
The current interconnection capacity of TenneT is approximately 5670 MW and will increase to 8670 MW by 2021 (TenneT Holding B.V., 2014c). Increasing the interconnection capacity is necessary to maintain the stability of the transmission grid, as renewable energy sources negatively influence the stability of the grid. Electricity production from other countries could then help to obviate shortages in the electricity grid.

4.1.4 The Installed Capacity

The installed capacity of the system domain consists of four electricity generation methods; Coal, Gas, Nuclear and Wind. The input data on the installed capacity of 2005 is 4182 MW for Coal, 11031 MW for Gas, 450 MW for Nuclear and 1224 MW for Wind (TenneT Holding B.V., 2014d).

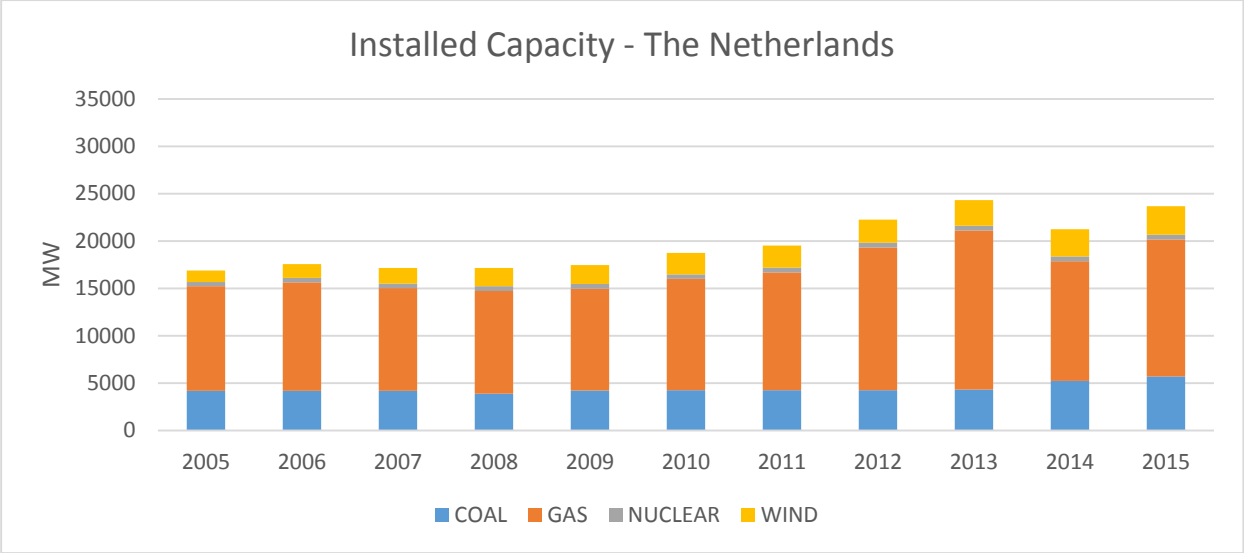

Figure 4.14 Installed Capacity - The Netherlands (TenneT Holding B.V., 2014d)

The remaining historic data (2005 – 2015) is used for calibrating and validating the System Dynamics model. The behavior of the SD model should correctly describe data between 2005 and 2014. Once the SD model is tested, the System Dynamics could deliver simulation realistic output towards 2030.

The installed capacity depends on the preferences of generation methods (i.e. affinity) and the investments made in the development of capacity – explained in chapter 4.1.6. Next to the preferences and investments, the market determines for a large stake which investments should be made – as only the most competitive installed power plants will survive in the market.

Factors influencing the installed capacity are the adoption of new capacity or the destruction of power plants or wind parks, which are part of the System Domain and do not count as external forces. Furthermore, the installed capacity is not really subject to external forces.

The only external forces influencing the installed capacity is are:

- The construction times (in year) of new generation methods
- The life time of a certain generation method
- The decision of the energy utility company to destruct the power plant or shut it down for a while – when there is over capacity and thus a low financial feasibility.

In Figure 4.15, the used times for construction duration and life time of the different generation methods are shown.

	Coal	Gas	Nuclear	Wind
Construction Duration (year)	5	2	6	1
General Life time (year)	40	30	40	10
Installed Capacity in 2004 (MW)	4182	11031	450	1124

Figure 4.15 Construction duration and general life times of installed capacity (Energie-Nederland, 2013)

The Electricity Production Capacity is calculated by the integral of the incoming and outgoing flows, in this case the incoming value is the newly installed capacity and the outgoing value is the electricity production capacity retirement. The retirement of installed capacity is calculated by dividing the initial capacity by the general life time.

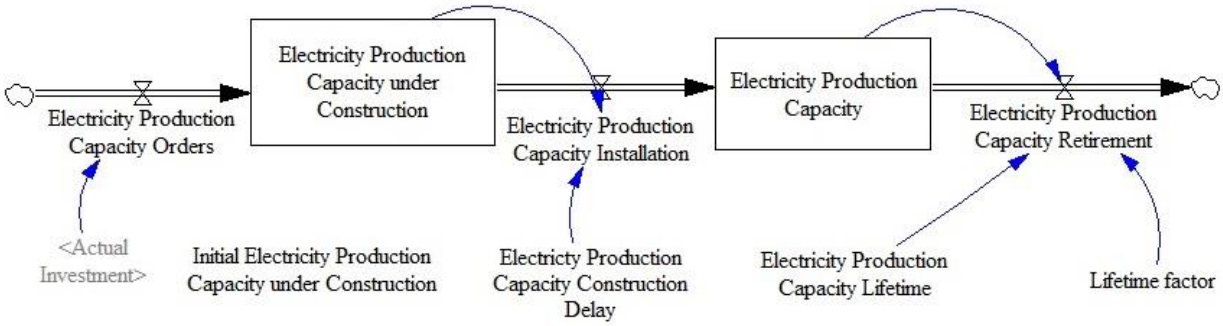

Figure 4.16 Installed Capacity

4.1.5 Yearly Turnover and Investment Budget

The Investment budget is dependent on the yearly turnover and thus the electricity prices. The Yearly turnover is calculated by multiplying the number of hours each demand phase by the electricity price of that certain demand phase. Thereafter the investment budget is calculated through an investment percentage of the yearly turnover. Generally, the investment factor of the yearly turnover of energy utility companies are approximately 6% - 8% of the yearly turnover (Energie-Nederland, 2014). Though, this investment percentage is not only appointed to adoption of new capacity, but also to its own infrastructure, offices and so on. The exact investment factor shall be determined through historical data in financial reports of energy utility companies and through the validation process – as the model should match the historical investments done for capacity adoption.

This means the formula to calculate the Investment Budget is as following:

$$Investment\ Budget = Investment\ Percentage * Yearly\ Turnover$$

$$Yearly\ Turnover = ((electricity\ supply + (Export - Import)) * electricity\ price)$$

If more electricity is produced than demanded, the residual electricity is exported to neighbor countries through the interconnectors of the Transmission System Operator - TenneT. The sold electricity to neighbor countries is added to the yearly turnover.
The investment budget is the integral of the investment budget increase minus the investment budget decrease.

The actual investment is determined based on the allocation formula that is also used to allocate actual electricity supply to the different generation methods. A more detailed explanation on this ALLOCATE BY PRIORITY formula is provided in Appendix B.4.

$$Allocated[y] = ALLOCATE\ BY\ PRIORITY(request[y], priority[y], size(y), width, available)$$

The [y] stands for the four different generation methods – Coal, Gas, Nuclear and Wind. The request variable has been named as *Electricity Investment*, which is the desired capacity development per generation method – based on a forecasting function in Vensim. The Investment priority is based on the affinity to a certain generation method, the LCOE (discussed in the next section) and the price of CO2. The size, are the number of different generation methods. The width is a variable that is determined through the priority. The closer the variable to 1, the more exclusivity is given to a certain subscript. The available variable is connected to the available *Investment Budget*.

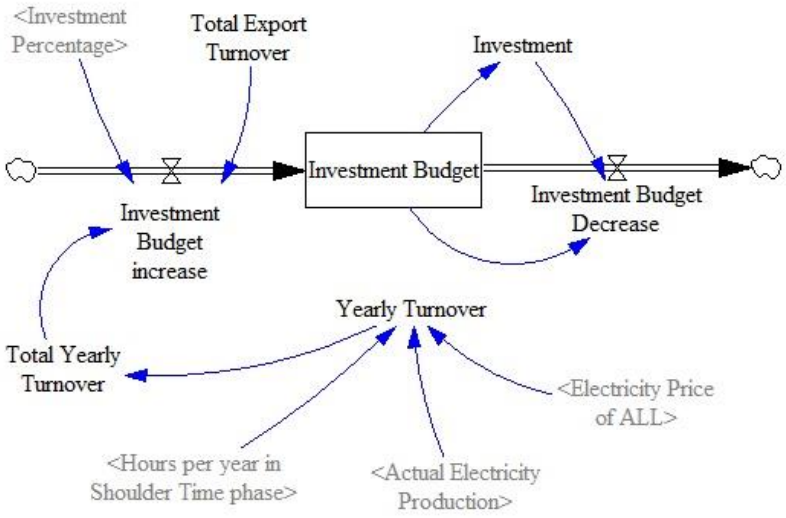

Figure 4.17 Yearly Turnover and Investment Budget

After determining how much money is invested, it will flow to the investment budget decrease variable, where after it will be subtracted from the Investment Budget.

4.1.6 Adoption of Installed Capacity

One of the factors influencing the installed capacity adoption is the Levelized Cost of Electricity (LCOE). The LCOE – in euro per MW – is a method to compare different generation methods based on cost. The LCOE is the total (expected) cost of a generation method over the entire lifetime divided by the (expected) electricity generation over the entire lifetime. The lower the cost, the higher the chance the generation methods gets adopted.
The subsidy policy (SDE+) only influences the LCOE of Wind. Depending on the amount of money available as subsidy, the more 'discount' could be given to the LCOE of Wind.
Through the subsidy policy, the desired generation method of the Dutch government (since it is the most sustainable generation method) becomes more cost competitive.

The LCOEs per generation method are determined based on literature. The LCOE base values for 2005 are shown in Figure 4.18. The development of the LCOE towards 2030 is influenced by the energy prices of gas, coal and nuclear. Next to the LCOE is influenced by the CO2-price. A rise of the CO2-price leads to a higher LCOE.

Besides the financial determination whether a generation method will receive an investment, there are also other factors influencing the investment. The affinity to a certain generation method is important to take into account – the higher the affinity the higher the investment preference. Although this affinity factor is hard to determine mathematically – as it is a social factor – a number should be attached to the different generation methods. This will be done in the validation phase. This could be done through calibration, where the simulation results of capacity adoption should match the historical adoption of capacity between 2005 and 2014.

Generation Method	LCOE (€/MWh)
Coal	95.6
Gas	64.4
Nuclear	96.1
Wind	140.3

Figure 4.18 Levelized Cost of Electricity per Generation Method (Frayer, Ibrahim, Bahceci, & Pecenkovic, 2007)

Also the costs of CO2 influence investment decisions. When CO2 costs are high, Coal and Gas are less likely to be adopted. The price of CO2 is based on a scenario sketched by the European Commission is described in section 4.1.1. The EC assumes that the carbon price will be 46 €/tCO2 in 2020 and 186 €/tCO2 in 2030 (Neuhoff & Schopp, 2012). In the validation phase, the uncertainty to these prices will be determined.

Figure 4.19 shows schematically which factors influence the LCOE.

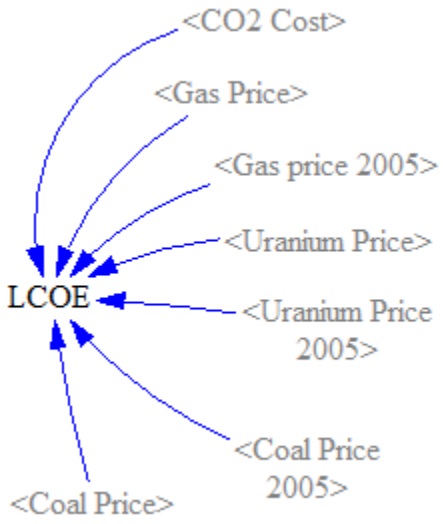

Figure 4.19 LCOE influences in Vensim

Part III – Validation and Modeling Results

5. Verification and Validation of the System Dynamics model

This chapter provides insights on the verification and validation process for the designed System Dynamics model, which is based on input from John Sterman (2000). An important note – by John Sterman – is that all (simulation) models are wrong as they are a simplification of the real world. Through the verification and validation process, trust in the model is built up. A trusted model would be usefulness for modeling the future electricity system. Being able to perform trusted simulations has the goal to explore electricity prices and provide insights in the future investment environment.
The information gathered from chapter 3 and 4 – System Domain, External Forces and Policies – which form the basis of the System Dynamics model, are validated through the process of Sterman. After the System Dynamics model has been validated, simulations towards 2030 can be done. These results are provided in the next chapter.

5.1 Verification and Validation Process

In order to be able to test the model, the built System Dynamics model starts in 2005. This provides 10 years of historic information that can be used to determine the accuracy of the model. Where after it can be simulated towards the future – having set up scenario's for external forces and policies.
The validation phases checks whether the conceptual model – and consequently the simulation model – represent the future adequately (Sterman, 2000). The definition of adequacy could be different for every model.

5.1.1 Verification and Validation Process Design

Figure 5.1 – next page – provides a schematic overview of the verification and validation process of Sterman.
The process of verification and validation starts with a qualitative Structure Assessment, which examines whether the model is consistent with literature and real world situations. This step consists of four different tests.

1. Boundary Adequacy Test: analyses whether the model contains the appropriate variables and feedbacks and whether it has the right structure to serve its purpose (Savio Martis, 2006)
2. Structure confirmation Test: analyses whether the model structure is consistent with the real system.
3. Parameter Confirmation Test: analyses whether the parameters and their numerical values of the model represent the real system.
4. Dimensional Consistency Test: Analyses the units per variable and checks whether they are consistent with the variables in the SD-model.

The second part consists of a quantitative analysis, wherein a Structure Oriented Behavior test is executed. For the quantitative analysis, two main tests have been chosen to validate the model – as these test also provide more insights in the behavior of the model and the influences of relations between variables.

1. Extreme Condition Test: Examines whether the model provides realistic output even when it is subjected to extreme – but possible – values of variables. For example, if the CO2 price is extremely high, investments in coal power plants should not be made.

2. Behavior Sensitivity Test: Determines the sensitivity of all variables in the model and examines what the effects of a certain change of a variable has on the output of the model. The sensitivity could occur in three different ways: Numerical sensitivity, Behavioral sensitivity and policy sensitivity (Sterman, 2000). Numerical sensitivity means that changes of parameters resulting in numerical changes of variables. Behavioral sensitivity stands for changes of parameters leading to behavioral changes of the model, like when the adoption of wind turbines changes from exponential to reaching an equilibrium (S-curve). The meaning of policy sensitivity is the influence (reversing or enhancing effect) a change of policy parameter has on the entire system. An example is that investments in carbon intensive power plants were made after the tumbling of the CO2 price – in the Emission Trading Scheme – when the financial crisis hit in 2008.

The final step in the validation process checks whether the behavior of the model and its output is consistent with real world data. For this process two steps were chosen to be executed: R^2-Metric testing and Mean Absolute Error (MAE) metric testing. The R^2-Metric provides information on how well the model

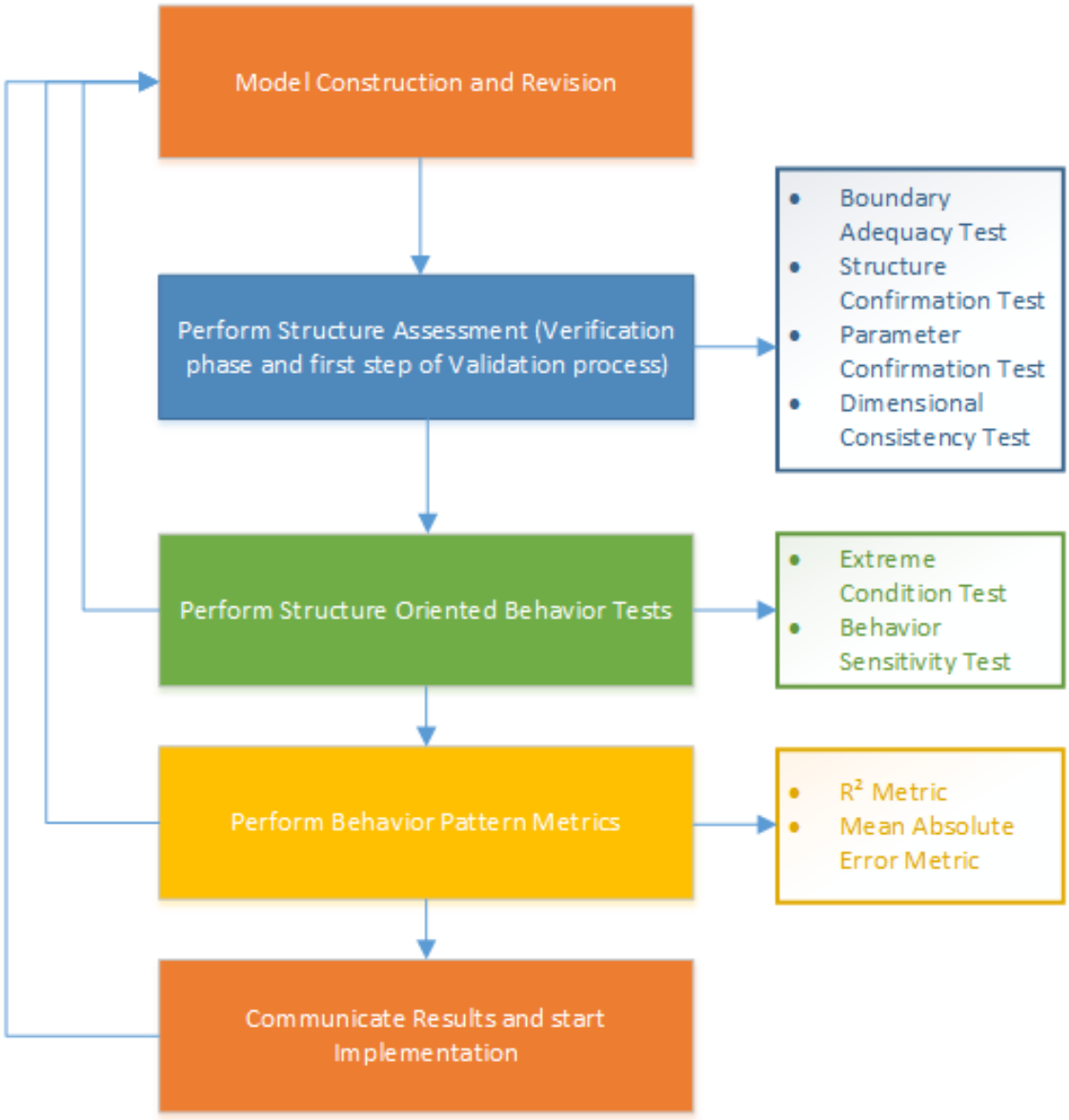

Figure 5.1 Verification and Validation process (Sterman, 2000)

data fits the shape (or correlation) of the real world data and the MAPE metric calculates the percentage error between the model data and the real world data.
To effectively execute these two tests, Key Performance Indicators (KPI's) should be defined. For testing the future electricity price model, the following variables – provided in Figure 5.2 – are appointed as KPI's.

Key Performance Indicators (KPI's)	Meaning
Adoption of Installed Capacity	The adoption of new generation capacity - e.g. investments
Installed Capacity	Available generation capacity
Electricity Demand	Peak, Shoulder and Base Electricity Demand
Electricity Supply	Generated electricity
Electricity Price	Cost of electricity per MWh
Investment Budget	Available budget for new generation capacity

Figure 5.2 Key Performance Indicators (KPI's) for Behavior Pattern Metric Testing

The defined KPI's shown in Figure 5.2 are the components of the System Domain and the core of the System Dynamics model. These components directly influence the electricity price development and the investment behavior, which is researched in this thesis. Therefore, these components are chosen to be tested for validating the model.

The next section performs the validation testing according to the process for model validation designed by Sterman – Figure 5.1. Some tests are general and not specifically focused on KPI's whereas others show test of KPI's separately.

5.2 Implementation of the Verification and Validation Process

In this chapter the validation process provided in Figure 5.1 will be executed. Even though – according to Sterman – all simulation models are wrong. Having done validation test lead to a more trusted model. During the validation tests, modifications to the model will be made until the model and the behavior of the model is trusted. If modifications to the model do not lead to improvements, then an explanation will be given why the model does not provide the desired output.
This iterative approach is also used for the quantitative tests – the Oriented Behavior Test and the Behavior Pattern Test – of the validation process.

5.2.1 Structure Assessment Test

The following test aims at checking whether the model is consistent with the literature as well as with the real world. In order to qualitatively check, the model a Boundary Adequacy test, a Structure Confirmation test, a Parameter confirmation test and a Dimensional Consistency test will be conducted.

Boundary Adequacy Test

This qualitative test analyses whether the model sufficiently represents the real world – in this case the Dutch electricity system. The test analyses the exogenous variables in the model and thereby determines whether those variables should not represent endogenous aspects of the model. If not, the variables stay exogenous.

The list of external variables of the SD-model of the Dutch electricity system are provided in Appendix C.

From the list can be seen that most of the external variables are input variables for the Dutch electricity system. For example, determining the CO2 emissions is based on how much CO2 a gas or coal power plant emit – *CO2 Emission per generation method.*

An important part of the SD-model is the investment decision sub-model. In this part of the model, an *Investment Budget* is determined based on profit and the external variable *investment percentage.* This percentage is determined based on literature and calibration of the model, but this is a simplification on how an *Investment Budget* is determined in the real world – economical, ecological, social and political aspects will play an important role as well as the strategy of the company. As this *Investment Budget* is more complex than the approximation in this SD-model, more research could be done on this to examine whether this could be modeled as an endogenous variable.

Another important aspect in the model is *Import.* This factor is not an external variable in the model itself (as it is calculated based on electricity shortages), but it is external factor from the Dutch electricity System. During this research, it is assumed that sufficient electricity is available from neighbor countries. This means that real shortages do not occur in the model, while in the real world an shortage leads to an extremely high electricity price and measurements like rolling black-outs should be taken. Electricity prices will go up when shortages occur in the System Dynamics model, but as electricity from imports is always available this might prevent electricity prices to go sky high.

On the other hand, import of electricity could also influence electricity prices to go down. This occurs when electricity prices in neighbor countries are lower than in the Netherlands – mostly due to a surplus of available electricity in that country. Figure 5.3 shows that average electricity prices in the Netherlands are much higher than in Germany. An explanation for the lower electricity price in Germany is that it has a large amount of renewable energy source (mostly solar and wind) installed. When there is sufficient wind and sun available, Germany could export its relatively cheap electricity to neighbor countries. In the real world, the imported electricity (from Germany for example) is part of the power exchange and thus competes the cheaper electricity with more expensive produced electricity – leading to lower electricity price in the Netherlands as well.

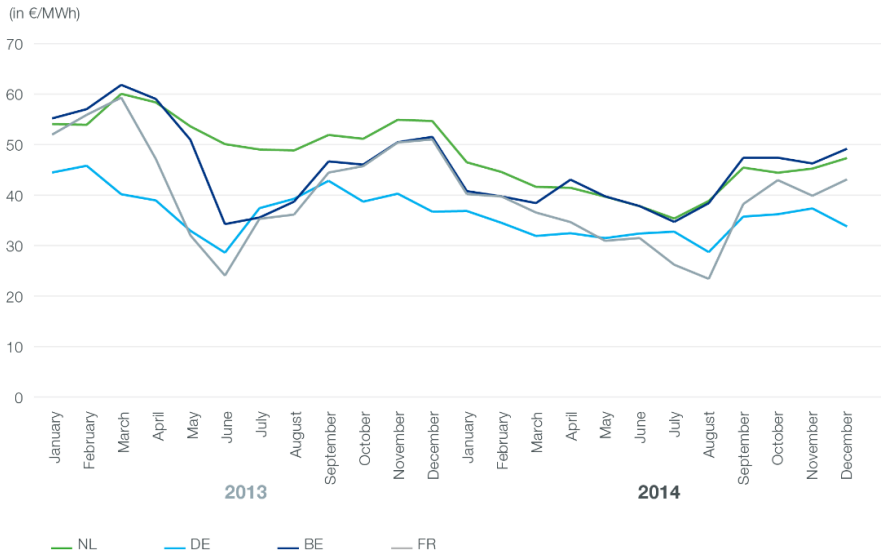

Figure 5.3 Average Electricity Prices in the Netherlands, France, Belgium and Germany (TenneT, 2015)

Since electricity import has an external character in the System Dynamics model, the dynamics around electricity import has not been taken into account. For future research it would be interesting to examine how this dynamics could be added to the simulation model.

Structure Confirmation Test

The Structure Confirmation Test examines whether the aggregation level of the SD-model is appropriate and whether it is consistent with the real system (Sterman, 2000)

This SD-model analyses the future electricity from the perspective of the electricity system. To build a realistic SD-model, the design of the Dutch electricity system and the stakeholders of the system have been taken into account. From this perspective the design of the SD-model matches the real world system. The model is lacking structurally on two aspects. First of all, the model is lacking compared to the real system is on the electricity *Import* and the electricity price determination – taken into account the availability of electricity and the prices connected to this electricity in neighbor countries.
Secondly, the decision rules of new capacity adoption is based on the Levelized Cost of Electricity, the Affinity for a certain generation method and the price for CO2 from the ETS. The *Affinity* is a general factor incorporating aspects like the willingness to invest in a certain generation method. Though, not all unmeasurable factors could be taken into account in one factor. Strategies of Energy Utility companies or political aspects could influence investments but cannot be taken into account within the investment decisions.
The quantitative validation, where model data will be compared with real data, will provide information on how well investments are represented in the model.

For the other parts of the SD-model it could be stated that it passes the Structure Confirmation Test.

Parameter Confirmation Test

The Parameter Confirmation Test examines whether the parameters have real world counterparts and whether the factors are acceptable according to theory. Appendix B.1 provides a list with all the variables of the SD-model. From that list could be concluded that most of the variables have real world counterparts. The ones that do not have real world counterparts are listed in Appendix B.2 including a justification on each variable.

As stated in the justification in Appendix B.2., having to add non-real world counterparts in the SD-model was unavoidable. Not all variables are backed by scientific literature, so further research on these social variables should be done to validate. Though, for all the social aspects there is a reasonable justification and based on the quantitative validation (and sensitivity analysis) information could be gathered on the adequacy of the variables.

Dimensional Consistency Test

Dimensional Consistency Test examines the consistency of the units of the equations and specifically checks equations with no real world meanings. For parameters not having real world meanings, it is appropriate to use Dmnl (Dimensionless) as unit. This also counts for factors representing percentages.
An example of a variable that has a Dmnl-unit is the *Affinity.* The *Affinity* is a variable that indicates among others the willingness to invest in a generation method. The closer the value to zero, the lower the willingness to invest in a certain generation methods. The higher the value above one, the higher the willingness to invest is.

The step size is another important part of the model. The step size should be halved until the modeling output does not change any more. This has led to a step size of 0.0078125, which means that 128 steps are taken per year in the model.

5.2.2. Structure Oriented Behavior Test

The Structure Oriented Behavior Tests are an examination on the model simulation and reviews the behavioral changes under different circumstances. The first part of the Oriented Behavior Test is an Extreme Condition Test that evaluates the validity of the model by examining the simulation results when the model is exposed to extreme conditions. The simulations results of the extreme condition test will be compared with logical expectations on how the SD-model would behave (Barlas, 1996). The second step of the Structure Oriented Test is the Behavior Sensitivity Test which analyses the sensitivity between external factors and the most important variables in the System Domain.
In this section, both test will be conducted and based on the results, adjustments could be made so that the behavior of the model matches best with the expected behavior.

Extreme Condition Test

The Extreme Condition Test requires to have set up hypotheses on extreme changes of external factors and the expected behavior of the model. If the model behaves as expected, then it could be concluded that the model behaves realistically under extreme conditions as well. The hypotheses that will be tested are:

- If CO2-price is extremely high, Electricity price will be high leading to high investments in low carbon electricity production (Wind and Nuclear).
- If CO2-price is extremely low, Electricity price will be low leading to little investments in low carbon electricity production (Wind and Nuclear) and higher investment in carbon intensive electricity production (Coal and Gas).
- If the affinity of generation technologies are high, high investment in the generation technologies will be made.
- If the affinity of generation technologies are low, little investments will be made.
- If energy prices (Oil, Gas, Uranium and Coal) are high, more investments will be made in wind energy production.
- If energy price (Oil, Gas, Uranium and Coal) are low, Electricity prices are low and investments in non-renewable electricity production will be low.
- If GDP is extremely high, then the electricity demand will be high and the electricity price and investments in new electricity production capacity will increase.
- If GDP is extremely negative, then the electricity demand will be low and the electricity price and investments in new electricity production capacity will drop.
- If the Dutch population is high, the electricity demand and the electricity prices will be high.
- If the Dutch population would be lower, the electricity demand and the electricity prices will be low.
- If the wind speed is low, then investments in wind energy will drop and electricity prices become more stable.
- If the wind speed is high, then investments in wind energy will soar and electricity prices will decrease.

- If energy prices (that consumers pay) decreases, the electricity demand will go up and electricity prices will increase.
- If energy prices (that consumers pay) increase, the electricity demand will go down and electricity prices will decrease.
- If the investment percentage increases, the investments in capacity adoption will increase and the electricity price will decrease.
- If the investment percentage decreases, the investments in capacity adoption will decrease and the electricity price will increase.

These hypotheses have been chosen as these external forces affect the output of the modeling output when the external forces are changed.
These hypotheses are tested one by one. The results of the Extreme Condition Test are shown in Appendix G.1. The test has led to adjustments to equations of different variables, but no structural changes were made to the model. It shows that the model behaves realistically under extreme conditions. If not all the identified KPI's are shown in the results of the extreme condition test, it means that the sensitivity is insignificant.

Sensitivity Analysis

This analysis examines the sensitivity of the system domain of the model when external factors vary. The Monte Carlo-Analysis in the System Dynamics software – Vensim – is used to vary external factors with 10 percent according to a random uniform distribution. 1000 simulations runs have been executed to test as much possible scenario's while automatically varying the external factors.
The sensitivity analysis exists of two types of analysis: a Univariate Sensitivity Analysis and a Multivariate Sensitivity Analysis. The univariate analysis is executed by varying only one external factor at the time. In the multivariate analysis, different external factors are varied uncorrelated in the same simulation run. For the multivariate analysis, the external factors are divided into three groups that are varied; energy prices, megatrends and policies. At last, using all the external factors, a Monte Carlo analysis is executed with a variation of 10 percent – except for the *Wind Speed Variety* as this factor follows a normal distribution, with a standard deviation of 3.68 m/s and a mean of 7.27 m/s.
It is interesting to execute a multivariate analysis as different external factors could strengthen or weaken each other.

The results of both sensitivity analyses are provided in Appendix G.2. – the output of the sensitivity analysis is provided with an examination of the simulation results.
The univariate analysis shows that a couple of external factors show to be relatively sensitive – which means that a 10% change of an external force leads to an approximate of 10% modeling output.

Below the influences of external forces on the entire system is set aside:

- Energy prices – gas and coal – influence the electricity price and as gas prices influence the spending money of consumers, it also influences the electricity demand.
- The *initial marginal cost* of the generation methods influences the electricity price. A lower marginal cost leads to a direct decrease of electricity prices.
- The price of CO2 influences the marginal cost and therefore changes to the CO2 price, directly influences the electricity price.

- The efficiency of the generation methods – CO2 emissions per generated MWh – influences the marginal cost. This because more efficient power plants lead to less CO2 emissions and thus lower CO2 cost and marginal cost.
- The development of the Dutch population size is highly sensitive – which means that a variation of 10%, leads to a variation of more than 10% of the modeling output – for the demand of electricity and thereby influences the electricity price. The larger the population, the higher the electricity demand.
- One of the trends in electricity production is that consumers start producing the own electricity – decentralized electricity production. One of the reasons is the accessibility and affordability for small scale renewable electricity production. The affordability of renewable energy sources in general is due to the SDE+ subsidy. This policy stimulates the adoption of small scale renewable energy sources, but it also stimulates larger wind energy projects. Therefore, this subsidy is an important factor in the SD model. The sensitivity analysis shows that the adoption for wind energy production capacity is highly sensitive for changes in the SDE+ subsidy amount.
- Also, electricity prices are slightly sensitive to variations of the SDE+ subsidy, since wind energy production is relatively cheap electricity compared to other generation methods.
- Varying the wind speed with 10 percent already shows a high sensitivity for wind capacity adoption and electricity prices. In real situations the wind speed varies more than 10 percent – explained in Appendix F.1. Since other external factors have been varied by 10 percent according a random uniform distribution in this sensitivity analysis, this will be done for wind speed as well. For the real modeling results, wind speed will be varied according a normal distribution. The determination of the mean and standard deviation of this external factor is explained in Appendix F.1.

  The wind speed variety shows to highly influence the CO2 emissions as well. This is due to the fact that a higher wind speed leads to a higher yield and thus less carbon intensive electricity generation are needed to meet demand. Besides, a higher yield in wind energy production positively influences wind capacity adoption and demotivates carbon intensive capacity adoption, and contrariwise.

From the multivariate sensitivity analysis it can be concluded that energy prices highly influence the electricity prices. This because it influences the electricity demand as well as the cost for electricity production.

Megatrends (population growth, decentralization and electric vehicle adoption) mostly influence the CO2 emissions and the electricity demand. Next to that the electricity price in peak hours is highly sensitive to megatrends. This is due to the fact that a larger population leads to higher electricity demand and an increased uncertainty on extremely high electricity demand in the peak hours.

The policies (Emission Trading Scheme (ETS) and SDE+ subsidy) mostly influence the electricity price and the CO2 emissions. The electricity price is sensitive for the policies as higher CO2 cost lead to higher marginal cost. The CO2 emissions decrease with the help of the policies as the ETS demotivates carbon intensive electricity production and the SDE+ subsidy stimulates the adoption of renewable energy sources.

In chapter 6.2 and 6.3 a more detailed analysis is done on the influences of external forces and policies on the Dutch electricity system.

5.2.3 Behavior Pattern Test

The purpose of the Behavior Pattern Test is to compare the modeling data with real data. The Behavior Pattern Test is the reason why the SD model starts in 2005, so that 10 years of real data are available to compare the modeling data with. Within this test R^2 and Mean Absolute Error/Mean (MAE/Mean) metrics are calculated to determine whether the model behaves well or not.

The R^2 metric, which is called the coefficient of determination, measures the fraction of variance in the data explained by the model (Sterman, 2000). If the modeling results exactly fit the real data, the R^2 value is one. If the value is zero, it means that the covariance of the modeling output and the real data is zero. MAE/Mean determines the average error between the modeling output and the real data. This means that the closer the MAE/Mean value is to zero, the better the modeling results fit the real data.

The formulas for calculating the R^2 value and the MAE/Mean are shown below.

$$R^2 = \frac{1}{n}\sum \frac{(Xd-\overline{Xd})}{Sd} \cdot \frac{(Xm-\overline{Xm})}{Sm} \text{ where, } \bar{X} = \frac{1}{n}\sum X \text{ and } s = \sqrt{\frac{1}{n}\sum (X-\bar{X})^2}$$

$$\frac{MAE}{Mean} = \frac{MAE}{\overline{Xd}} \text{ where, } MAE = \frac{1}{n}\sum |Xm - Xd|$$

Below the results of the R^2 and MAE/Mean calculations are given of the five most important factors of the system domain of the SD-model. In Appendix G.3 more specific information is given on the calculations and the results of the R^2 metric and MAE/Mean metric calculation. Next to that, graphs will visually show the differences between modeling output and real data.

	R^2	MAE/ Mean
Electricity Demand	0.80	3.0%
CO2 Emissions	0.53	7.3%
Average Electricity Price	0.57	9.3%
Electricity Production	0.26	5.1%
Installed Capacity (Gas)	0.35	12.4%
Installed Capacity (Coal)	0.01	6.8%
Installed Capacity (Nuclear)	-0.77	5.0%
Installed Capacity (Wind)	0.83	11.7%

Figure 5.4 R^2 and MAE/Mean metrics

The best R^2 metrics of the five most important output variables of the system domain are the Installed Capacity of wind and the Electricity Demand. This means that the shape of the modeling output of these factors fits best to the real data. The best average deviation metric between real and modeling data of the five output variables are the Electricity Demand (Figure 5.4) and the Average Electricity Price.

The worst R^2 metric is the one of the Installed Capacity of Nuclear. This value is negative, which means that the shape of the modeling output is totally different than the real data. This is due to the fact that the real data of installed capacity of nuclear is stable towards 2030. It is known that the only nuclear reactor in the Netherlands will close in 2033 (Staatscourant, 2006). Though, since System Dynamics is a continuous modeling technique, the dismantling is done in yearly steps towards 2033 – which causes the deviating shape and thus the negative R^2 value.

The R^2 value of coal and gas Installed Capacity are far from close to one. The cause of these low values is that the price for CO2 became so low around 2012, that it led to high investments in carbon intensive generation capacity. These investments are also done in the model, but two to three years later – which

is caused by the Forecast formula that has been used in the model. A research on how to thwart this delay could increase both metrics and thus improve the model. Overall this means that after 2015 the average deviation between modeling data and real data will be smaller again. The delay – causing this low R^2 value – is an important to take into account and it shows that one of the weak aspects of the System Dynamics are sudden changes. The low R^2 value of Electricity Production is also caused by the investment delay in the model compared to the real data.

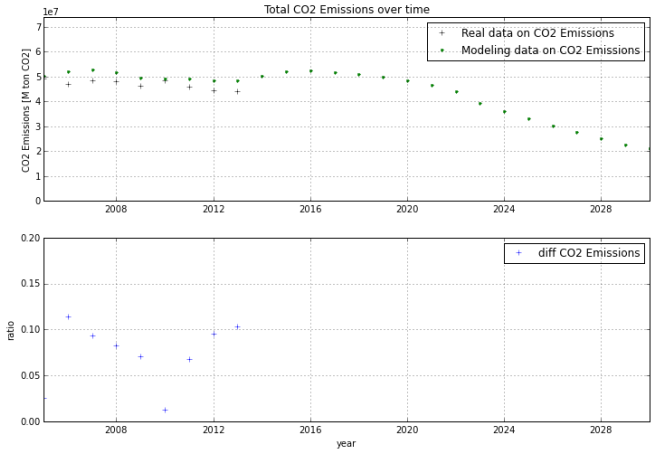

Figure 5.5 Total CO2 emissions - Modeling output and real data

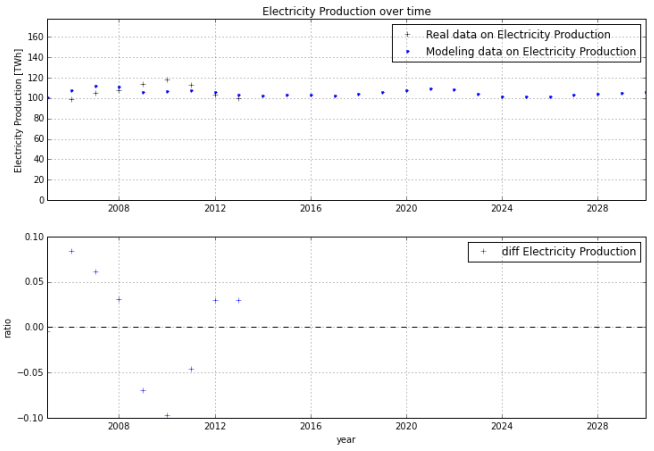

Figure 5.8 Electricity Production - Modeling output and real data

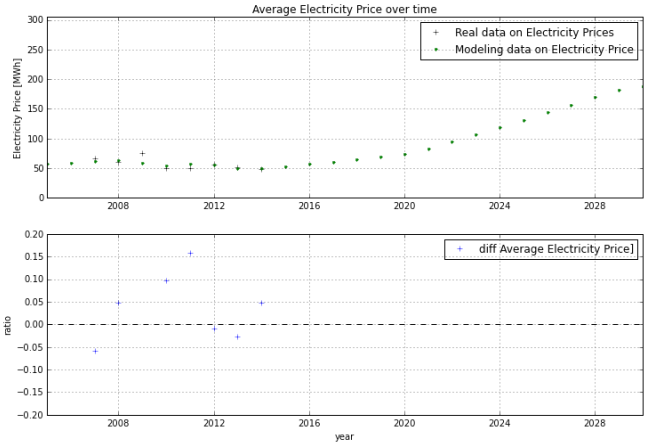

Figure 5.6 Average Electricity Price - Modeling output and real data

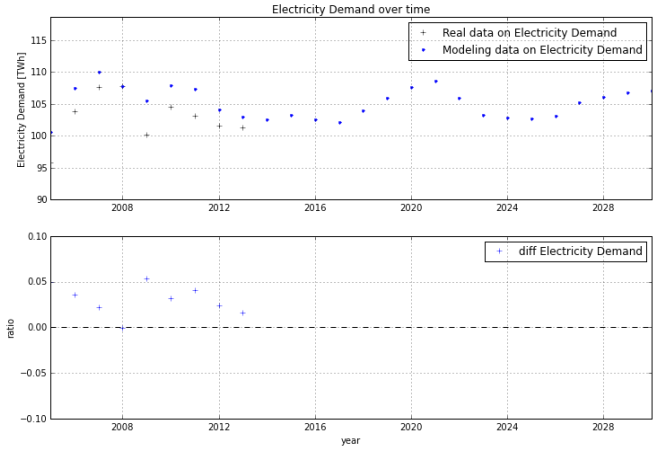

Figure 5.7 Electricity Demand - Modeling output and real data

The R^2 value of the average electricity price is reasonable, especially when taking into account that this variable is determined based on electricity demand and supply which deviate from the real data already. Mostly, the low value for Electricity production causes the low R^2 value of the Average Electricity Price.

From the Behavior Pattern Test could be concluded that the modeling results fit reasonably well to the real data, but that there is room for improvement as well. In the next section an explanation will be given on which aspects have been improved during the validation already and within which aspects there is still room for improvement – which could be used as starting points for future research.

5.3 Discussion of the validation results

The validation shows that the model fits the purpose reasonably, though there is still room for improvement which could be concluded from the Behavior Pattern Test. This test shows some low R^2 values which do not have the correct shape. Even though the real data falls within the bandwidth of the modeling results from the Monte Carlo simulation (with an among others varying wind speed), the R^2 values should be improved.
An example of an important factor that is currently missing in the SD-model, is a more comprehensive determination of electricity import and the price of the imported electricity. This because cheaper electricity prices from, mostly, Germany influence the Dutch electricity prices.

During the validation process, some improvements were made already.
Before the validation, a decision was not made yet on how the *Investment Budget* should be determined in the System Dynamics model. In the Behavior Pattern Test, better results were achieved when the *Investment Budget* was determined based on the profit instead of based on the revenue. An explanation for this is that when an energy utility company does not make any profit – because cost are too high – investments are less likely to be made. Besides, if fixed cost are not covered due to high cost and overcapacity it would be unrealistic when more investments would be made leading to an higher overcapacity.
Another important improvement made is the addition of external financing to the SD-model. If no profits are made and thus no *Investment Budget* from energy utility companies would be available, it would not directly imply that no investments are made. Within a positive investment environment for certain generation capacity, investment budget could be obtained from investors or banks. In this way, the electricity production mix could faster be developed if and only if the investment environment is good enough for external investments. In Appendix B.3. an explanation is given on how external investments are added to the model.
Since external investments could be made to develop the electricity production mix, closing down power plants earlier when not profitable could make the SD-model more realistic as well. The closing-down-decision is made when the investment environment for certain generation capacity is negative and if certain generation capacity is not profitable. This could be due to low production hours and high fixed cost or to high variable cost in combination with low electricity prices. In Appendix B.3. it is also explained how the closing-down decision is added to the SD-model.

The last important improvement to the SD-model is the addition of an *Price of imported electricity factor,* which ensures that the lower electricity prices from neighbor countries influence the Dutch Electricity prices – which happens in the real system but which was not part of the SD-model yet. As Figure 5.3, in chapter 5.2.1., shows is the average electricity price in Germany 20% lower than in the Netherlands. Therefore, it is assumed that the *Price of Imported electricity factor* should be 0.8 (Appendix B.3). This factor is validated in the Behavior Pattern Test and it shows that by adding this factor the average electricity price in the model only has an average deviation of 9.3% compared to the real data (see Figure 5.4). Figure 5.4 shows the results based on the latest situation.
Having added these improvements, the SD-model fits the purpose fairly well. In the next chapter, the modeling results are described. This delivers input for a discussion about the strong and weaker aspects of the designed System Dynamics model (chapter 7), which are determined based on a comparison with existing simulation models.

6. Modeling Results

This chapter answers the sub-question: *What are possible developments of the Dutch electricity system towards 2030, taking into account uncertainty factors?*

The uncertainty factors towards 2030 have been taken into account by executing a Monte Carlo (MC) Analysis. A Monte Carlo Analysis is a computational method where simulations are executed a number of times, while randomly varying certain aspects in the simulation. In the System Dynamics model, the varying factors are uncertainty factors with an assumed normal distribution or a random uniform distribution.

The uncertainty factors are connected with the external factors of the model. By running the model 8000 times and thereby varying the external factors, future scenarios have been covered – within the uncertainty range. This final number of 8000 runs are determined by doubling the number of runs each time and comparing the simulation outputs. Once the simulation outputs do not differ from each other, the final number of runs have been identified. The simulation runs showed that this was the case with about 8000 runs. Figure 6.1 shows an example of a Monte Carlo simulation output (after 80000 runs) in the System Dynamics software – Vensim. This simulation output is further analyzed in this chapter.

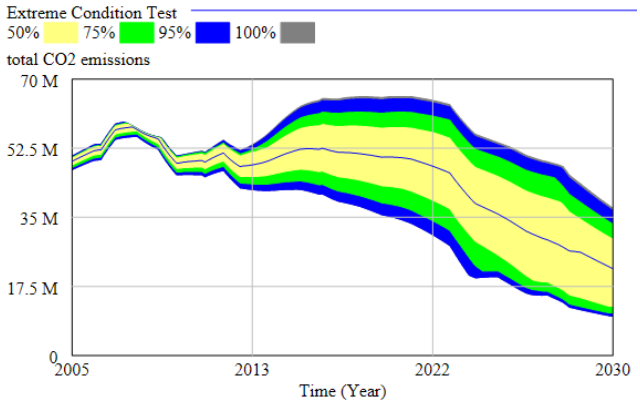

Figure 6.1 Example of Monte Carlo simulation output from Vensim – CO2 emissions

This chapter firstly focuses on the modeling output of the system domain factors from 2005 to 2030. Next to that, a qualitative analysis is executed to explain the behavior of the modeling output. The effects of energy storage have been analyzed briefly and those results will be shown in the import and export section as energy storage is connected to these variables in the model.

Hereafter, influential external factors and policies from the SD-model are plotted against modeling results of the system domain. This provides interesting insights for different stakeholders in the electricity system. For example information could be gathered on the behavior of the SDE+ subsidy and its influence on CO2 emission reduction.

Finally, in chapter 6.4 a discussion will be held on the overall modeling results of the System Dynamics model. This to provide insight for the stakeholders and to come up with recommendations for the stakeholders.

6.1 System Domain Modeling Results

6.1.1 Electricity Demand

The previous chapter – verification and validation – showed that the central modeling output of the electricity demand from 2005 to 2014 matched well with the real data. The electricity demand side of the System Dynamics model is the foundation for the Monte Carlo Analysis towards 2030. The uncertainty factors influencing the electricity demand are, population growth, energy price development, decentralization of electricity production, Electric Vehicle (EV) adoption and Gross Domestic Product

(GDP). In Appendix D the assumptions on development towards 2030 of these external factors are explained. All the external factors influencing the electricity demand will increase towards 2030. It is expected that the decentralization of electricity production and EV adoption will increase the most. As literature does not provide information on the distribution of these external factors, a variation of 10% according to a random uniform distribution is assumed for the Monte Carlo Analysis. Possibly, not all these variations are as realistic, but research needs to be done to investigate what the appropriate variations of the external forces.

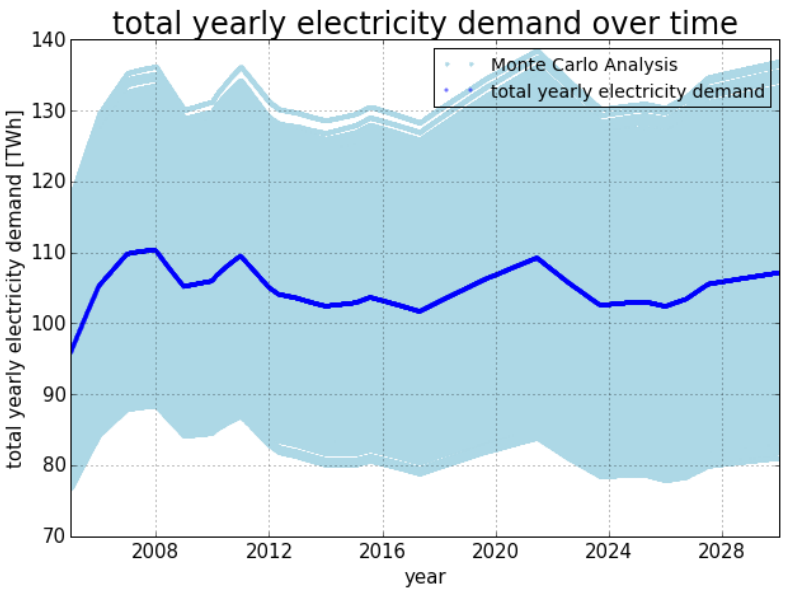

Figure 6.3 Electricity Demand

The result of the Monte Carlo analysis is provided in Figure 6.3 – where all external forces (shown in Appendix C) are provided. The blue dots represent the modeling output of the electricity demand if all external forces are not varied. The light blue area is the Monte Carlo Analysis output and represents the bandwidth of conceivable electricity demand towards 2030.

The central modeling output is relatively stable. The undulation is mostly caused by GDP development and decentralization, which is indirectly enhanced by economic growth. If decentralization would not be taken into account – which is mostly the case in other electricity demand forecasts – then the central value would grow towards approximately 140 TWh per year (see Figure 6.2). When taking into account the same uncertainty factors, the bandwidth of electricity demand towards 2030 would correspond with the electricity demand forecast in the Netherlands – Figure 6.4 by ECN (energy Research Centre in the Netherlands). To compare with the forecast of the ECN, a simulation run has been executed when the decentralization is not been taken into account. This shows that the simulation results and the forecast of ECN show similarities – with both an expected electricity demand of 140 TWh in 2030.

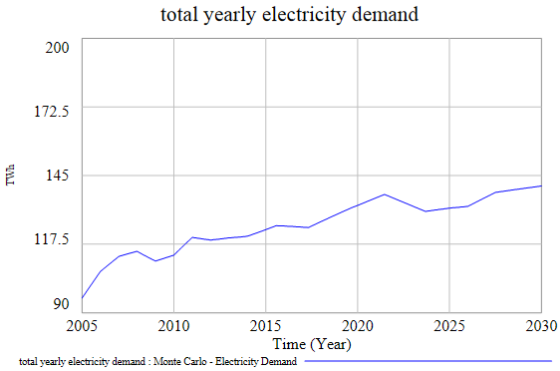

Figure 6.2 Electricity Demand without Decentralization

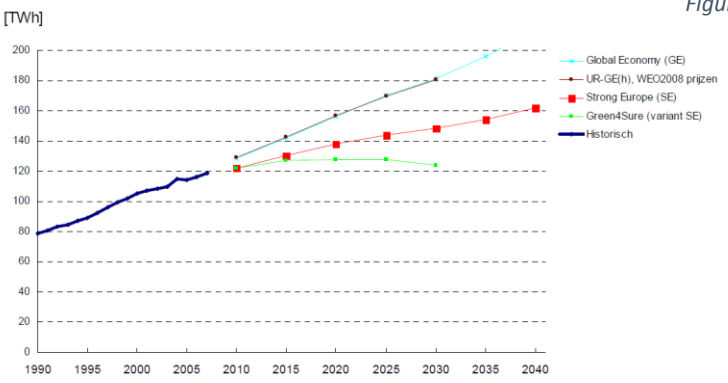

Figure 6.4 Electricity demand forecast (Seebregts et al., 2009)

The modeling output of electricity demand, when taking decentralization

into account, lies between 88 – 128 TWh per year. From Figure 6.3 and Figure 6.5 could be concluded that most of the output lies between 96 – 116 TWh (with 500 or more simulation results within this bandwidth).

Next to GDP and decentralization, the population growth has a large influence on the development of electricity demand (see sensitivity analysis results in Appendix G.2). It is expected that the Dutch population will grow from 16,8 million to 17,07 million in 2030. That this relatively small population growth, compared to developing countries like China and India, already influences the electricity demand underlines the importance of closely monitoring this development (KPMG, 2012).

The last external factor that is positively correlated with electricity demand is the adoption of Electric Vehicles (EVs). The adoption of EVs ensures the reduction of gasoline usage and CO2 emissions, but the electricity demand increases – both from the central grid as well as from decentralized electricity production.

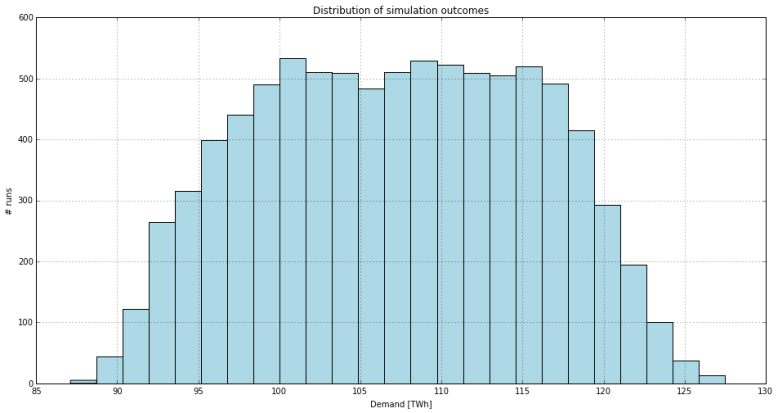

Figure 6.5 Distribution of simulation output in 2030 - Electricity Demand

Energy prices are negatively correlated with electricity demand. The WorldWatch Institute predicts that energy prices will continue to grow towards 2030 (WorldWatch Institute, 2013). This growth has been taken into account in the SD-model and thus negatively influences the electricity demand growth.

6.1.2 Electricity Production Capacity

The verification and validation chapter showed that the central modeling output of the gas and coal installed capacity did not match well to the real data at all times. Wind capacity showed to behave well compared to real data, whereas gas and coal did not which was caused by an investment delay in the model. Further research should be done to improve the investment process by eliminating the delay. The installed capacity of nuclear has an extremely low R^2 value, but this could be justified as it is caused by the modeling characteristics – continuous modeling – of System Dynamics. To deal with uncertainties, a Monte Carlo Analysis has been executed on the Electricity Production Capacity (i.e. Installed Capacity) as well.

The uncertainty factors directly influencing the installed capacity of the different generation methods are:

- The available investment budget (dependent on which percentage of the profit – *Investment Percentage* – is invested in new electricity production capacity and the profits made)
- How much external financing becomes available for investments in electricity production capacity
- The affinity with a certain generation method
- The development of the CO2 price in the Emissions Trading Scheme
- The available SDE+ subsidy for sustainable investments

Uncertainty factors that indirectly influence the installed capacity – like factors influencing the electricity demand – have also been taken into account in the Monte Carlo Analysis as all the external variable have been varied in these MC-analyses.

The increasing volatility of electricity prices towards 2030 (see chapter 6.1.4) leads to smaller profit in the future, leading to smaller Investment Budget. Therefore, investments are dependent on external financing and the SDE+ subsidy for wind electricity production capacity. External financing will only be available when the investment environment is favorable. This is dependent on the affinity for the generation methods and the CO2 price. These are the two external factors the electricity production capacity is mostly sensitive to.

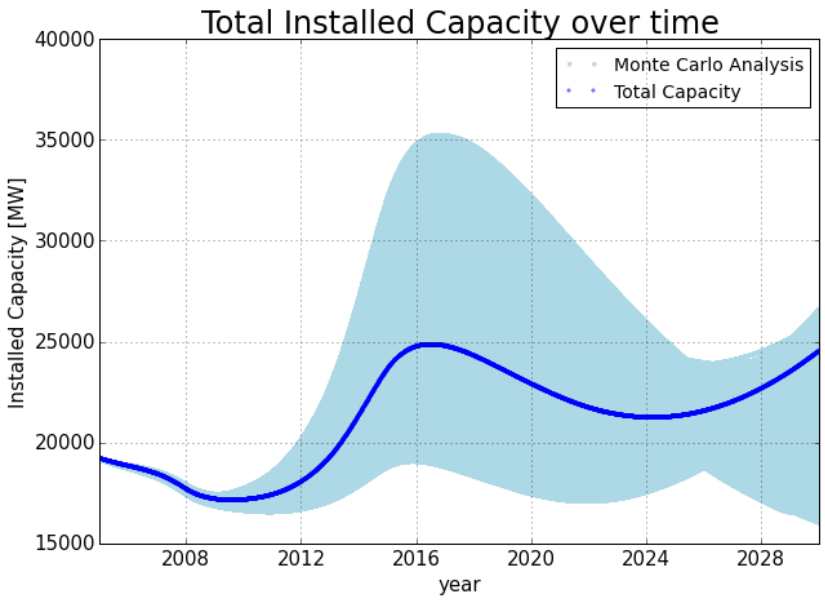

Figure 6.6 Monte Carlo on Total Installed Capacity

As literature does not provide information on the distribution of these external factors, a variation of 10% according to a random uniform distribution is assumed for the Monte Carlo Analysis.

The results of the Monte Carlo Analysis is provided in Figure 6.6 and Figure 6.7 provides the distribution of the Electricity Production Capacity in 2030. The blue dots represent the modeling output of the total capacity development if all external forces are not varied. The light blue area is the Monte Carlo Analysis output and represents the bandwidth of a conceivable total capacity development towards 2030.

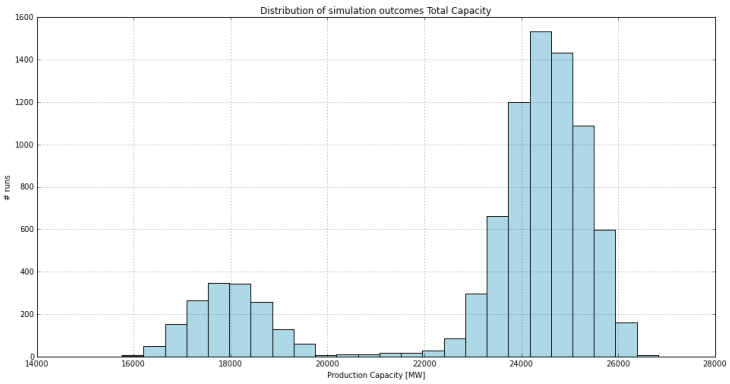

Figure 6.7 Distribution of Monte Carlo Analysis in 2030 - Electricity Production Capacity

Figure 6.6 shows that the total installed capacity from 2011 towards 2015 increases fairly fast. This is due to the fact that large investments in coal and gas capacity are done, mostly because of a low CO2 price and thus a high affinity for these generation methods. This leads to a large overcapacity for electricity production, leading to lower electricity prices. The lower electricity price negatively influences the operating income of energy utility companies in the Netherlands (Climategate, 2013).

Figure 6.7 shows a distribution of the Electricity Production Capacity with two tops. This is caused by the two-top distribution of the installed capacity of wind – shown in Figure 6.9.

The Monte Carlo Analysis output of total capacity around 2015 is extremely divergent compared to the output in other years. This is due to a fairly low CO2 price in combination with a varying affinity, which leads to a positive investment environment. Therefore, more investments in new generation capacity have been done around 2015 leading to a larger absolute variety around this time. The CO2 price is expected to increase rapidly towards 2030 and therefore the variation of total capacity is less in 2030

compared to 2015. Also, the CO2 price causes the investments to mostly focus on wind energy capacity instead of on carbon intensive capacity methods as these investments becomes too expensive.

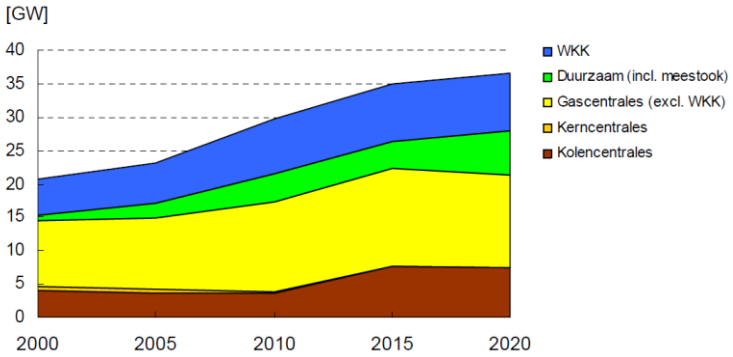

Figure 6.8 Installed Capacity Forecast (Seebregts et al., 2009)

Figure 6.8 shows forecasts towards 2020 of the ECN (Energy Research Centre in the Netherlands) on the total installed capacity development in the Netherlands. The blue area (WKK) should be subtracted from the total as this is installed capacity to deliver heat. The other four colors contain the data on the same generation methods as in the SD-model. In 2020, the total installed capacity is around 28,000 MW. These numbers match well with the modeling output of the Monte Carlo Analysis of the total capacity.

The installed capacity of wind energy is shown in Figure 6.9. It shows that towards 2030, the variation of installed capacity is high. The variation lies between 7,000 MW and 20,500 MW, though the distribution on the right side shows that it is mostly likely that the installed capacity will be between 17,000 and 19,000 MW in 2030.

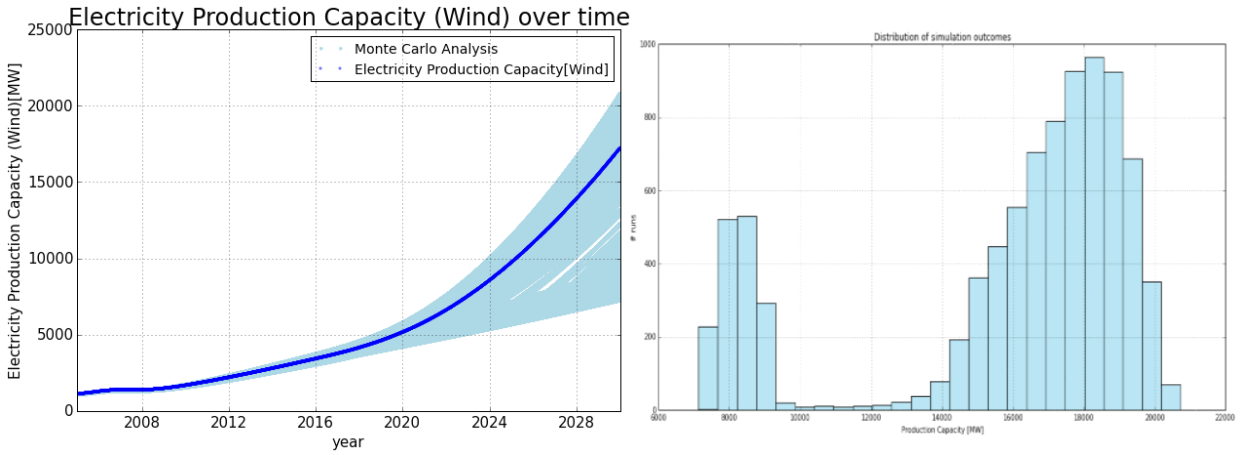

Figure 6.9 Installed Capacity over time (Wind)

The reason the distribution graph consists of two tops, has to do with the SDE+ subsidy. Apparently an installed capacity of wind generation of more than 14,000 MW can only be reached when the investment environment is positive. In the scenario that the investment environment for wind energy adoption is poor, investments in wind energy will still be made through the SDE+ subsidy – this explains the left top of the distribution graph.

Figure 6.10 (next page) shows the installed capacity of gas. It shows that towards 2030 the installed capacity of gas decreases. The distribution graphs (on the right) show that it is mostly likely that the installed capacity will be between 2,600 and 3,600 MW by 2030. The maximum in the installed capacity development around 2015 is caused by low CO2 prices, which leads to a positive investment environment for carbon intensive production capacity.

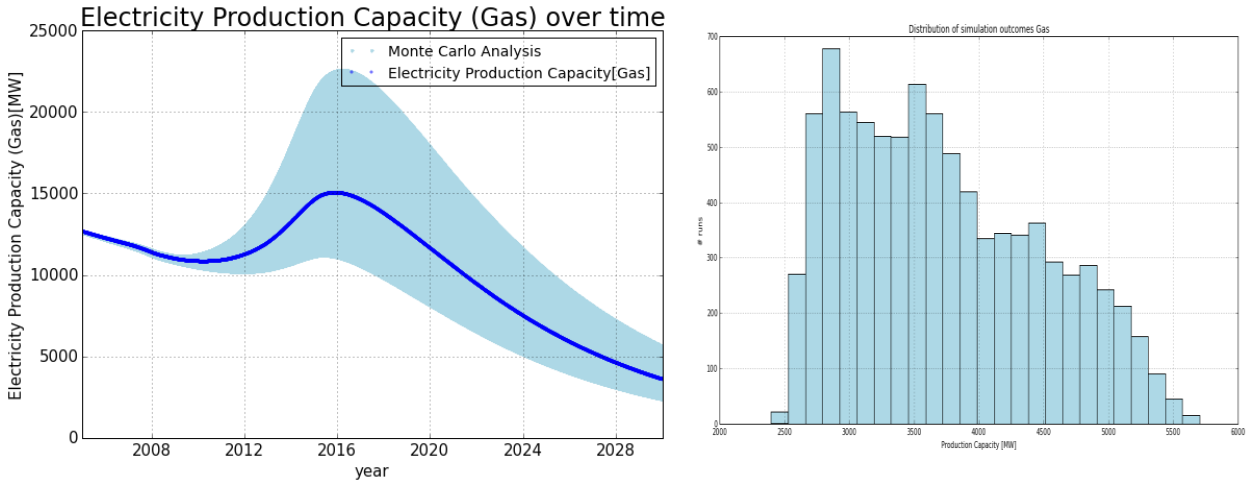

Figure 6.10 Installed Capacity over time (Gas)

The installed capacity of coal energy is shown in Figure 6.11 and displays a downward trend – as well as for gas capacity in Figure 6.10. Also for coal production capacity this is due to the fact that the CO2 price increases towards 2030. Coal production is even more sensitive to CO2 price fluctuations than gas production capacity, this because coal emits approximately twice as much CO2 per generated MWh. By 2030, it is most likely that the installed capacity lies between 1,500 and 2,500 MW (above 500 runs).

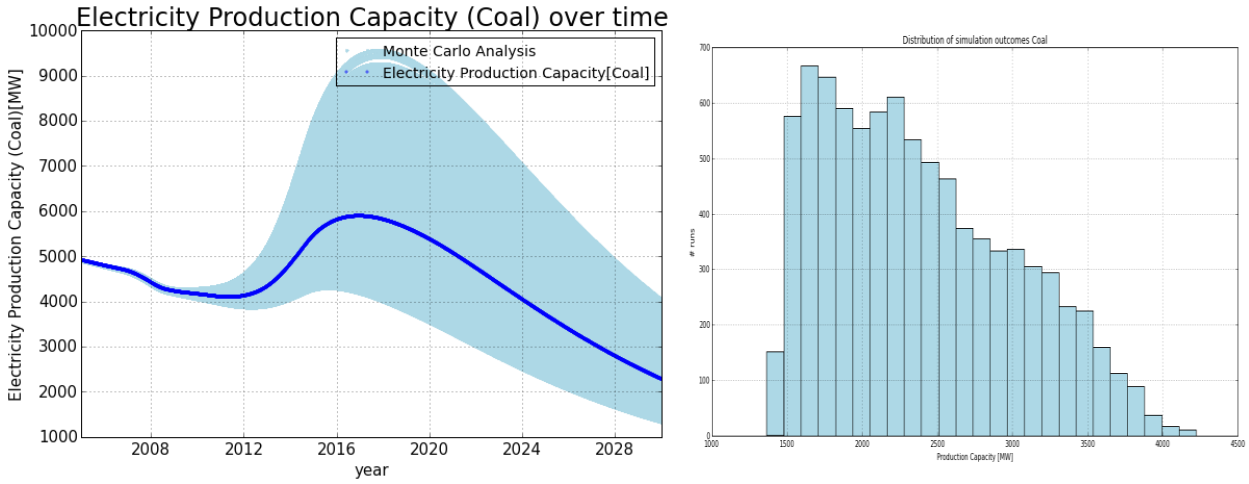

Figure 6.11 Installed Capacity over time (Coal)

Figure 6.12 (next page) shows the modeling results of installed capacity of nuclear energy. Due to the increasing CO2 price after 2015, the investment environment for nuclear energy becomes better which leads to the adoption of nuclear capacity. This is consistent with the real world, as the Dutch government has been discussing the last couple of years whether to build a second nuclear power plant of maximum 2,500 MW (VROM, 2010). This discussion was postponed in 2012. However the investment environment towards 2030 is expected to improve, which could trigger the discussion to start again. In this discussion the public opinion is also an important factor, but this factor has not been taken into account in the System Dynamics model.

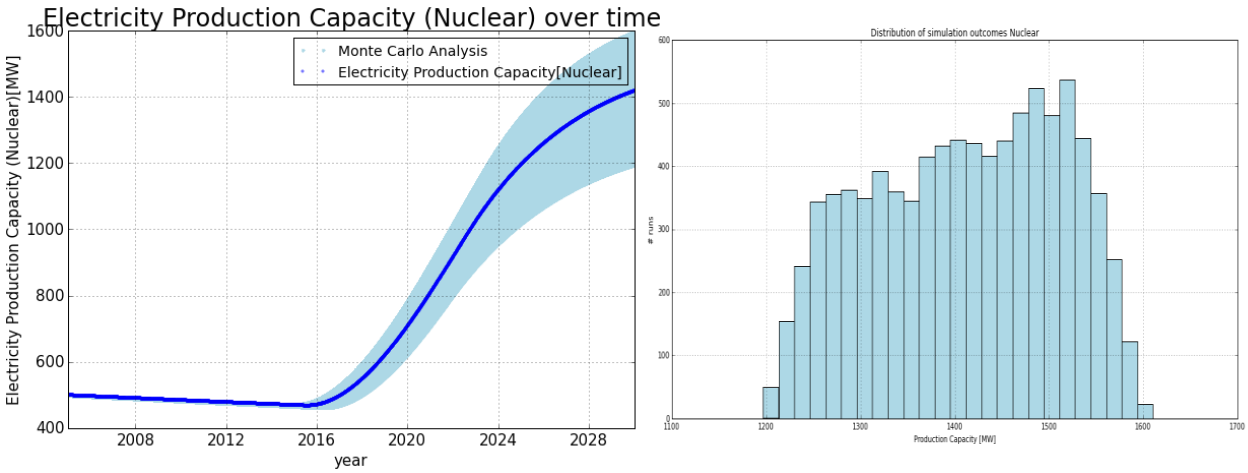

Figure 6.12 Installed Capacity over time (Nuclear)

The current nuclear power plant in the Netherlands (Borssele) of 500 MW is expected to close in 2033, but the SD-model already anticipates on this closure – since it is a continuous modeling technique. The same counts for the anticipation of the SD-model to open a new nuclear plant in the future – it is done step by step. This explains why the R^2 value in the validation chapter is extremely low. Based on the modeling results and its explanation for the behavior, it could be concluded that the model is reasonably realistic.

Based on the modeling results it is most likely that the installed capacity of nuclear energy will lie between 1,250 and 1,550 MW by 2030 (when above 300 runs).

6.1.3 Electricity Production

When validating the electricity production side of the SD-model – by calculating the R^2 value – it showed that this part of the model did not match the real data very well. It showed that the SD-model was too slow in adapting to sudden changes that happened in the real world situations. This has to do with the demand forecast within the SD-model, which has delay of about two to three years. As the electricity production is based on the electricity demand – which matches the historic data reasonably well – it could be concluded that this SD-model could provide interesting insights on the future electricity production. Though, as the R^2 value of electricity production is relatively low, it should be noted that there is still room for improvement for this part of SD-model.

The uncertainty factors influencing the yearly electricity production and have been taken into account in the SD-model are:

- The wind speed, which varies constantly. When the wind speed is low and thus low wind electricity production is achieved, electricity should be generated through flexible gas power plants – and vice versa. The distribution of wind speed is determined Appendix F.1. based on ten years of historical data. It follows a normal distribution, with an average of 7.27 m/s and a standard deviation of 3.68 m/s. By integrating a wind energy production model (Pieter Bots, 2015), the yield of wind electricity production is calculated based on the available wind speeds.
- The demand forecast factor. Based on the demand forecast it is calculated how much electricity needs to be produced. Just like in the real case, where demand forecasts will be made to organize

the production mix most efficiently. The uncertainty of this external forces is varied with 10% according a random uniform distribution.

The dynamics of both factors – wind availability and demand forecast – causes the electricity production to vary from the central modeling output when varying all external factors, which is shown in Figure 6.13. The central modeling output of the SD-model shows to be relatively stable, which is as expected since the electricity demand was stable as well. Towards 2030, more variation from the central modeling output starts to occur. This can be assigned to the increasing wind production capacity, which around 2025 starts to increase faster. The large installed capacity of wind energy in combination with high wind speeds, lead to a large electricity production. From the distribution graph in Figure 6.13 it can be concluded that those volumes of electricity production do not occur very often.

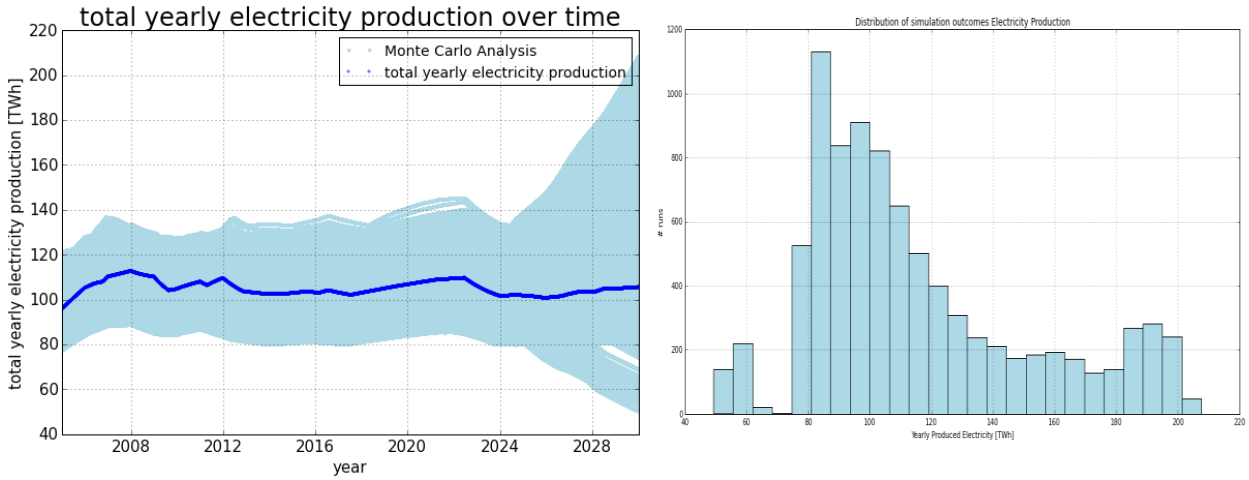

Figure 6.13 Electricity Production over time

The small gap around 2030 and an electricity production of 80 TWh – which is also shown in the distribution graph as a gap on the left – corresponds with the bottom in Figure 6.9 of installed capacity of wind.

In chapter 6.2 a more detailed analysis is done on the effect of wind speed, the electricity production capacity of wind and the electricity price. In this analysis the sudden increased variation around 2025 is shown as well.

Based on the modeling results it is most likely the yearly electricity production lies between 85 and 105 TWh per year.

6.1.4 Electricity Price

The verification and validation chapter has shown that the designed SD-model works fairly well for determining electricity prices in the past. The relatively high R^2 value indicates that the modeling output matches well with the real data.

The electricity price is an ouput of the electricity demand, electricity production and the cost of electricity production – all determined in the SD-model. Deviations between the modeling data and real data of these three factors strengthen the deviations between the modeling output and the real data of the electricity price. This also implies that the external factors that directly influence the electricity demand, electricity production and the electricity production cost, indirectly influence the electricity price. Therefore a Monte Carlo Analysis is executed to determine the electricity price under as many possible circumstances, wherefore all the external forces have been varied.

The electricity price part of the SD-model contains two external factors that directly influence the electricity price. The first external factor is the initial marginal cost per generation method. This initial value is determined based on marginal cost of power plants in the United States (Frayer, Ibrahim, Bahceci, & Pecenkovic, 2007). Whether these values correspond to the marginal cost of power plants in the Netherlands is uncertain, since no literature was found on Dutch power plants. Therefore an uncertainty factor to the initial marginal cost was added, which varies the initial marginal cost with 10%. The second external factor that directly influences the electricity price is the *Direction Coefficient Marginal Cost* variable. This factor has been added to the SD-model to more realistically model the bid prices in the APX Power Exchange. Marginal cost of power plants of the same generation method are never the same. The power plants with the cheapest marginal cost will be used first and the highest marginal cost power plants will be used last. In order to add dynamics to these marginal cost in the same generation method region, the *Direction Coefficient Marginal Cost* variable was called into place – which is also be varied in the MC-analysis.

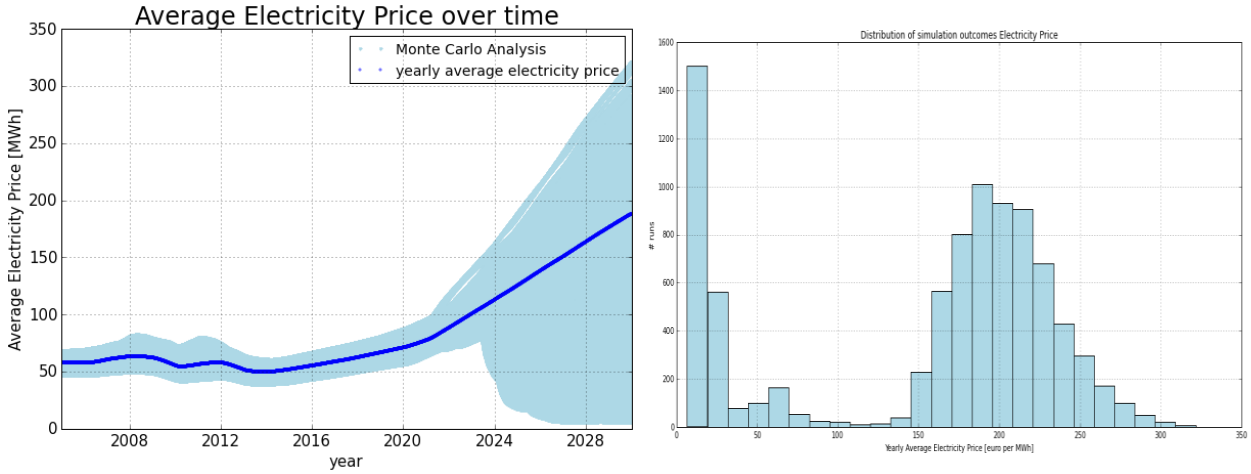

Figure 6.14 Yearly Average Electricity Price over time

Figure 6.14 shows the modeling results of the Monte Carlo Analysis of the *yearly average electricity prices*. The central value output indicates that there yearly average electricity prices have an upward trend towards 2030. The modeling results of the Monte Carlo Analysis clearly indicates that electricity prices become very volatile, with an approximate range of €5 to €320 per MWh. This is mostly debit to the large available capacity of wind energy and the volatility of wind availability. When wind is available in abundance, an increasing amount of demanded electricity could be covered by wind energy production. If wind becomes unavailable, all the demanded electricity should be covered with relatively expensive power plants and electricity import.

The fast increase of the average electricity price – dark blue line – after 2020, is mostly caused by the fast increase of the CO2 price. Figure 6.15 shows the sensitivity of the yearly average electricity price when the CO2 price becomes 25% lower and 25% higher.

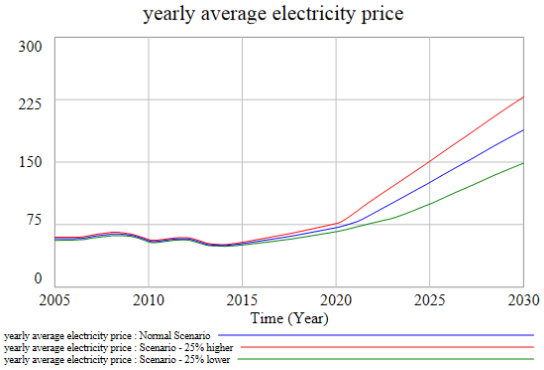

Figure 6.15 Sensitivity analysis after varying the CO2 price scenario by 25%

The sudden drop in Figure 6.14 around 2025 is caused by the transition phase in the merit order from one generation method to another generation method. The first drop is caused by the transition from the marginal

cost of gas to the marginal cost of coal. Eventually around 2027, scenarios start to occur where the marginal cost of wind start to determine the electricity price. The distribution graph in Figure 6.14 indicates that this low average electricity price occurs about 1400 times of the total 8000 runs.

The volatility of electricity prices could be seen more clearly when determining the electricity price per phase – Base, Shoulder and Peak.
The volatility in the base towards 2030 shows an approximate range of 5 to 260 euro per MWh. From the distribution graph (in Figure 6.16) can be concluded that it is most likely that the electricity price is approximately 10 euro per MWh or approximately 170 to 190 euro per MWh.

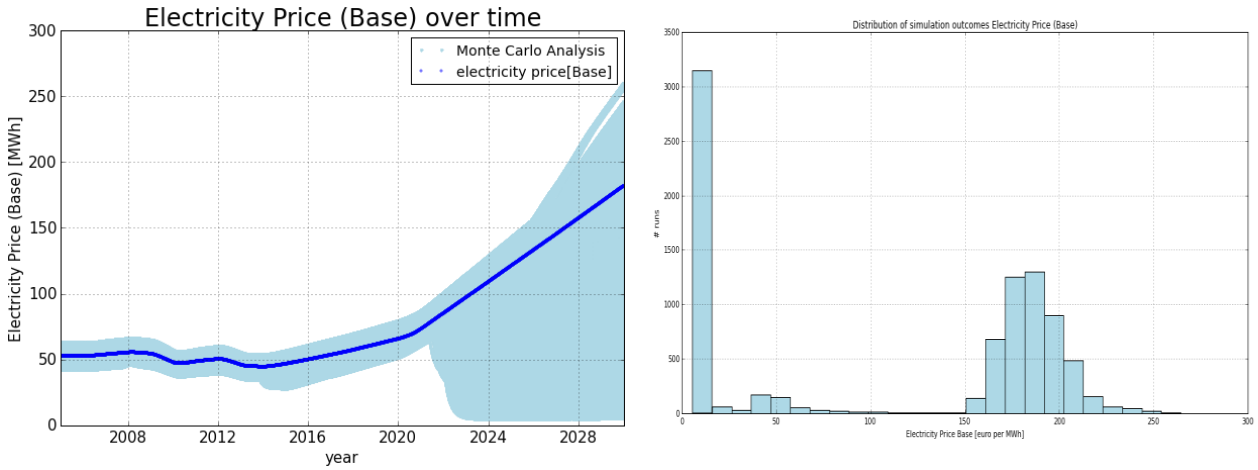

Figure 6.16 Electricity price (Base)

The volatility in the shoulder towards 2030 shows an approximate range of 5 to 320 euro per MWh (see Figure 6.17). From the distribution graph could be concluded that is is most likely that the electricity price is approximately 10 euro per MWh or approximately 170 to 225 euro per MWh.

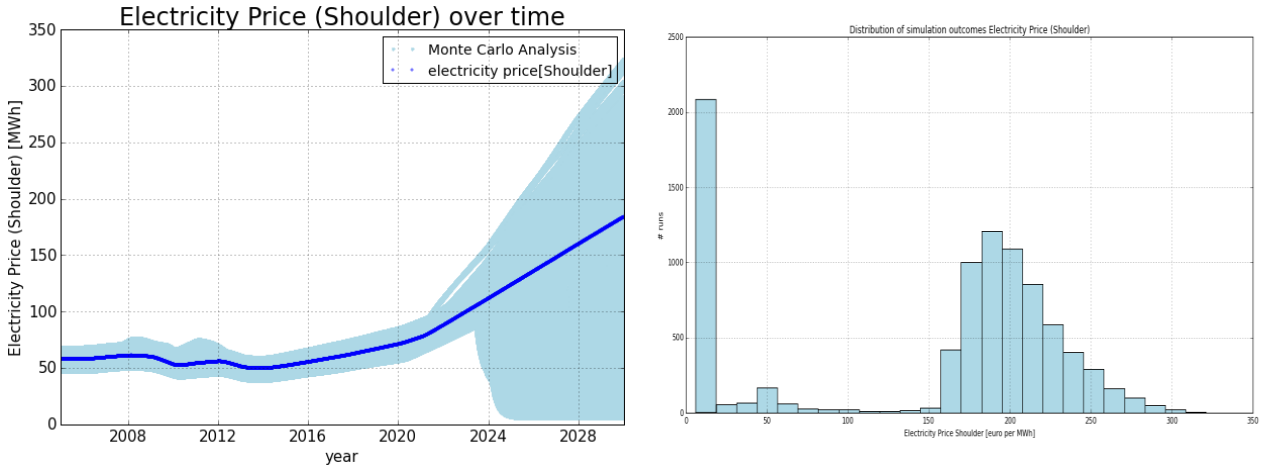

Figure 6.17 Electricity Price (Shoulder)

The volatility in the peak towards 2030 shows an approximate range of 5 to 385 euro per MWh (see Figure 6.19 – next page). From the distribution graph could be concluded that it is most likely that the electricity price in the peak is between approximately 165 and 285 euro per MWh. Though, it sometimes occurs (almost 1200 hours in a year) that the electricity is around 10 euro per MWh.

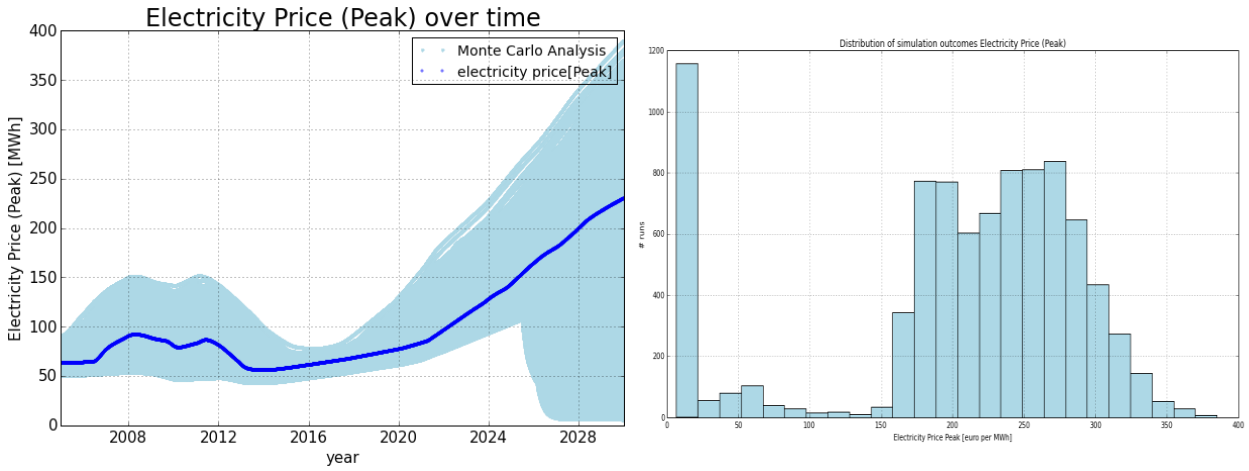

Figure 6.19 Electricity Price (Peak)

Electricity demand is high during peak hours. When wind becomes unavailable, all the demanded electricity – which is high in volume – should be produced with the remaining available production capacity and possibly electricity could be imported from abroad. In extreme conditions, the electricity demand could exceed the available supply, which causes an electricity shortage. In these situations, the electricity price will become extremely high and the grid operators will take measures (i.e. rolling black-outs) to lower the electricity supply. The extremely high electricity prices do not occur in the SD-model, since it is assumed that importing electricity is always possible. In the real world, this is not always the case, which causes high electricity prices and an unstable electricity system. Figure 6.18 shows the electricity import over time and provides an indication on when shortages could have occurred in the Dutch electricity system – when electricity import exceeds the installed capacity of interconnectors. The total installed capacity of interconnectors was 3600 MW in 2005 and it is expected to grow to 9000 MW in 2030 (TenneT Holding B.V., 2015)

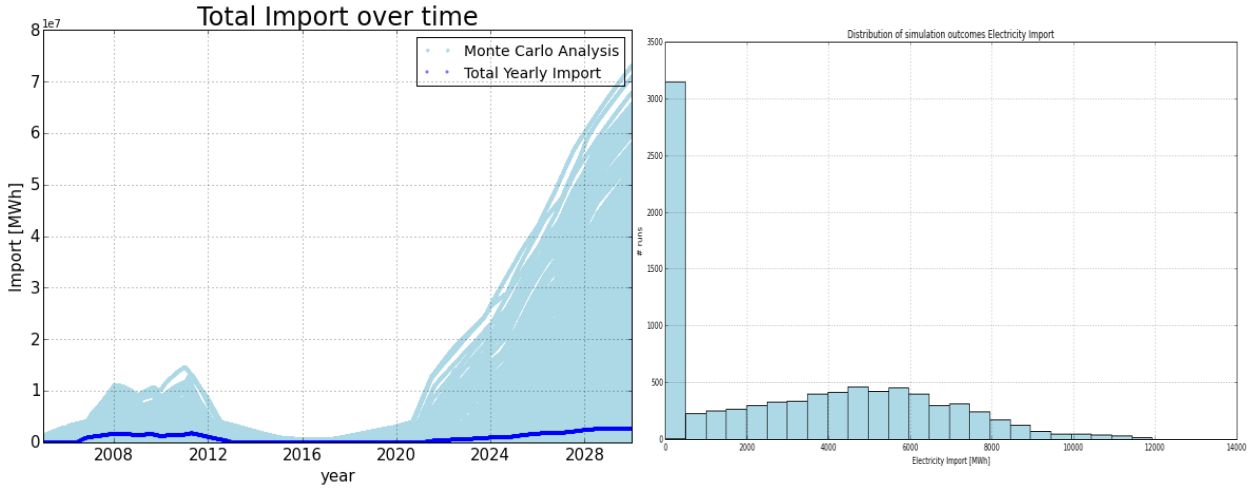

Figure 6.18 Electricity Import

From Figure 6.18 it can be concluded that towards 2030 more than 9000 MW of installed interconnector capacity could be needed. The distribution graph shows that the electricity import exceeds the interconnector capacity approximately 400 times – of the 8000 simulations runs – in 2030.

Electricity demand is relatively low during base hours. When wind becomes highly available during those hours, demanded electricity could be covered increasingly easy. As nuclear and carbon energy production are relatively inflexible, it could be assumed that this electricity will also be produced during those hours. This leads to an extreme surplus of electricity in the system. Electricity prices will be close to the marginal cost of wind energy production, since the demanded electricity could already be covered by electricity generated from wind.

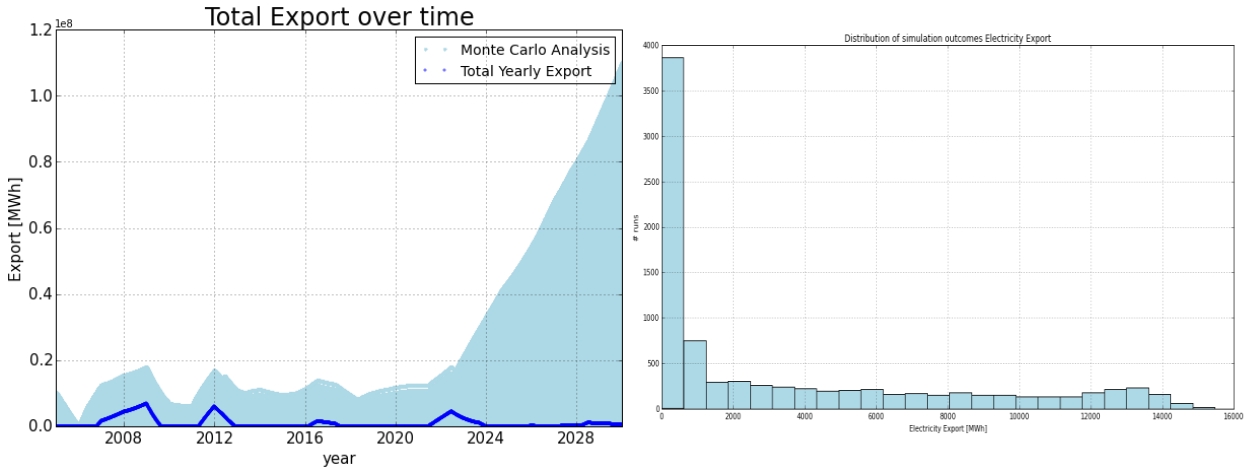

Figure 6.20 Electricity Export

In order to keep the electricity stable, demand and supply of electricity should be matched. Therefore the grid operators shall try to get rid of the excess electricity by exporting it to neighbor countries. In the SD-model it is assumed that electricity could always be exported to neighbor countries. In the real world, this is not always the case. Situations could occur where not all the excess electricity could be exported. During those extreme conditions, the electricity price could become negative. This basically means that the grid operator will pay consumers to use electricity.

Very low or negative electricity prices will lead to higher demand, which will stabilize the system again.

The total electricity that in theory could be exported equals the interconnector capacity (9000 MW). Based on Figure 6.20 it could be concluded that this capacity might be exceeded – approximately 1500 times per 8000 simulation runs – towards 2030.

The effects of energy storage on the Dutch electricity system have been analyzed briefly in the System Dynamics model. Energy storage is added to the SD-model in such a way that when there is surplus electricity, it will not directly be exported but first the storage capacity will be filled. When no storage capacity is left, it will be exported to neighbor countries. When a shortage of electricity occurs, electricity will be supplied from the energy storage before electricity is imported from neighbor countries.

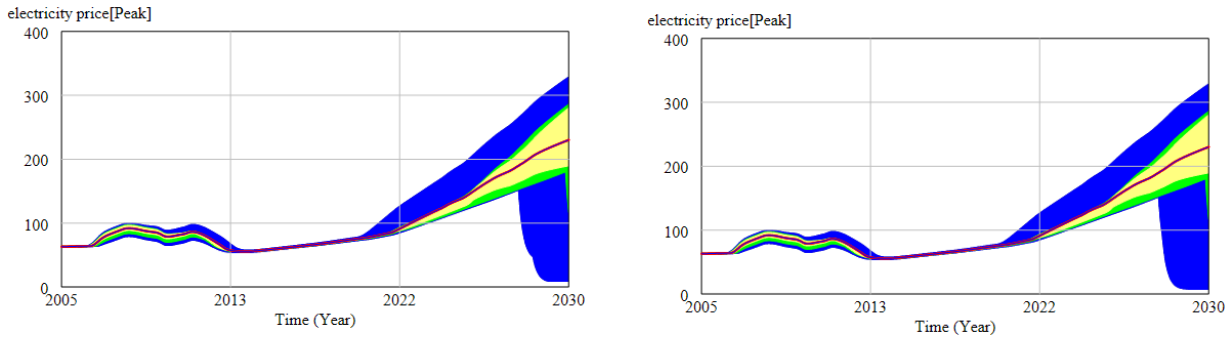

Figure 6.21 The modeling effects of energy storage - No Energy Storage (left) and Energy storage (right)

The simulation results show that energy storage does not affect the Dutch electricity system, which is contradictory to expectations of energy storage development. This is due to the fact that the built SD-model looks at long term trends, whereas energy storage is done in short term periods. Future research is needed to add the short term effects of energy storage in the long term trend model that is built in this research.

6.1.5 CO2 Emissions

The verification and validation chapter showed that the determination of the yearly CO2-emissions in the SD-model match relatively well with the real historical data. CO2-emissions depend on how much electricity is produced and which generation methods are used for the production. Deviations from the real data and the modeling results of electricity production thereby add up to the deviations of the modeling results of CO2-emissions. Taking this into account, the R^2 value is still relatively high. This indicates that the modeling data of CO2 emissions matches reasonably well with real data and thus that this part of the model provides a foundation for a Monte Carlo Analysis.

The external factors that directly influence the CO2 emissions are the CO2 price from the Emissions Trading Scheme (ETS) and the CO2 emissions per generation technology, which should contain an uncertainty factor – like the other external factors.
The CO2 emissions are mostly sensitive for variations in CO2-price (see appendix G.2. – sensitivity analysis). It is expected that the CO2 price will reach 186 euro per ton CO2 in 2030 (Neuhoff & Schopp, 2012). As the development of the CO2 price towards 2030 is uncertain, a uncertain factor of 10% (uniform random distribution) is included to the CO2 price.
The efficiency of a power plant – CO2 emissions per generated MWh – influences the total CO2 emissions as well. An uncertainty factor of 10% (uniform random distribution) has also been added to this factor.
Figure 6.21 illustrates the Monte Carlo Analysis output of the CO2 emissions of the Dutch Electricity system.

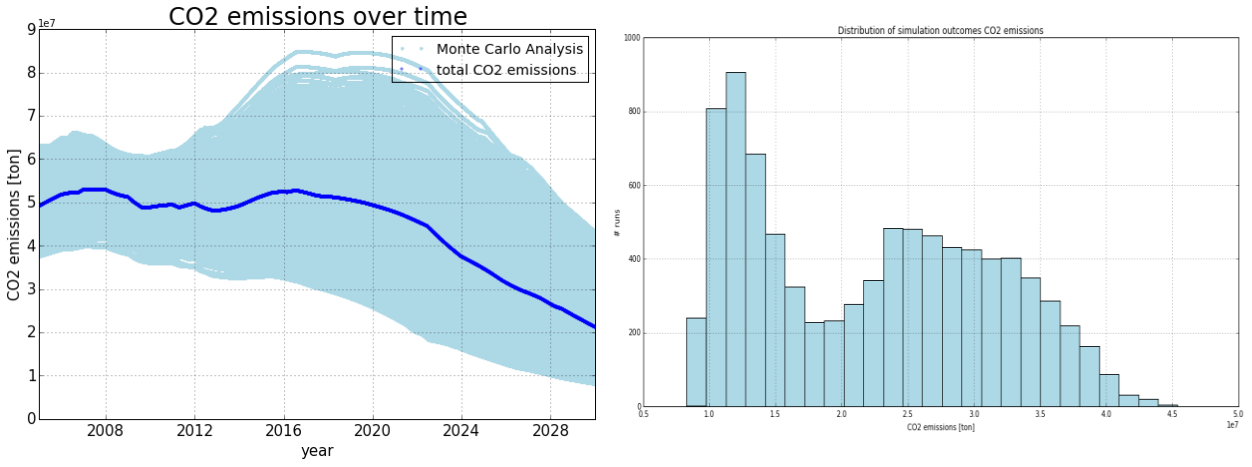

Figure 6.22 CO2 Emissions

The central output shows a downward trend, which is caused by the decrease of carbon intensive production capacity. The Monte Carlo output shows a short increase of CO2 emissions around 2015, which is due to the investments made in coal and gas capacity.
Towards 2030 it is likely – taking the model and its assumptions into account – that the yearly CO2-emissions will be around 10 to 15 million tons of CO2, compared to 50 million tons in 2005. In another plausible situation – which could occur when the adoption of wind energy capacity is slower – the yearly

CO2-emissions will be around 23 to 33 million tons of CO2. Comparing the expected CO2 emissions of 2030 with the CO2 emissions of the Dutch electricity system in 1990 – 45.2 million tons of CO2 – it translates to an expected reduction of CO2 emissions of 27% to 50%. As the Dutch government focuses on 40% CO2 reductions by 2030 compared to the levels of 1990, reaching a reduction between 27% to 50% would significantly help to achieving these sustainability targets.

6.2 External Forces

Section 6.2 and 6.3 focus on creating more understanding on the behavior of the Dutch electricity system under different circumstances. There are three important stakeholders that could gain from the analysis done in section 6.2 and 6.3, energy utility companies, grid operators and policymakers. The analysis for energy utility companies focuses on the development of electricity prices and the effect of external forces on the prices. For grid operators, the analysis targets on import and export of electricity under different circumstances in order to keep the electricity grid stable. At last, an analysis is made on the effects of megatrends on CO2 emissions – for policymakers.
Section 6.3 focuses on existing policies and how it influences CO2 emissions – as policymakers are interested in reducing CO2 emissions.

6.2.1. Interesting Results for Energy Utility Companies

One of the most important aspects for energy utility companies is the development of electricity prices. In the end, the electricity prices will determine how much revenue will be made. The production portfolio of electricity should be governed well – based on information of electricity prices – as production cost should be kept as low as possible to optimize profits.

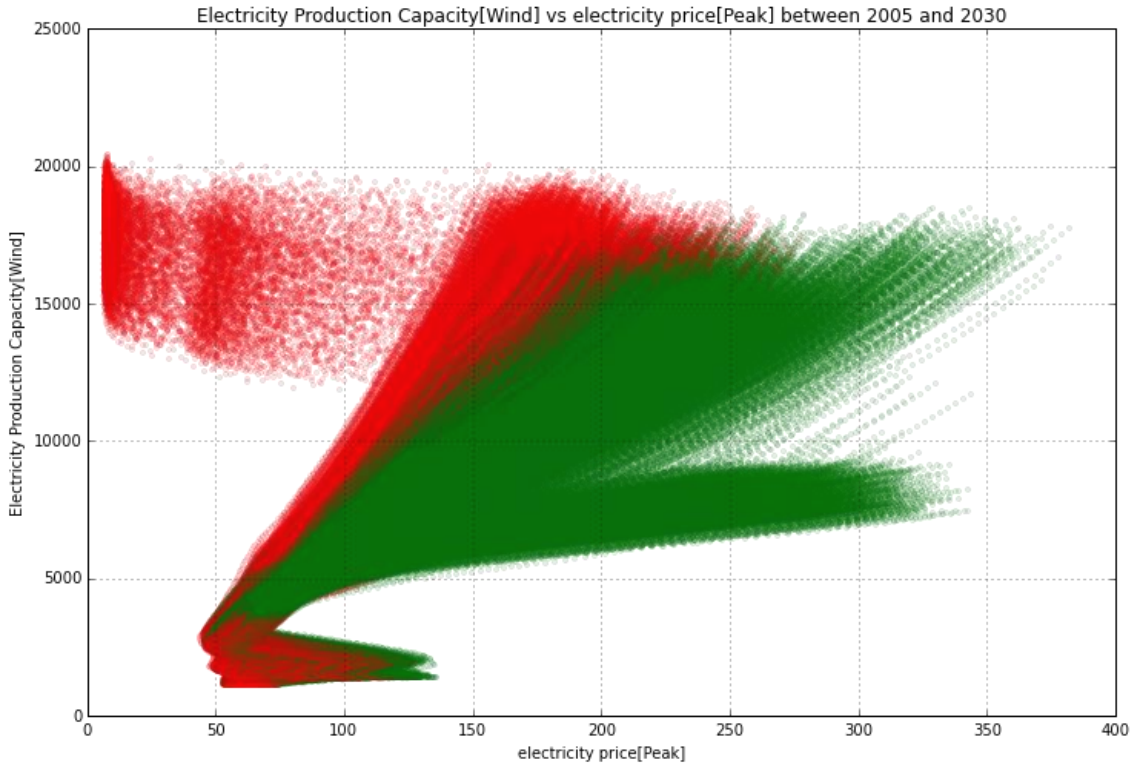

Figure 6.23 Electricity Production Capacity[Wind] versus electricity price[Peak] over time

The rise of renewable energy production – like wind energy – changes the way the production capacity portfolio has to be managed. The increased wind energy production capacity over the years has increased the volatility of electricity prices and it is expected to increase even more. The high volatility is caused by the increased effect of wind speed on the electricity price with a larger wind capacity. With high wind speed, there is a high availability of electricity and thus a low price, and contrarily.
Figure 6.22 shows the Monte Carlo modeling output of *Electricity Production Capacity* of wind and the *electricity price* with peak electricity demand. Another dimension – wind speed variations – has been added to the graph by dividing the output into colors. The average wind speed in the Netherlands is 7.27 m/s, which equals a *Capacity Factor* of 38.49%. When the value is below the average *Capacity Factor* – thus less wind available – then the output becomes green. When it is above the average *Capacity Factor*, the output will turn red.
One of the interesting aspects for utility energy companies is the effect of *Electricity Production Capacity* on the *electricity price* in the peak. Above 5000 MW installed capacity of wind energy, wind speed starts to have effect on the *electricity price* when it is below average. While high wind speeds starts to influence the *electricity price* in the peak when the installed capacity of wind is above 12,500 MW. The V-shape gap in the area with *electricity prices* between 200 and 350 euro per MWh, are caused by the bottom in the distribution of wind *Electricity Production Capacity* (Figure 6.9).
Next to that, there is a clear boundary between the red and the green. The sloping line – i.e. boundary line – shows that the *electricity price* during average wind speed increases. This is due to the fact that CO2 prices are higher – and thus higher electricity prices.
The narrow area between 3,000 MW and 5,000 MW *Electricity Production Capacity* is caused by the large investments in coal and gas capacity. In this period the electricity prices went down due to the large available production capacity available in the market.

6.2.2 Interesting Results for Grid Operators

One of the most important targets for the Transmission System Operator (TSO) in the Netherlands is to keep the electricity system stable at all times. With the increasing adoption of renewable energy sources – and not having a feasible way to store energy yet – it becomes more and more challenging to realize this stabilization target.
One of the critical situations is as following. The more installed capacity of wind energy, the more sensitive the electricity system will become for wind speed variations. With high wind energy production capacity available and a relatively low electricity demand, the electricity system will contain a large volume excess electricity. Of which it needs to get rid of to keep the system stable. Exporting electricity to neighbor countries would be a logical solution. Though, if neighbor countries do not need electricity or if the interconnector capacity between countries is not large enough, the TSO has to find other options to get rid of the excess electricity. This mostly leads to extremely low electricity prices which eventually will lead to a higher electricity demand. Extremely low electricity prices – sometimes even negative – are an undesired scenario, as fixed cost cannot be covered.
Another critical situation is completely contra to the previous situation, where a shortage of electricity occurs and electricity has to be imported from neighbor countries.

Information on the behavior of the import (or export) of electricity in combination with wind speeds could be of great interest for the TSO (TenneT) in The Netherlands. This information could possibly be used to decide how much interconnection capacity to install or to understand how much electricity should be exported to neighbor countries to keep the grid stable.

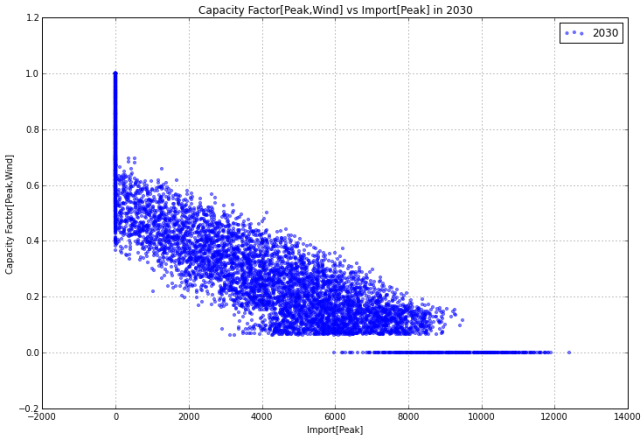

Figure 6.24 Capacity Factor [Peak, Wind] and Import[Peak]

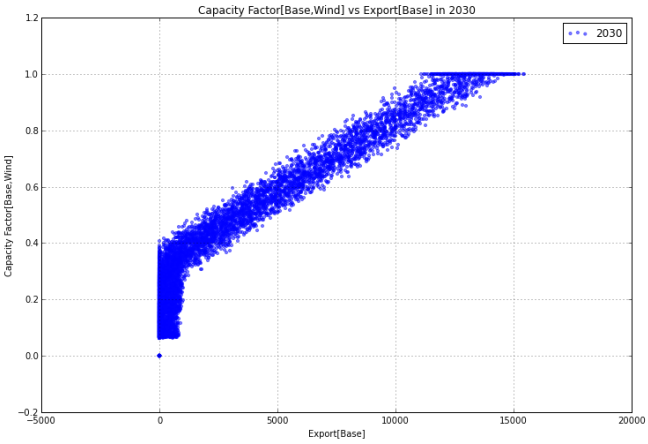

Figure 6.25 Capacity Factor [Base, Wind] and Export[Base]

This information is provided in Figure 6.23, where the *Import* of electricity in the peak and the *Capacity Factor* of wind during peak hours is shown. When wind speeds higher than 9 m/s are expected (*Capacity Factor* = 0.73), no electricity will be imported. If no wind is available at all it could occur that more than 12,000 MW electricity import is demanded – under the assumed modeling circumstances and uncertainty factors. This implies that the TSO should have that much interconnector capacity installed by 2030, in order to keep the electricity stable at all times in this situation.

Figure 6.26 shows exactly the opposite of Figure 6.23. It shows that if the *Capacity Factor* of wind is above average – 38.49% – that the *Export* in the base increases linearly towards 12,500 MW. When the wind speed is above 10 m/s (*Capacity Factor = 1)*, the *Export* in the base will be at maximum 15,500 MW – given the assumed uncertainties and modeling assumptions. This provides interesting information for the TSO on how much interconnector capacity is needed to keep the electricity grid stable at times of excess electricity.
Figure 6.25 and Figure 6.26 provide more detailed information on how much electricity is exported and imported under the different *Capacity Factor* circumstances.

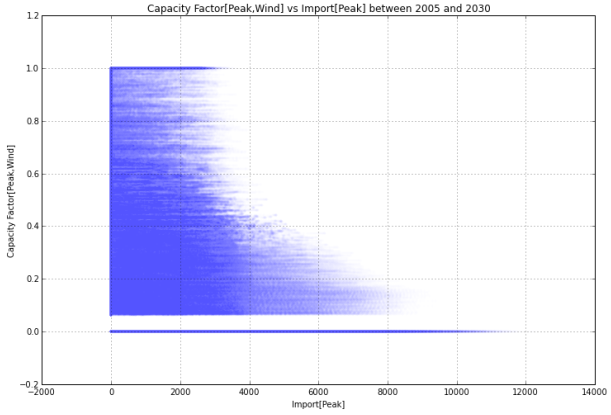

Figure 6.27 Capacity Factor [Peak,Wind] vs Import [Peak] between 2005 and 2030

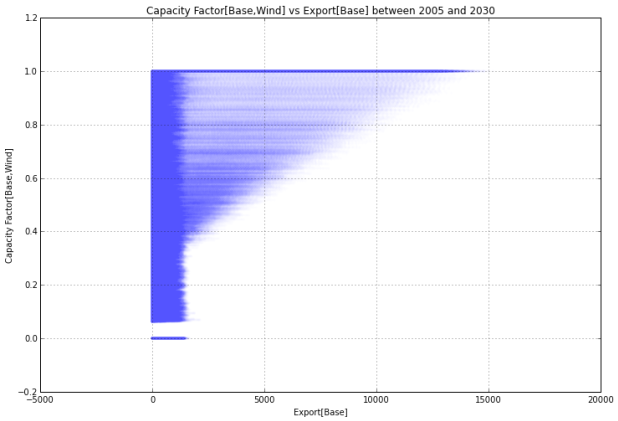

Figure 6.26 Capacity Factor [Base,Wind] vs Export [Base] between 2005 and 2030

6.2.3. Interesting Results for Policymakers

Policymakers of the Dutch government focus among others on designing policies to reduce CO2 emissions from the Dutch electricity system. External forces influence the effectiveness of policies.

Megatrends are external forces that develop over the long term. It is of great importance for policymakers to know how megatrends could influence the electricity system and the CO2 emissions from this system over the long term.

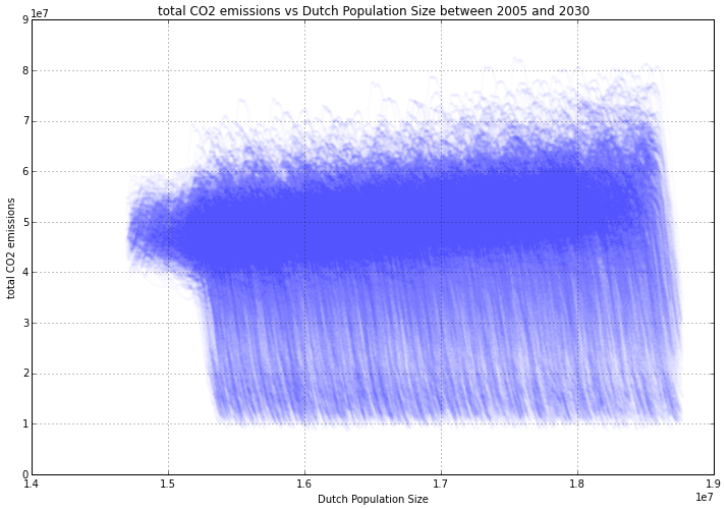

Figure 6.28 Total CO2 emissions and Dutch Population Size between 2005 and 2030

One of the important megatrends is the population growth (KPMG, 2012). More specifically, the population growth in developing countries and not in a western country like the Netherlands. Though, for this thesis the population growth has been marked as a megatrends, to show how these factors could be analyzed. It is expected that the Dutch population size will have grown to 17.07 million people by 2030. This information has been taken into account, where the *Dutch Population Size* – including all variations – and the total CO2 emissions are plotted in Figure 6.27.

This figure shows a correlation between total CO2 emissions and the growth of the Dutch population, when looking at the rectangular blue center part – which increases when the population size increases. However, the noise below 40 million ton CO2 and above 60 million ton CO2 indicates that more research should be done to get a clearer picture on the exact correlation.

When eliminating the time effect of Figure 6.27 – by calculating the cumulative CO2 emissions from 2005 to 2030 – a clearing image of the relation between CO2 emissions and population growth can be drawn. Figure 6.29 shows the correlation between the population growth and the cumulative CO2 emissions between 2005 and 2030 when a multivariate Monte Carlo simulation has been executed – meaning that all external forces have been varied according the variation and distribution of the uncertainty factors

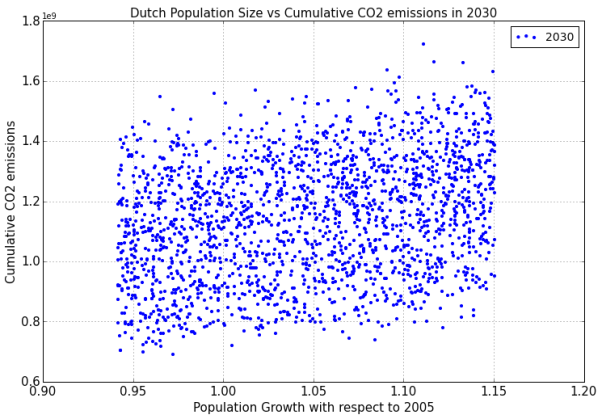

Figure 6.30 Population Growth vs Cumulative CO2 emissions - Multivariate Monte Carlo Analysis

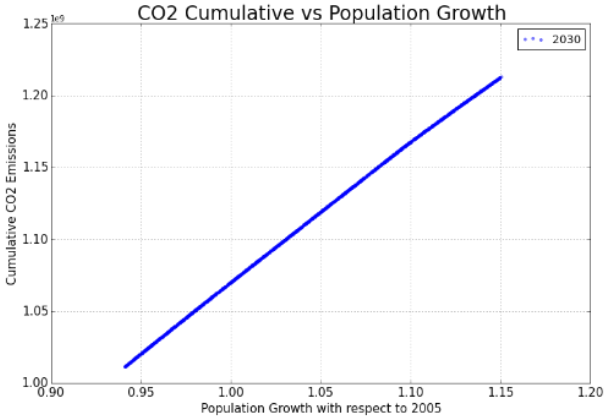

Figure 6.29 Population Growth vs Cumulative CO2 emissions - Univariate Monte Carlo Analysis

connected to the external forces. To determine the effect of the population growth itself within the multivariate analysis, an univariate Monte Carlo Analysis – only varying one external force – has been executed which is shown in Figure 6.28. This figures indicates that an one percentage increase of population (with respect to 2005) leads to 10 million tons of cumulative CO2 emissions increase between 2005 and 2030. Detailed analysis needs to be done, to research how the population growth force influences other external forces – as a correlation after a multivariate Monte Carlo Analysis cannot be determined yet. Especially since there is some noise below 40 million ton CO2 emissions and above 60 million tons.

The same analysis is done with Gross Domestic Product (GDP) growth and CO2 emissions. Though this analysis has not led to a clear correlation. More detailed analyses have to be done to determine the correlation between CO2 emissions and GDP growth.

The way a detailed analysis can be executed is by comparing the simulation results of the Monte Carlo simulation when varying all the external forces with the simulation results when varying only one specific factor. Figure 6.30 shows the results of the Monte Carlo analysis when varying all the external forces with the uncertainty factors. The other graphs (Figure 6.31, Figure 6.32, Figure 6.33 and Figure 6.34) show the results of the Monte Carlo analysis when varying only one external force – respectively GDP, Population growth, EV adoption and Decentralization.

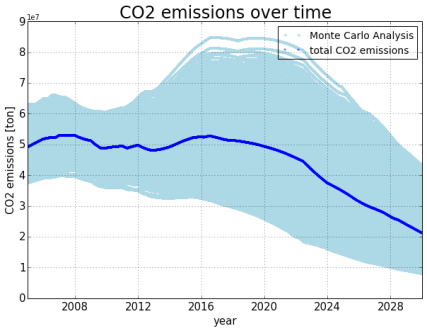

Figure 6.31 Total CO2 Emissions – Varying all external forces for Monte Carlo Analysis

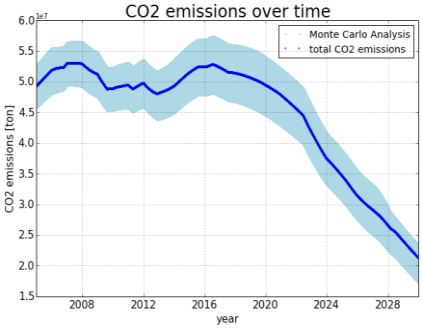

Figure 6.33 Total CO2 Emissions – Only Varying the Population growth in MC

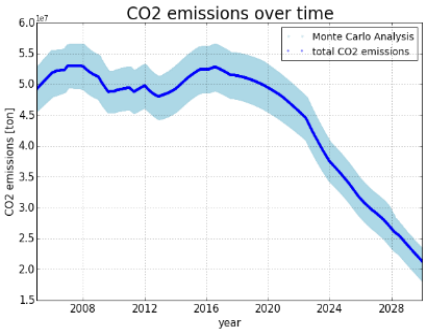

Figure 6.32 Total CO2 Emissions – Only Varying the GDP in Monte Carlo Analysis

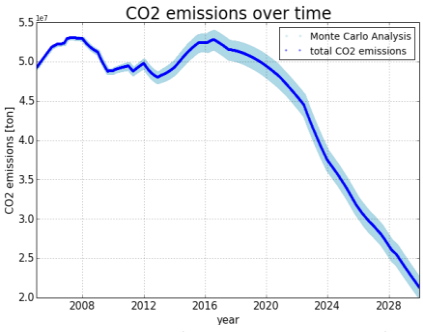

Figure 6.35 Total CO2 Emissions – Only Varying the Decentralization in MC

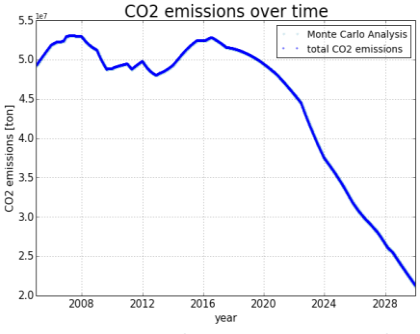

Figure 6.34 Total CO2 Emissions – Only Varying the EV Adoption in MC

The sum of the simulation results of the univariate Monte Carlo analysis equals the multivariate Monte Carlo simulation result. In such a way, the effect of population growth on the CO2 emissions can be quantified. As well as what the influence of population growth is on the entire system – as certain factors could strengthen or weaken each other, this can be interesting.

To execute a more detailed analysis on specific factors of the system, Exploratory Modeling and Analysis (EMA) can be executed. This can for example be used to determine which ranges of uncertainty lead to a which simulation output. This sort of research and analyses can be of great importance to improve the understanding of the effects of uncertainties on the SD-model. These kind of analysis tool lie outside the scope of Vensim specifically.

6.3 Policies

It is of interest for policymakers to monitor the developments of external factors and its influence on the Dutch electricity system. When unexpected situations occur, policies might need adjustments in order to function more efficiently under those circumstances. Having better insights in the possible influences of external factors of the Dutch electricity system, could be of high interest for policymakers. As policymakers focus on reducing CO2 emissions, an analysis has been done of the influence of policies on CO2 emissions. Modeling data of external forces have been plotted against policies. This to create a better understanding of the behavior of CO2 emissions in combination with implemented policies.
Two policies that have been added to the System Dynamics model are the SDE+ subsidy and the Emissions Trading Scheme of the European Union. Plots of these policies and CO2 emissions are provided in chapter 6.3.1 and chapter 6.3.2.

6.3.1. SDE+ Subsidy versus CO2 emissions

The SDE+ Subsidy is a national subsidy of 3.5 billion euro in 2014 to stimulate sustainable development (Rijksdienst voor Ondernemend Nederland, 2014). It is assumed that 275 million euro will be used to stimulate wind energy adoption in 2015. This is based on the average percentage of the total SDE+ that has gone to wind energy investments over the years the SDE+ exists. For policymakers – that have designed and currently monitor this policy – it is of importance to understand the influence of the SDE+ policy for wind adoption on the CO2 emissions.

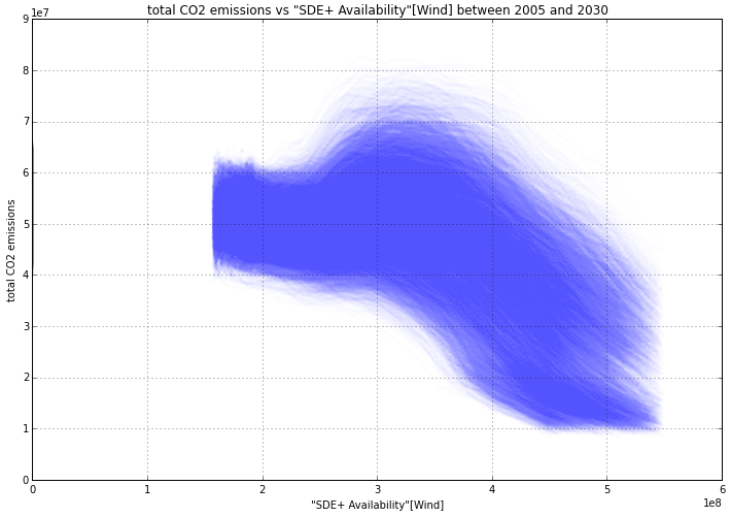

Figure 6.36 Total CO2 emissions and SDE+ Availability[Wind] between 2005 and 2030

In Figure 6.35 the CO2 emissions have been plotted against the SDE+ availability for the adoption of wind energy capacity. This shows that when the *SDE+ Availability* increases, the total CO2 emissions decreases – given the modeling assumptions and uncertainties. The plot indicates that a *SDE+ Availability* of approximately 350 million to 450 million euro, has the most effect on CO2 emission reductions. Between 150 and 350 million of *SDE+ Availability* the subsidy seems not have much effect on CO2 emission reductions. The same counts for the CO2 emissions reductions after 450 million euro of *SDE+ Availability*. In order to quantify the correlation between total CO2 emissions and the SDE+ availability, more detailed research is needed. Especially for the simulation results in Figure 6.35 a more extensive research is required to assure the statement on the correlations of SDE+ Subsidy and CO2 emissions in this paragraph.

The top around 300 million SDE+ Availability is caused by investments in gas and coal capacity, leading to more CO2 emissions.

When eliminating the time effect when looking at the cumulative CO2 emissions and SDE+ Subsidy for renewable energy source development, a clearer correlation is shown in a univariate analysis of the SDE+ Subsidy (see Figure 6.37). The multivariate Monte Carlo Analysis in Figure 6.36 – when varying all external forces – does not show a clear correlation yet. It requires detailed analysis, focusing on how external forces influence each other – to get a clearer picture on this correlation in the multivariate Monte Carlo Analysis. Figure 6.37 shows that the SDE+ Subsidy as a single factor influences the CO2 emissions towards 2030 in such a way that when the yearly SDE+ subsidy is increased with €5 million, it will lead to 2 million ton CO2 emission reduction between 2005 and 2030 – according to the SD-model.

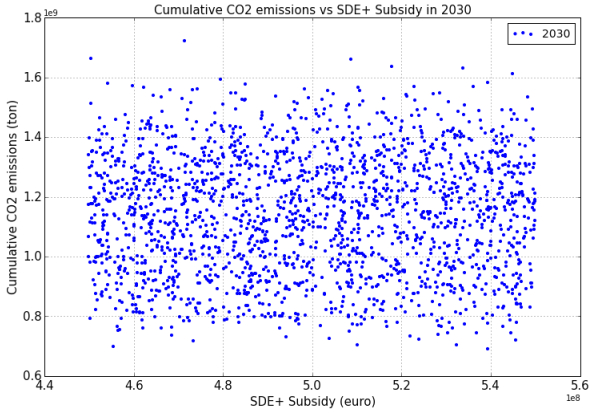

Figure 6.37 Cumulative CO2 emissions vs SDE+ Subsidy in 2030 - Multivariate Monte Carlo Analysis

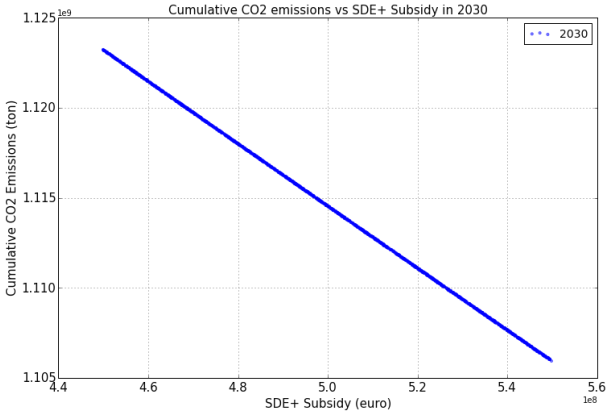

Figure 6.38 Cumulative CO2 emissions vs SDE+ Subsidy - Univariate Monte Carlo Analysis

6.3.2. Emission Trading Scheme versus CO2 emissions

The Emissions Trading Scheme (ETS) is an initiative of the European Union, where policymakers have designed a market for CO2 allowances that every large organization needs to have to cover its CO2 emissions. This policy is called into place to demotivate investments in carbon intensive systems. Due to the economic crisis in 2008, the demand for CO2 allowances decreased significantly resulting in a low price for these allowances (i.e. CO2 price). This has led to undesired investments in carbon intensive systems over the past years – of which the SD-model even shows, as it shows investments in gas and coal production capacity around 2012. The policymakers of the EU had to adjust the policy in order to create a better CO2 price, leading to the desired effects of CO2 reductions. Once more, this underlines the importance of understanding the influence of external forces and policies on the electricity system and its CO2 emissions.

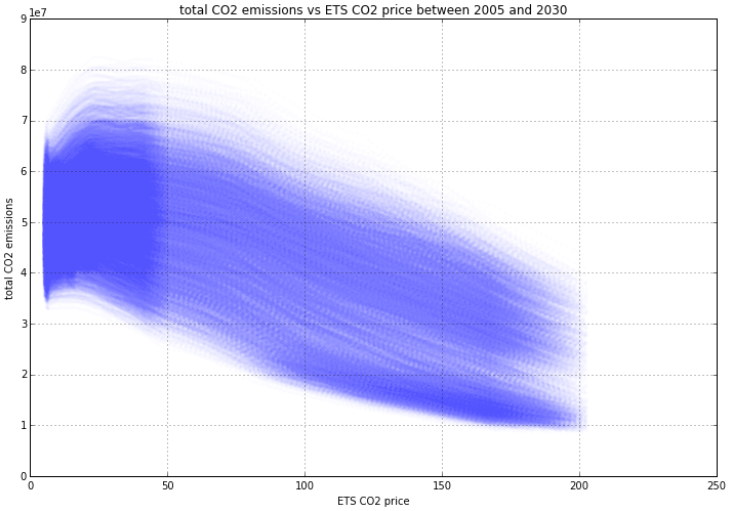

Figure 6.39 Total CO2 emissions and ETS CO2 price between 2005 and 2030

Figure 6.37 shows the modeling output of the ETS CO2 price, plotted against the CO2 emissions. Until 50 euro per ton CO2, the reductions of CO2 emissions are relatively slow. After 75 euro per ton CO2, it shows that the CO2 price starts to have more effect on the CO2 emissions. After 100 euro per ton CO2 it looks like the CO2 price starts to have less effect on the total CO2 emissions again. Whether this has to do with less investments being done around this time, due to a lower *SDE+ Availability* or a worse investment climate is not known. Therefore a more detailed analysis needs to be executed to confirm these results and quantify the correlation.

Figure 6.39 and Figure 6.40 shows the correlation analysis between CO2 emissions and ETS CO2 price towards 2030, after eliminating the time effect – by cumulating the CO2 emissions between 2005 and 2030. From the univariate Monte Carlo analysis – when varying the ETS CO2 price – could be concluded that an increase of one euro in CO2 price (In the SD- model and between the price range of €167 and €204), leads to a decrease of 1.7 million ton CO2 between 2005 and 2030.

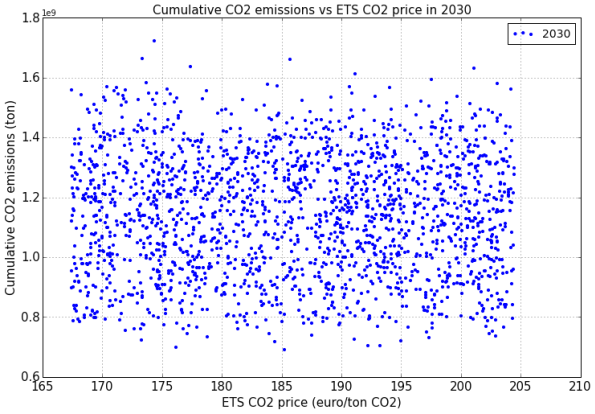

Figure 6.41 Cumulative CO2 emissions vs ETS CO2 price - Multivariate Monte Carlo Analysis

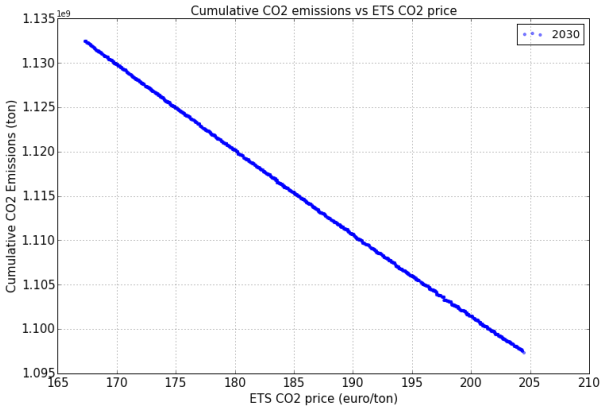

Figure 6.40 Cumulative CO2 emissions vs ETS CO2 price - Univariate Monte Carlo Analysis

6.4 Discussion on Modeling Results

In this section the combined modeling results – System Domain, External Forces and Policies – are discussed. This will lead to overall recommendations for the stakeholders of the Dutch electricity system. Figures from other chapters are collected and shown in this section again to create a better overview.

When looking at the modeling results towards 2030, an interesting development of the installed generation capacity occurs (Figure 6.41). From 2005 to 2012 there is a downward trend in the available production capacity of coal and gas. Around 2012 investments in coal and gas generation capacity are made again, leading to a steep increase of carbon intensive generation capacity – an effect that is contradictory to the desired results of policymakers that aim to reduce CO2 emissions.

The investments in carbon intensive generation capacity has led to an overcapacity for electricity production in the Dutch electricity system. This overcapacity resulted in a poor investment

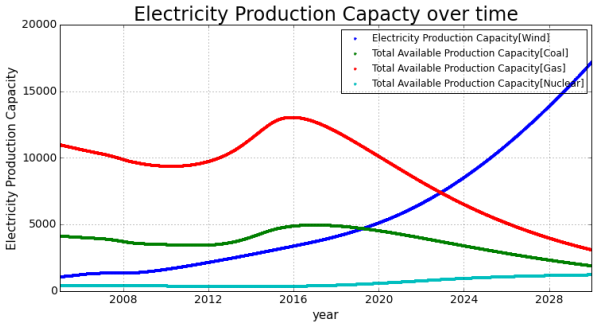

Figure 6.42 Electricity Production Capacity per Generation Method

environment. The only investments done, are the investments in wind energy capacity which are only made because of the SDE+ subsidy policy. As shown in Figure 6.41, after 2020 the wind energy investments start to grow exponentially – instead of linearly between 2008 and 2012. The exponential growth is caused by the investments in wind energy made through external financiers. This means that the investment environment starts to become better after 2020, which is partly due to the fact that electricity generation capacity of gas and coal are decreasing again and thus the overcapacity shrinks.

In the Dutch Energieakkoord (Energy agreement on sustainable growth) it is agreed that before the beginning of 2017, five coal power plants in the Netherlands need to be closed (Europese Unie, 2013). Through this agreement the Dutch government forces a faster decline of carbon intensive generation capacity. According to the simulation output, the effects of this decline of carbon intensive generation capacity have been taken into account. However the decline of carbon intensive generation capacity is slower as System Dynamics is a continuous model and the decision to close down five carbon intensive power plants is in real life discontinuous.

The policy of forced mothballing – earlier closing down of power plants – of carbon intensive generation capacity is not a part of the System Dynamics model. Though over the long run – towards 2030 – the System Dynamics output shows the same declining behavior. The effects will mostly likely be the same, but through the policy the resulting effects – better investment environment, more (external) investments in wind energy – will happen earlier. The kink in Figure 6.42 around 2027 indicates the moment in time where the investment environment for wind energy becomes so good that large volumes start to be adopted. The lower kink around 2027 is the caused by the intersection between the lowest wind energy capacity adoption and the fastest decrease of carbon intensive generation capacity (See Figure 6.9, Figure 6.10 and Figure 6.11).

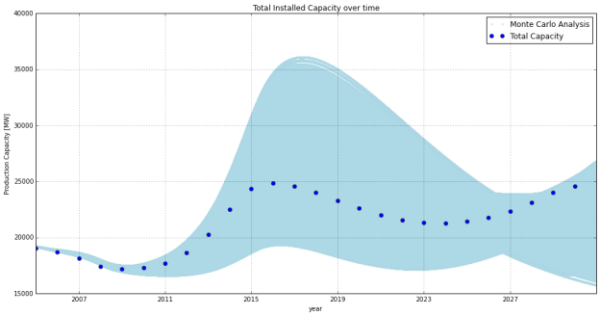

Figure 6.43 Total Installed Capacity

Thus, from the System Dynamics model can be concluded that mothballing has a positive effect on the investment environment. However, there are also negative effects when mothballing power plants. Due to the increased adoption of wind electricity production capacity, the electricity grid's stability becomes increasingly instable at an earlier point of time. Figure 6.43 shows that before 2025, there is a relatively stable electricity price – which is partly caused by the overcapacity in the Dutch electricity system around that time. The increased volatility after 2025, could happen much earlier if mothballing is forced to take place. This means that to policymakers should keep in mind that when forcing to close down power plants, that it will have a negative effect on the grid stability. Investments in interconnector capacity should for example be done to increase the ability to import and export electricity when the grid becomes instable.

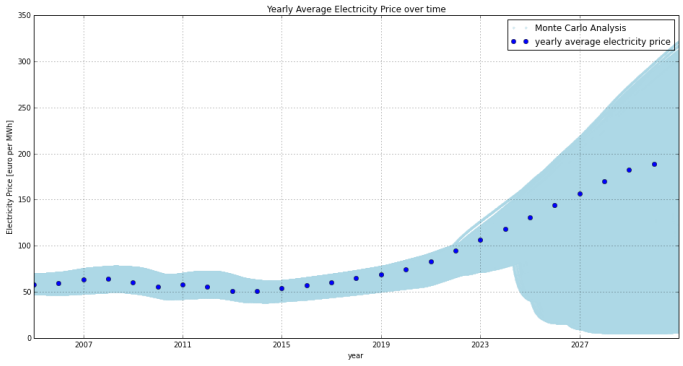

Figure 6.44 Yearly average electricity price

As stated before, the timing of when these events might occur is most likely not correct – because political decisions and the implementation of (new) policies make it uncertain. However, this System Dynamics model provides insights on the effects of the implementation of policy or the change in behavior of an external force.

Part IV – Model Comparison

7. Model comparison

In this chapter the sub question – *How does the System Dynamics model contribute to research on future electricity prices compared to existing electricity price simulation models?* – will be answered. The answer to this question provides insight on the added value of a System Dynamics model of the Dutch electricity system. The insights are valuable for further developments of the SD-model in the future.
Firstly, information is provided on the characteristics of both System Dynamics and Agent Based Modeling – as these techniques are both used for electricity system modeling. Secondly, three models are chosen which will be compared with the developed System Dynamics model in this thesis. Thereafter, Key Performance Indicators (KPI's) are defined, which the electricity system models will be tested on. After the qualitative analysis of the three models, a conclusion is provided on the strengths and the weaknesses of the developed SD-model in the thesis.

7.1 System Dynamics versus Agent Based Modeling

Systems Dynamics can be described as a technique that helps to trace patterns of behavior of dynamical systems to its feedback structure (Scholl, 2001). The feedback structure is of great importance for SD-models. This because it is assumed that complex systems have a multiplicity of interacting feedback loops containing flows with nonlinear relationships. Through the System Dynamics technique, complex systems can be quantitatively analyzed from a relatively high aggregation level.
One of the weaknesses of System Dynamics – described by Gregory Hayden - is that "System Dynamics is an inadequate tool for explaining the institutional systems principle of hierarchy, feedback and openness" (Hayden, 2006). Meaning that the behavior of hierarchy, feedback and openness cannot be described sufficiently within a System Dynamics. Though, this contradicted by Forrester and Barlas, as they state that System Dynamics models are often used for the wrong purposes (Featherston & Doolan, 2012).

The aggregation level of Agent Based Models (ABM) is the opposite of System Dynamics models. The aim of ABM's is to explore the emergent behavior of individual agents following a certain set of rules, while interacting with other agents (Reynolds, 1999). Agent Based Modeling techniques can be categorized in a bottom-up structure model – from individualistic behavior of agents – more globalized patterns are analyzed.
Analyzing complex systems from an individualistic behavior towards a higher aggregation level, leads to more detailed modeling output – especially when comparing it to modeling output of SD-models. However, if rules for agents are not known or cannot be discovered by some sort of observation, the process of Agent Based Modeling is anything but straightforward and makes the modeling output unreliable (Scholl, 2001).

7.2 Key Performance Indicators for testing Electricity System Models

Building a simulation model for electricity systems from scratch has helped to understand of which subsystems a simulation model on the Dutch electricity system should be built up. Assumptions had to be made to be able to build a simulation model, delivering the desired output, within six months.
As stated earlier, there is room for improvement to develop this System Dynamics model. To understand the level of improvements that could be made and to understand the strengths and weaknesses of the SD-model, a short comparison study is executed.

Based on the obtained simulation experience of electricity system modeling during the thesis process, a few indicators for model comparison have been identified to test the models. The six Indicators that have identified are as following:

1. Starting year of development of the model
   - The starting year of development of the model has been added to the comparison KPI's to get insight on the maturity of the model.
2. Commercial versus open-source
   - Commercial versus open-source is an important financial aspect for stakeholders of the electricity system. An expensive simulation model might not fit the stakeholders purposes when it wants to get a general idea on the behavior of the electricity system.
3. The purpose of the model
   - This KPI provides details on the purpose of the modeling insights.
4. The ability to execute short term analysis, long term analysis or both – short term, long term or both.
   - As both short-term and long-term effects are important to research the behavior of an electricity system, a simulation model should be scored based on the level of flexibility between short and long term modeling.
5. The geographical focus of the simulation model – National or Multi-national
   - The geographical focus provides insight on the ability to take influences from neighbor countries into account in the simulation model. This is important for electricity supply, electricity prices and import and export capabilities from neighbor countries which influences the electricity system.
6. Design flexibility to adjust the model – inflexible versus flexible
   - The flexibility to add or to remove components of the model could be important for stakeholders when certain scenarios need to be tested. An example could be to add the adoption of Electric Vehicles to the simulation model – when it is not yet part of the model.
7. The degree of uncertainty analysis that could be executed – None, low or high.
   - The degree of Monte Carlo Analysis that could be executed depends on the maximum number of MC simulation runs that could be done. If more external forces and/or uncertainty increases, then the number of MC simulations should be increased. When there is a maximum for the number of simulation runs, then the model is limited.
8. The ability to export data for further data analytics – yes or no.
   - Exporting simulation data could be of interest for stakeholders or data scientists in the field of electricity systems. This to execute more detailed analyses or to combine simulation data with other data.

Based on these Indicators and the comparison study, the strengths and weaknesses of the models are identified.

7.3 Alternative electricity system models

For the benchmarking study, three other electricity system models have been chosen; Power2Sim (Energy Brainpool, 2015), EMlab (Delft University of Technology, 2015) and Plexos (Energy Exemplar, 2015)

7.3.1 Power2Sim

Power2Sim is a model designed by German experts in electricity markets that simulates the European energy market based on the merit order principles (Swager, 2014). The model consists of three main aspects: load model with hourly electricity prices, Import-Export model which simulates cross-border flows and the simulation of the Emissions Trading Scheme market.
It is a commercial energy model that is sponsored by Allianz, Apo, EBM and PWC. Apart from a website of the model and one master thesis – by Christian Swager, TU Delft, 2014 – there is not much information available.
A schematic overview of the model design is shown in Appendix I.1.

7.3.2 EMLab

EMLab is an Energy Modeling Laboratory which is an experimentation environment for electricity policy analysis, designed by the Delft University of Technology (De Vries et al., 2005). It is an open source package which is based on Agent Based Modeling. It consists of three aspects:

- Generation Lab, with the main purpose to explore the long-term effect of climate policies through simulations of investments of energy utility companies.
- Congestion Lab, focused on simulating congestion of the national electricity grid where the Transmission System Operator is responsible for.
- Network Evolution Lab, which models the long-term development of an electricity transmission network.

A schematic overview of the model design is shown in Appendix I.2.

7.3.3 Plexos

Plexos is an energy model simulation tool, which is based on linear, mixed integer models and uses quadratic optimization and game theory. Besides, it has distributed computing methods to execute Monte Carlo Simulations.
The primary focus of Plexos is to make operational decisions and make business plannings.
The software has a wide variety of (detailed) system components of the electricity system, that have been developed over the last 15 years.
A schematic overview of the model design is shown in Appendix I.3.

7.4 Comparison Overview

Based on the comparison analysis, general feedback on the different models can be given. In the research of Swager, it is stated that Power2Sim lacks the ability to translate simulation output of the model to investment decisions for adoption of electricity production capacity (Swager, 2014). Therefore, his thesis focused on exploring the possibilities to add an investment component to the software. However, this investment component was validated based on one year of simulation data.

As the duration of investment processes are mostly longer than one year, it cannot be stated whether this investment component has built up enough trust to add it to the Power2Sim software.

Looking at the counterpart of System Dynamics – Agent Based Modeling – the research of H.J. Scholl could be concluded that a weakness of ABM is that when rules for agents are difficult to determine – especially within complex system – there is a higher chance the modeling output will be biased (Scholl, 2001).

Figure 7.1 shows an overview of the comparison study of four different electricity system simulation models.

1. Plexos and Power2Sim show to have the most experience in electricity system modeling. EMLab is relatively new.
2. Plexos and Power2Sim show to be mostly focused on the systems behavior and are used for resource planning modeling. EMLab focuses on analyzing the effects of policies on the electricity system. The goal of the designed System Dynamics model is to mostly create insight in the influences of external forces on the electricity system.
3. Both Plexos and Power2sim are able to be used through a commercial license. The designed System Dynamics model is basically open-source, but a commercial license is needed to use the SD-modeling software. EMLab is the only model which is fully open-source.
4. Plexos and Power2Sim have the ability to model both on the short term as well as on the long term. EMLab and the SD-model are both designed to analyze the long term effects on the electricity system.
5. Power2Sim, EMLab and Plexos are simulations models where multiple countries can be taken into account. This to model the import and export of electricity from one country to the other. In the SD-model it is assumed that electricity could always be imported as well as exported. The effects of import and export on the national electricity could thereby not be analyzed.
6. The design flexibility of the SD-model is high. It is relatively easy to add components to the existing model, in the System Dynamics software – Vensim. For the commercial software and the Agent Based Model it is assumed that it is more complicated to make adjustments to the model.
7. In Power2Sim the maximum Monte Carlo simulation runs are a 1000. For the SD-model, 8000 Monte Carlo Runs were done – as with more than 8000 simulation runs the simulation output does not change anymore. This means that a maximum of a thousand runs is too low. EMLab does not have Monte Carlo capabilities. Plexos and the SD-model have a high capability of Monte Carlo simulation usage.
8. As Power2Sim and Plexos are complete software packages, it is assumed that it does not have to capability to export simulation data.

	Power2Sim	EMLab	Plexos	SD-model
1 Starting year of development of the model	2003	2013	2000	2015
2 The purpose of teh model	Resource Planning Modeling	Policy Analysis	Resource Planning	Exploring future electricity prices
3 Commercial versus Open-Source	Commercial	Open-Source	Commercial	Commercial
4 Short and Long Term Analysis	Both	Long term	Both	Long term
5 Geographical focus	Multi-National	Multi-National	Multi-National	National
6 Design flexibility	Inflexible	Inflexible	Inflexible	Flexible
7 Uncertainty Analysis Capabilities	Low	Low	High	High
8 Simulation Data Export	No	Yes	No	Yes

From the comparison study could be concluded that Plexos is the most advanced electricity system simulation model and that there is still room for improvement for the designed System Dynamics model. A large advantage of the System Dynamics model is that it is relatively cheap and it is flexible for adjusting the systems design. The ability to export simulation data, to execute more extensive analytics is a large advantage as well. An example of a tool for data export and more specific analytics, is the EMAworkbench – designed by Jan Kwakkel (Kwakkel, 2012).
EMA stands for Exploratory Modeling and Analysis, and is an analytics tool that can be used for future research to more specifically analyze the future behavior of the Dutch electricity system towards 2030.

Part V – Conclusions & Recommendations

8. Conclusions & Recommendations

This thesis research aimed at answering the following research question:

How will the changing energy production mix interplay with the future electricity price towards 2030 in the Netherlands?

To answer this research question, a System Dynamics (SD) model on the Dutch electricity system is built to explore the behavior of this system under assumed developments of external factors towards 2030. The SD model is built based on two important assumptions: The Dutch electricity system consists of four generation methods – Coal, Gas, Nuclear and Wind – and the capability to import and export electricity is infinite. Next to the system design assumptions, scenario assumptions on the development of external forces – i.e. population growth, CO2 price, economic growth etc. – towards 2030 are made. Under these assumptions, this research shows that the production mix towards 2030 will change in a way that increasingly more renewable energy production capacity will be available. This causes the electricity prices to become more volatile, leading to a worsening investment environment for production capacity development.
First the five sub-questions of this research are answered based on the observations during this thesis. Subsequently, the contribution to literature and practical recommendations for different stakeholders in the Dutch electricity sector are mentioned. Third, the limitations of this study are described, which leads to recommendations for future research – described in the last section.

8.1 Sub-Questions

What does the system domain of electricity prices of the Netherlands in 2030 look like?

To build a simulation model of the Dutch electricity system, a Policy Approach Framework was used. This framework consists of a system domain (core of the simulation system), External Forces and Megatrends, Policies and as main outcome of interest the electricity prices towards 2030.
Based on the design of the Dutch electricity system, six system components were identified. As input for the power exchange (e.g. determination of the electricity price) the electricity demand and the electricity supply were determined as two important sub-systems. The electricity supply is delivered through the installed production capacity available in the Netherlands (and possibly the production capacity in neighbor countries). For this thesis it is assumed that the production capacity consists of four generation methods – Gas, Coal, Nuclear and Wind – and other methods have been left out of this research.
Through the output of the power exchange sub system, the yearly turnover is calculated based on the hourly electricity price and the volume of sold electricity. A part of the yearly turnover is used as investment budget to further develop the electricity production capacity – sub-system 'Adoption of Installed Capacity' – in the Netherlands when needed.
Since it is known how these sub systems of the electricity system qualitatively relate to each other, next steps can be taken by quantitatively implementing the relations and the sub-systems in System Dynamics.

Which external forces mainly influence the behavior of the system domain of future electricity prices in the Netherlands?

The electricity system is sensitive to influences of external forces. Based on literature and the analysis of the sub systems of the electricity system, the most important external forces have been identified. For each external force in the model – i.e. population growth, CO2 price development, economic growth etc. – a scenario has been assumed.
The most important external forces that influence the power exchange are the marginal cost of electricity production, which is built up of fuel cost (Gas, Uranium and Coal) and maintenance costs.
For the electricity demand, studies have shown that an important external factor influencing the demand is the price of energy. When the price of energy goes up, the energy demand will go down. Besides, there are long term external forces – megatrends – that influence the electricity demand over the long run. The megatrends are the slight expected growth of the Dutch population, the Gross Domestic Product of the Netherlands, the decentralization of electricity production and the adoption of Electric Vehicles (EV's).
The supply of electricity is dependent on external forces influencing the electricity production capacity, the generation efficiency of the generation methods, the operation efficiency of the generation methods and the wind speed influencing the production of wind energy. Next to that, electricity imported from neighbor countries can be added up to the available electricity supply.
The adoption of new production capacity is dependent on the investment environment during a period of time, where a favorable investment environment could be identified through the growth of the Gross Domestic Product. Besides, it is dependent on the affinity for a certain generation method and the cost aspects, like the expected total cost of the installed capacity – measured as Levelized Cost of Electricity – and the expected future energy prices.
Next to the external forces influencing the adoption of new production capacity, it is also dependent on the available Investment Budget. This Investment Budget is determined based on the yearly turnover – dependent on the electricity prices of the power exchange – and the percentage of the yearly turnover that is reserved to make investments, which is an external force as well. Investments could also be done by investors, but these investments are only done when the investment environment is positive.

What kind of policies guide the electricity system to a more sustainable system?

The two main policies that influence the Dutch electricity system are the SDE+ Subsidy and the EU Emissions Trading Scheme (ETS). The SDE+ subsidy policy, is a policy implemented by the Dutch government to stimulate sustainable development and thus influences the adoption of wind energy production capacity.
The ETS is a policies designed by the European Union to demotivate investments in carbon intensive systems. In the ETS, CO2 allowances are traded by large organizations in Europe that need these allowances to cover their CO2 emissions. A high price for these allowances will drive up the cost for the use of carbon intensive generation methods and thus affect the investment decisions of energy utility companies towards renewable energy sources.

What are possible developments of the Dutch electricity system towards 2030, taking into account uncertainty factors?

After having implemented the system domain, external forces and megatrends and policies in System Dynamics software, the simulations of the model could be executed. Before being able to execute simulations, a validation process was performed to build up trust in the designed model and its behavior. The validation has shown that the designed System Dynamics model is competent to execute simulations. However, there is always room for improvement. These aspects are illustrated in section 8.3 and 8.4 of this conclusion.

The uncertainty factors of external forces influencing the Dutch electricity system have been endeavored to be covered by performing a Monte Carlo (MC) simulation. To each external force, an assumed uncertainty variable has been connected which varies with 10% according a random uniform distribution in the MC-simulation. By running the model 8000 times and thereby varying the external forces, most of the future scenarios should covered within the uncertainty range towards 2030.
The MC simulations show that the electricity demand is expected to behave fairly stable towards 2030 – mostly due to the growth of decentralized electricity production – and that it will stay between the range of 96 to 116 TWh per year. In 2013 the electricity demand in the Netherlands was approximately 101 TWh. It is expected that the production capacity of wind energy and nuclear energy will grow towards 2030. The wind energy capacity will either grow towards 8,000 MW installed capacity or to 18,000 – depending on the investment environment and the external investments done in wind energy capacity. The installed capacity of nuclear might grow to 1,350 to 1,550 MW, however this development is highly dependent on political and societal support for installing more nuclear power plants. Like other political decision, this support has not been modeled in the System Dynamics model because these discrete aspects do not fit the modeling characteristics of System Dynamics. Both Gas and Coal installed capacity are expected to decline as the price of CO2 is expected to rise significantly. The installed capacity of gas is expected to decline from approximately 12,500 MW in 2005 to about 3,000 MW by 2030. The model shows a decline of coal installed capacity from about 5,000 MW in 2005 to approximately 2,000 MW by 2030.
As the wind energy production capacity is expected to grow, wind speeds will have an increased influence on the supply of electricity. The electricity supply towards 2030 is expected to remain approximately the same but this highly depends on the development of wind availability towards 2030. The expected electricity supply – according to the System Dynamics model – will lie between 85 and 105 TWh per year. As the electricity supply is highly dependent on the wind availability, the electricity prices will become increasingly volatile in the model, which is also expected to happen in the real world. The simulation results show that the average electricity price will lie between 5 euro per MWh to 320 euro per MWh. This is an important signal to the TSO (grid operator) of the Netherlands, because the volatile availability of electricity increases the instability of the electricity system. Due to the increasing volatility of electricity supply, the simulation model shows that the capacity of interconnectors should widen as more import and export are expected to take place towards 2030. The System Dynamics model even shows circumstances where 12,000 MWh is imported and situations where 15,500 MWh of export to neighbor countries is required to maintain a balanced electricity system. Energy storage to reduce volatility does not affect the Dutch electricity system in the System Dynamics model. This is due to the fact that volatility is added in the SD-model by varying average wind speeds over a longer period of time, whereas energy storage is relevant within short time periods. If the wind volatility would have been modeled as the

demand volatility in the SD-model – through subscripts – energy storage would possibly show more volatility. Besides, assumptions are made in the SD-model that the import and export of electricity is always available. Therefore, if the electricity cannot be delivered from the storage capacity then it will be delivered through imported electricity.
Simulations show that towards 2030 the CO2 emissions will decline to about 30 million ton per year. Compared to the CO2 emissions in 1990 – 45.2 million ton per year – this would equal a reduction of approximately 34% by 2030.

The simulation results of the sub-systems of the Dutch electricity system show interesting results for different stakeholders. An analysis of the electricity prices, electricity production capacity and wind speeds have led to interesting results for energy utility companies. The analysis has provided more insights in the behavior of electricity prices, under certain amounts of installed electricity production capacity of wind and the variance of wind speed. This information could be of great importance for managing the production mix of energy utility companies.
An analysis on the variance of the demand of imported and exported electricity has provided interesting insights for Transmission System Operators. It shows how much electricity import or export is expected under different wind speeds. This could be valuable for the development of interconnector capacity.
At last, insights in the influences of population growth on the total CO2 emissions have been determined. It shows that a larger population size will lead to slightly more CO2 emissions. To quantify this correlation, more detailed analysis is required.
Besides, the analyses have shown that a SDE+ subsidy of 350 to 450 million euro per year for wind energy might have the most influence on the reduction of CO2 – in a positive investment environment. And a CO2-price between 75 euro to 100 euro per ton might have the most effect on CO2 emission reduction. Though, further analysis has to be done to ensure the statements on the influence of policies on CO2 emissions.

How does the System Dynamics model contribute to research on future electricity price compared to existing electricity price simulation models?

When comparing the designed System Dynamics model to existing electricity system models, it shows that there is still room for improvement. Especially improvements need to be executed in the field of import and export of electricity from and to neighbor countries.
The contribution of the System Dynamics model to scientific research mostly lies in the field of data analytics. The System Dynamics software has shown that it is relatively easy to export data to other programs, like Python. For further data analytics, Exploratory Modeling and Analysis (EMA) might be an interesting method. Using these programs can add value to the analyses already done in the System Dynamics model, as it becomes better accessible for data scientist which could contribute to more detailed analytics.

8.2 Contributions

This section provides the contributions of this research focusing on the added value for science, the stakeholders that are part of the Dutch electricity system and KPMG, the company where the thesis was executed.

8.2.1 Contributions to science

System Dynamics models have been used in abundance to analyze problems like climate change and future effects of climate change. Though, a System Dynamics model of the Dutch electricity system has never been designed. An analysis of what the future effects of the desire to become more sustainable are, is of added value to science in general and to stakeholders of the Dutch electricity system.

8.2.2 Contributions to stakeholders

The System Dynamics of the Dutch electricity system contributes to the stakeholders of this system as the modeling output provides interesting data for more specific analytics. Based on the data analytics of the modeling output, better insights could be provided to the stakeholders. More specifically, it could support energy utility companies on future production mix planning and investments decisions. For grid operators it could support in investment decisions on grid development and interconnector capacity development. Last, it could support policymaker to better understand the influences of external forces on the system and policies.

8.2.3 Contributions to KPMG

The process of System Dynamics modeling and the tool itself, can be of added value for KPMG in the future. It is an interesting way to connect qualitative knowledge with quantitative knowledge. More specifically, it is a good tool to illustratively show customers the dynamics of a system and connect it to external forces and megatrends to quantitatively describe the relations in the system.
This System Dynamics model specifically, could eventually – after further research – contribute to stakeholders (and customers of KPMG) in the field of electricity systems.

8.3 Limitations of the research

Scenarios could be improved

One of the limitations of the research is the lack of literature supporting some scenarios of the model. An example is the scenario of the expected development of the CO_2 price towards 2030, as only one study was found which could therefore not be verified.
Next to the scenarios specifically, more literature is needed to determine which distributions of scenarios and external forces are plausible. During this research, the distribution of wind speeds was determined through available data and further calculations. Though, for other scenarios and external forces the distribution could not be determine due to the lack of literature and thus assumptions needed to be made (Appendix D).

More extensive validation

As the process of the thesis is only six months, relatively little time could be spent to validate the System Dynamics model. Even though the relatively short validation has led to improvements and interesting insights, a longer validation could possibly lead to an even better understanding of the model.

Improvements to modeling the investment process

The investment process could be improved on various aspects. First of all, the determination of the investment budget is based on a percentage of the yearly turnover. Most likely this is not the way it is determined in the real world, so this process could be extended more.

Second of all, the process of determining the needed investments to be made is in the model rather confined, whereas in the real world this process is fairly complicated. Improvements might be possible on this aspect.
At last, the determination of when external financiers will invest in electricity production capacity is not extensive in the model and quite some assumptions needed to be made to model this process (Appendix B.3. and D). This because the process of external investments contain quite some social factors. On these aspects there is still room for improvements.

Modeling Energy Storage

A broad analysis has been made during in this thesis research, which have not shown the expected effects. This is due to the fact that the SD-model looks at long term trends, whereas energy storage is done in short time periods. Energy storage affect the electricity system in the SD-model better, when wind volatility is modeled the same as demand volatility is modeled. This approach has not been tested and therefore an important limitation to the research as it is expected that energy storage will have a large influence on the electricity system in the future.

No cross-border modeling

In the System Dynamics model it is assumed that electricity import and export could always take place, whereas in the real world there are limitations to these factors. If the availability for electricity import and export, and if electricity prices in neighbor countries would be simulated, the System Dynamics model of the Dutch electricity system might improve in accuracy. Influences of electricity prices from abroad on the national electricity prices has been taken into account by an Import price factor. In the real world, this influence is more complicated.

Improve electricity demand forecasting

In the System Dynamics model, available functions for forecasting in the System Dynamics software are used to provide a forecast on the future electricity demand. In the real world, it is most likely that more extensive models are used to determine future electricity demand. Insights in these models might be of added value to the current System Dynamics model.

Wind as the only renewable energy source

Wind electricity production is the only renewable energy source modeled in the System Dynamics model, whereas solar electricity production is becoming more important. Adding this generation method could add value to the System Dynamics model.

Long term contracts

Long term contracts have not been taken into account when modeling the Dutch electricity system. It is assumed that the electricity price only is determined through the power exchange – whereas in the real world approximately 33% of the total electricity supply in the Netherlands of 2013, was traded through long term contracts.

Number of Phases in the Load Duration Curve

For this research it is assumed that it is sufficient to model the power exchange when the load duration curve is divided into three phases – base, shoulder and peak. Though, the effect of dividing the load

duration curve into more phases has not been investigated. Ideally the load duration curve would be divided into 8760 phases – equal to the number of hours per year – but this lies outside the capabilities of the System Dynamics software, Vensim.
Even though the sensitivity of changing the size of the phases has been tested – which did not show a high sensitivity – varying the number phases could be of added value for the System Dynamics model.

8.4 Recommendations for future research

External forces and scenarios

As explained, the external forces in the model are not substantiated with literature. Especially the expected development of these external forces towards 2030 and the uncertainty of this development are not covered well. Research that focuses on the development of external forces – that influence the Dutch electricity system – towards 2030 would add value to the System Dynamics model.

Investment process

One of the limitations of the model is that a simplification of the investment processes – both internal investments (of energy utility companies) and investments from external financiers – has been used in the model. This because investment processes are complex processes. Research on how a more complex investment process could be used in the System Dynamics model, might improve the reality and accuracy of the system Dynamics model.

Cross-border modeling

Researching how the System Dynamics model of the Dutch electricity system can be coupled to the SD-models of neighbor electricity systems, would be interesting. At the moment assumptions are made on the import and export of electricity. It would be more realistic when electricity supply, electricity demand and electricity prices are determined in another SD-model which can then be combined. In this way, electricity prices would influence Dutch electricity prices more realistically.

Modeling wind volatility

An important limitation of this research is that energy storage has been analyzed briefly. Simulations results show that energy storage does not affect the electricity system much, which is contradictory with the expectations. The reason for these meaningless simulation results of the energy storage, has to do with the way wind volatility has been modeled in the current SD-model. If wind volatility would be modeled the same way as how the demand volatility has been taken into account, the effect of energy storage might influence the electricity more. Future research should verify whether this is a better way of modeling wind volatility when analyzing .

Demand forecasting process

In real life, demand forecasting by energy utility companies is most likely done with complex models. Within this thesis research, a simple demand forecast has been done – through forecasting functions of the System Dynamics software. A research on the demand forecast models of energy utility companies and combining it with the System Dynamics value would be of added value.

Solar electricity production capacity

It is expected that in the future solar electricity production will become more important in the Netherlands. In the designed SD-model, solar electricity has not been taken into account. The model only focuses on wind electricity. Research on how to add this electricity generation method to the model would make the SD-model more realistic.

When adding a new generation method, other processes like investment processes most likely need to be adjusted as well.

Exploratory Modeling and Analysis (EMA)

Future research should be done on the correlations between variables in the Dutch electricity system as well as determining the uncertainty factors of the external forces. EMA could be an interesting computational analysis method to further analyze these aspects.

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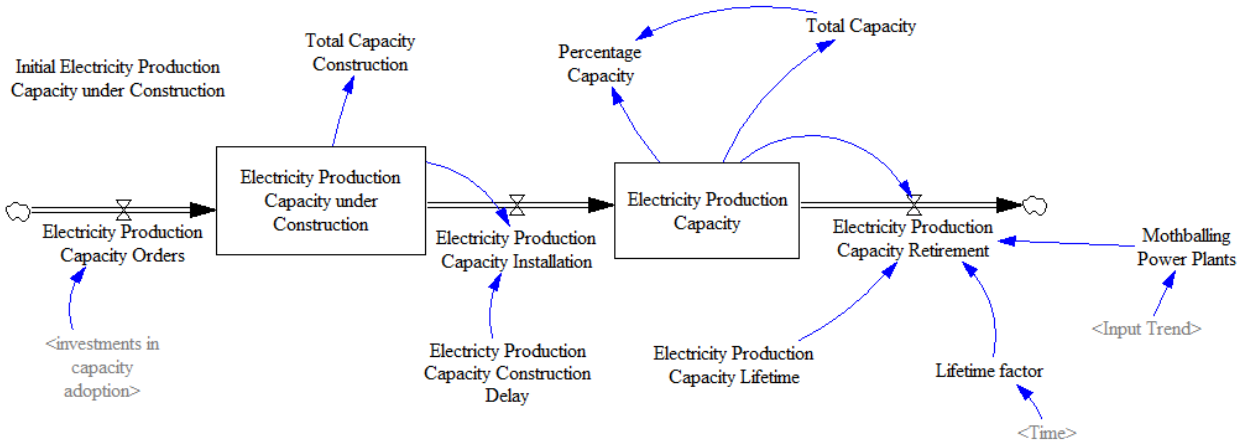
Appendices

Appendix A – Model Implementation

This appendix provides an overview on how the conceptualized model has been implemented in System Dynamics – Vensim. The System Dynamics consist of six components which are based on the conceptualization of chapter 3 and 4. In Appendix

Appendix A.1. – Electricity Production Capacity

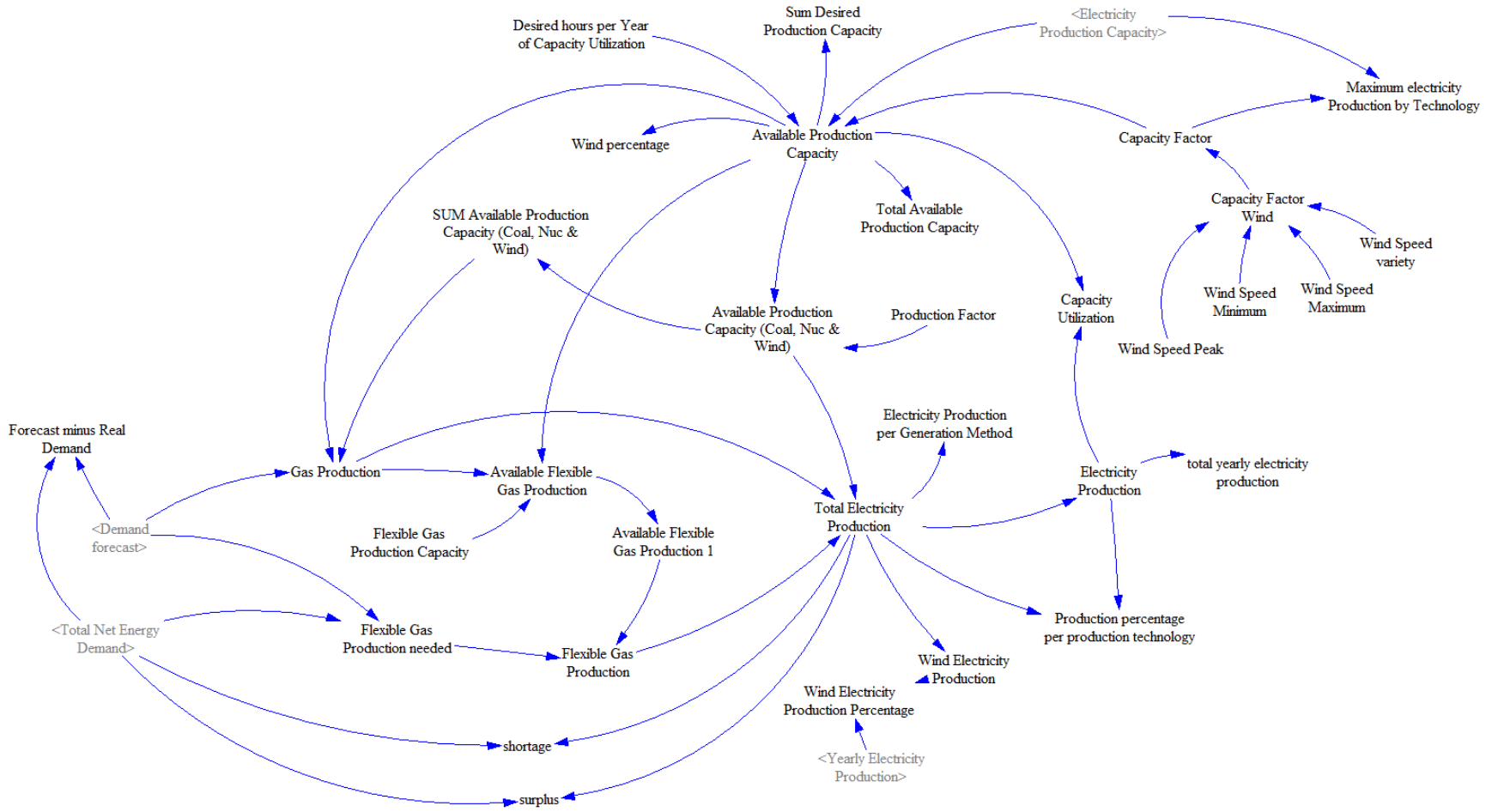
This view shows the determination of the electricity production capacity in the model. The electricity



production capacity has four different generation methods, which are added as subscripts to the model. The stock variable contain – as starting values – the installed capacity of 2005 and also an estimation - based on the difference of installed capacity between 2004 and 2005 – was made on how many MWs of different generation methods were under construction. In appendix B, all the components of the System Dynamics model are explained.

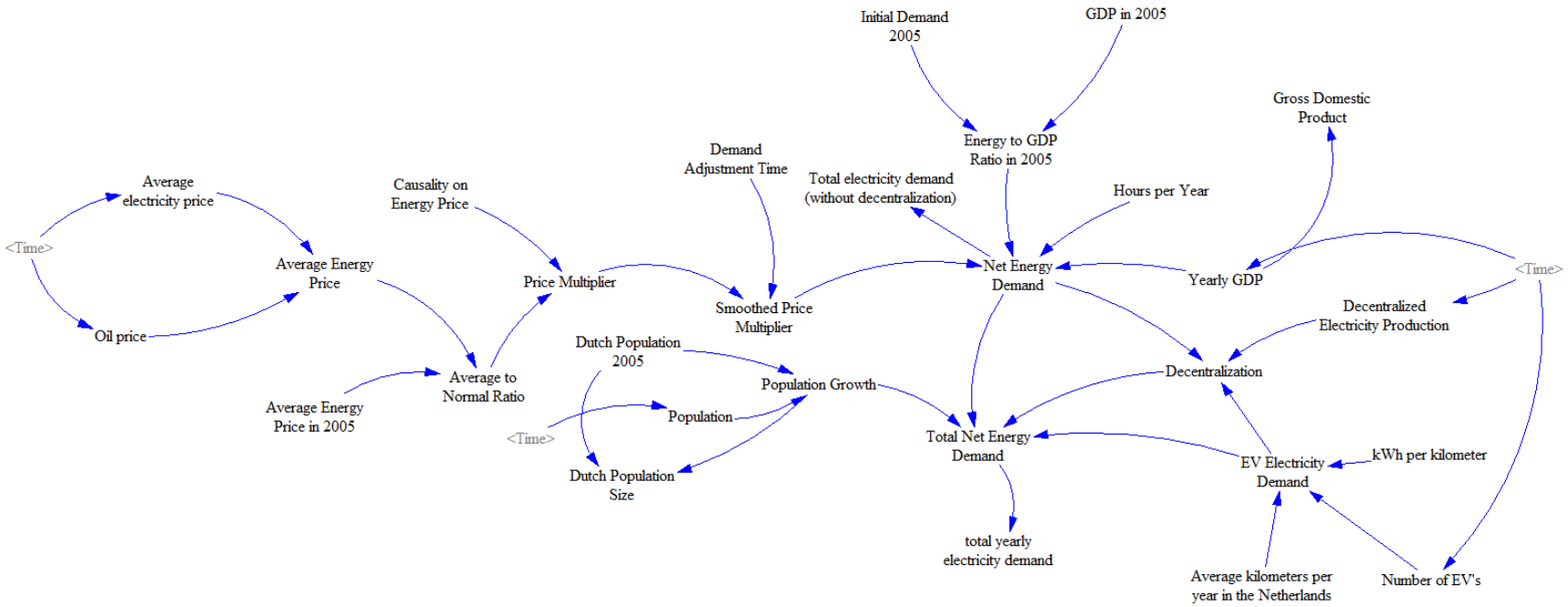
Appendix A.2. – Electricity Production

Below the electricity production component of the System Dynamics model is shown. The Electricity Production Capacity functions as input to this component, as based on the installed capacity to electricity production volume could be determined – based on the Capacity Factor. Another input to this model component is the electricity demand and the demand forecast. Based on the demand forecast the production planning is done. If the electricity demand turns out to be higher than expected, flexible gas production could be switched on to deliver the remaining electricity. When there is not sufficient gas production capacity left to deliver the remaining demanded electricity, then electricity is imported from neighbor countries – which is assumed to always be available.



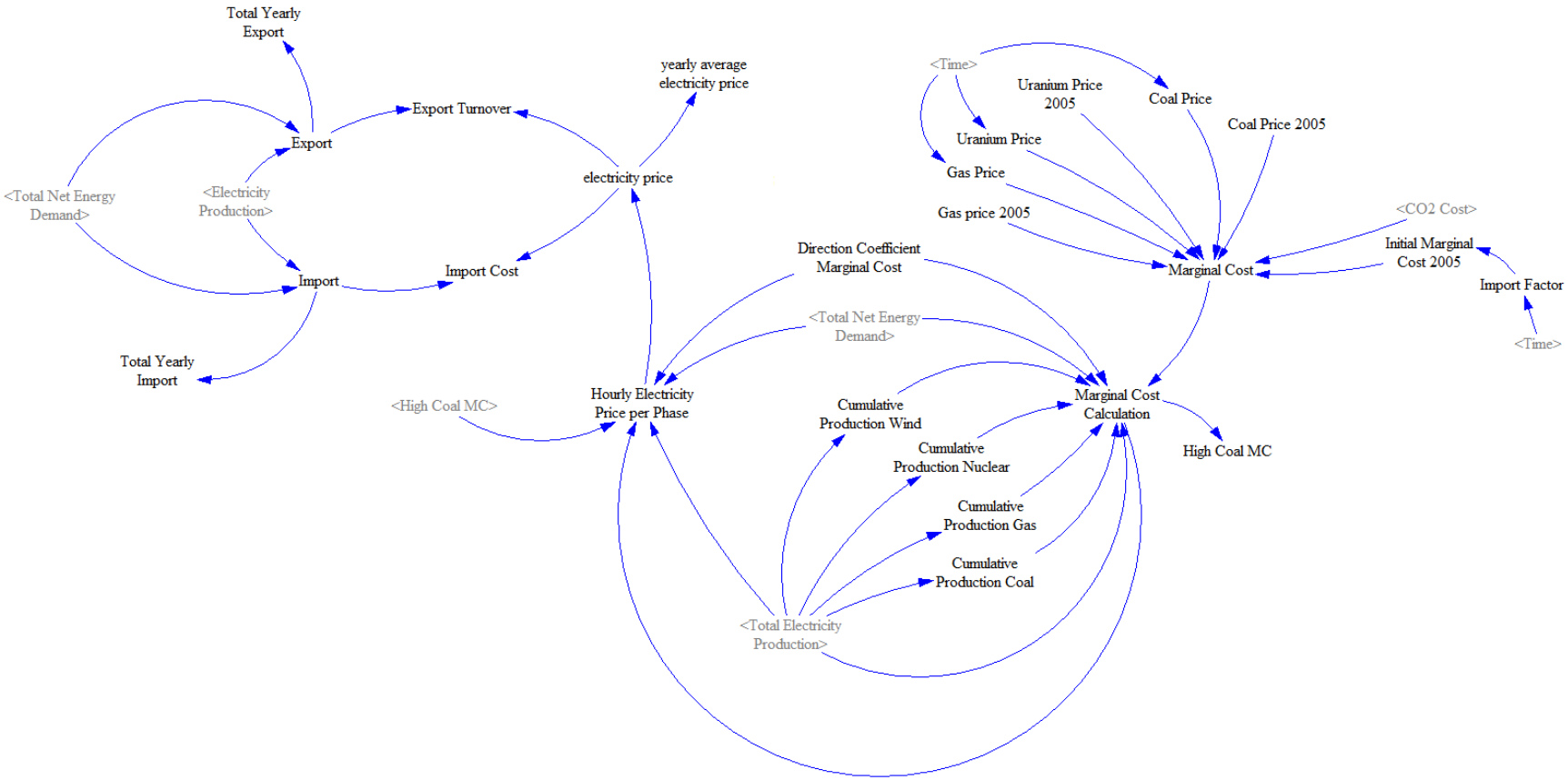
Appendix A.3. – Electricity Demand

Below the electricity demand component of the System Dynamics model is provided. The variables influencing the electricity demand are; Gross Domestic Product, Population Growth, Energy prices, Electric Vehicle adoption and decentralized electricity production. The electricity demand functions as input for the electricity supply component and the power exchange component.



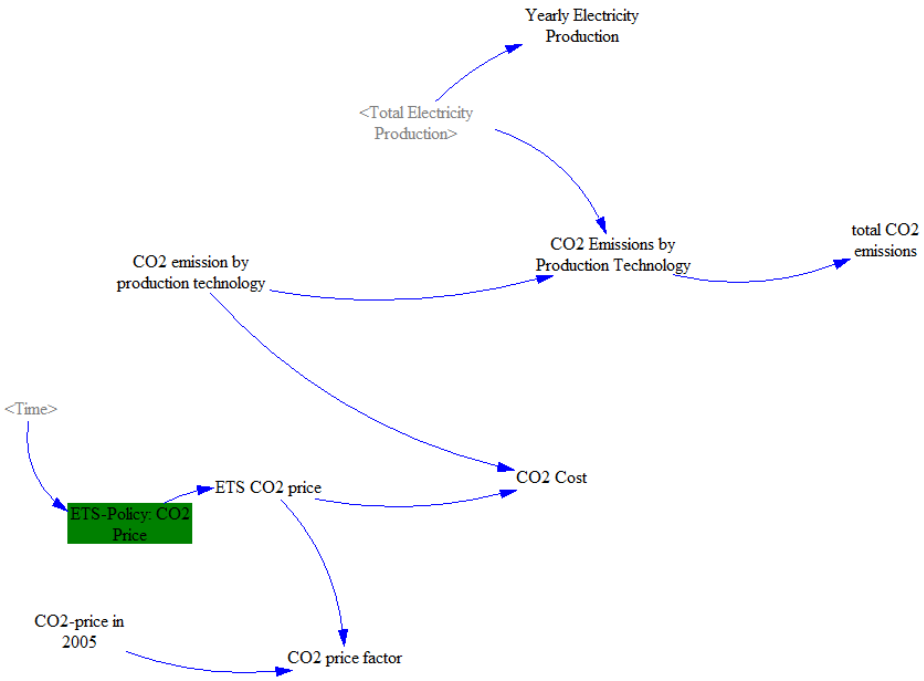
Appendix A.4. – The Power Exchange

Below the implementation of the Power Exchange component in System Dynamics is shown. The electricity demand and the electricity production are the two important components that function as input for the electricity price determination. Besides the demand and supply, the price for electricity production is an important aspect. This marginal cost determination is part of the power exchange view in the SD-model.



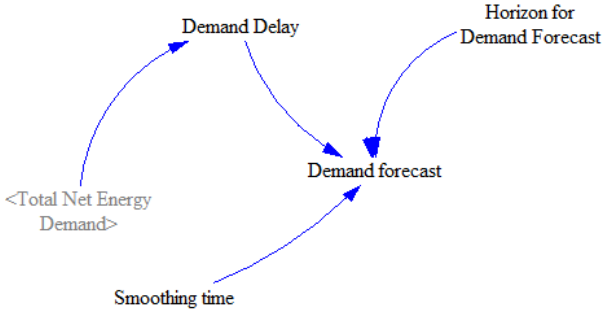
Appendix A.5. – CO2 emissions

Below the implementation of the CO2 emissions component in System Dynamics is shown. The electricity production component functions as most important input, because the CO2 emissions are determined based on how much electricity is produced and by which generation methods it is produced. Another important component in the CO2 emissions component is the CO2 price of the Emissions Trading Scheme policy of the European Union. The SD-model contains a scenario for the expected development of the CO2 price towards 2030. Based on this CO2 price, it is determined for each production method how much CO2 cost per MWh are related to the production method.



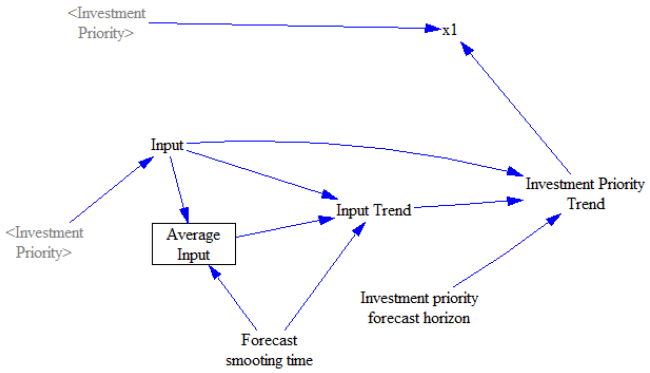
Appendix A.6. – Demand Forecast and Investment trends

Below the Demand Forecast component of the System Dynamics model is shown, which delivers input for the determination on electricity production planning. The demand forecast is done through a Forecast formula in the System Dynamics software. The input for the formula is the historical simulation demand data. Based on this data an extrapolation will be made. A detailed description on the functioning of the formula is described in appendix B.

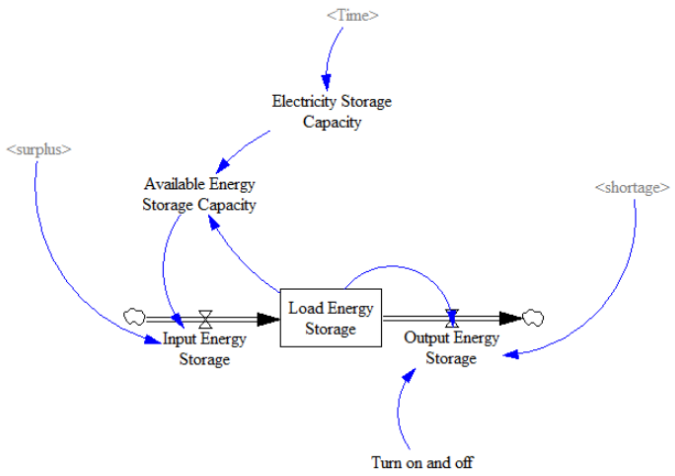


The next component is the Investment trend analysis which functions as input for determining how much should be investment in new generation capacity. This is determined based on a Trend formula in the System Dynamics software. A detailed description on the functioning of this formula is provided in appendix B.

An important input variable for this formula is the investment priority, which is based on the affinity and expected cost of a certain generation method. Then based on the available investment budget, the investment decision is eventually made. This is done through the ALLOCATE BY PRIORITY formula in the System Dynamics software. Also this formula is explained in more detail in appendix B.



Below the Energy Storage component of the System Dynamics model is shown, which stores and releases energy when surplus or shortages occur in the electricity system. Based on the capacity of energy storage, it is determined whether energy could be stored or whether it is exported to neighbor countries.



Appendix B. – Model variables and formulas

Appendix B.1. – Names, Formulas and Units of Variables

The table shows all the names, equations and formulas of the variables in the System Dynamics model. The squared brackets after the variables are the subscripts, the phases and/or the generation methods. If a variable is given with only one subscript, it means that the formula does not differ for the other variables. The variables with Dimensionless (Dmnl) are either a percentage or a social variable without a counterpart. In appendix B.2. the social variables will be explained. The variables with lookup are further explained in appendix E – Scenarios.

Variable	Formula	Unit
Affinity[Coal]	Look Up	Dmnl
Affinity[Gas]	Look Up	Dmnl
Affinity[Nuclear]	Look Up	Dmnl
Affinity[Wind]	Look Up	Dmnl
Affinity factor[Coal]	Affinity[Coal]/CO2 price factor	Dmnl
Available Flexible Gas Production[Base,Coal]	IF THEN ELSE(((Gas Production[Base,Generation Methods]/SUM(Available Production Capacity[Base,Generation Methods!]))>=0) , (Flexible Gas Production Capacity[Base]*SUM(Available Production Capacity[Base,Generation Methods!])), IF THEN ELSE(((Gas Production[Base,Generation Methods]/SUM(Available Production Capacity [Base,Generation Methods!]))>=(1-Flexible Gas Production Capacity[Base])), ((1-(Gas Production[Base,Generation Methods]/SUM(Available Production Capacity[Base,Generation Methods!])))*SUM(Available Production Capacity[Base,Generation Methods!])),0))	MWh/hour
Available Production Capacity[Base,Coal]	Desired hours per Year of Capacity Utilization[Phases,Generation Methods]*Electricity Production Capacity[Generation Methods]*Capacity Factor[Phases,Generation Methods]	MW
Available Production Capacity (Coal, Nuc & Wind)[Base,Coal]	Available Production Capacity[Phases,Generation Methods]*Production Factor[Generation Methods]	MW
Average Capacity Factor[Coal]	0.85	Dmnl
Average Capacity Factor[Gas]	0.87	Dmnl
Average Capacity Factor[Nuclear]	0.9	Dmnl
Average Capacity Factor[Wind]	0.3849	Dmnl
Average electricity price	Look Up	MWh/hour
Average Energy Price	((0.6*Oil price)/1.0607)+(0.4*(Average electricity price))	Euro
Average Energy Price in 2005	80.84	Euro
Average Input[Coal]	INTEG((Input[Generation Methods]-Average Input[Generation Methods])/Forecast smoothing time)	Dmnl

Average kilometers per year in the Netherlands	13500	km/year
Average to Normal Ratio	(Average Energy Price/Average Energy Price in 2005)	Dmnl
Capacity Factor[Base,Coal]	0.85	Dmnl
Capacity Factor[Base,Gas]	0.87	Dmnl
Capacity Factor[Base,Nuclear]	0.9	Dmnl
Capacity Factor[Base,Wind]	Capacity Factor Wind	Dmnl
Capacity Factor Wind	IF THEN ELSE(Wind Speed variety<Wind Speed Minimum,0,IF THEN ELSE(Wind Speed variety<Wind Speed Peak,(Wind Speed variety/Wind Speed Peak)^3, IF THEN ELSE(Wind Speed variety<Wind Speed Maximum,1,0)))	Dmnl
Capacity Utilization[Base,Coal]	IF THEN ELSE(Available Production Capacity[Phases,Generation Methods]>0, Electricity Production[Phases]/Available Production Capacity[Phases,Generation Methods],0)	Dmnl
Causality on Energy Price	-0.28	Dmnl
Mothballing Power Plants[Coal]	IF THEN ELSE(Input Trend[Gas]<0,Input Trend[Gas],0)	MW/year
CO2 Cost[Coal]	CO2 emission by production technology[Generation Methods]*ETS CO2 price	Euro/MWh
CO2 emission by production technology[Coal]	0.85	ton/MW
CO2 price factor	0.35	ton/MW
CO2-price in 2005	8	euro/ton
Coal Price	Look Up	Euro/ton
Coal Price 2005	2.12	Euro/GJ
Cumulative Production Coal[Base,Coal]	Total Electricity Production[Phases,Wind]+Total Electricity Production[Phases,Nuclear]+Total Electricity Production[Phases,Coal]	MWh
Cumulative Production Gas[Base,Gas]	SUM(Total Electricity Production[Phases,Generation Methods!])	MWh
Cumulative Production Nuclear[Base,Nuclear]	Total Electricity Production[Phases,Wind]+Total Electricity Production[Phases,Nuclear]	MWh
Cumulative Production Wind[Base,Wind]	Total Electricity Production[Phases,Wind]	MWh
Decentralization[Base]	((Net Energy Demand[Phases]+EV Electricity Demand)/(1-(Decentralized Electricity Production)))*(Decentralized Electricity Production)	MWh/hour
Decentralized Electricity Production	Look Up	Dmnl
Demand Adjustment Time	10	Year
Demand Delay[Base]	1	Year
Demand forecast[Base]	(FORECAST(Demand Delay[Base], Smoothing time , Horizon for Demand Forecast))	Mwh

Desired Capacity[Coal,Base]	IF THEN ELSE(Capacity Factor[Phases,Generation Methods]>0,(Demand forecast[Phases]-Electricity Production[Phases])* (Affinity factor[Generation Methods]/SUM(Affinity factor[Generation Methods!])*(1/Capacity Factor[Peak,Generation Methods])), Demand forecast[Phases]-Electricity Production[Phases])	MW
Desired Electricity - Stock[Coal]	Investment Cost[Generation Methods]*Desired Electricity production development[Generation Methods]*Average Capacity Factor[Generation Methods]	Euro
Desired Electricity production development[Coal]	SUM(Desired New Electricity Production Capacity[Phases!])*(Affinity factor[Generation Methods]/SUM(Affinity factor[Generation Methods!]))	MW
Desired Electricity production Development with Nuclear[Coal,Base]	IF THEN ELSE(Electricity Production Capacity[Nuclear]>2000, 0 , (Desired Electricity production development[Nuclear]/Electricity Production Capacity Lifetime[Nuclear]))	MW
Desired New Electricity Production Capacity[Base]	(Projected Electricity Production Requirements[Phases]+SUM Electricity Production Capacity Retirement[Phases])	MW
Direction Coefficient Marginal Cost[Coal]	0.003129	Dmnl
Direction Coefficient Marginal Cost[Gas]	0.000974	Dmnl
Direction Coefficient Marginal Cost[Nuclear]	0.000692	Dmnl
Direction Coefficient Marginal Cost[Wind]	0.00059	Dmnl
Dutch Population 2005	1.63E+007	People
Dutch Population Size	Dutch Population 2005*Population Growth	People
Electricity Investment[Coal]	INTEG((Investment Cost[Generation Methods]*Average Capacity Factor[Generation Methods])*Desired Electricity production development[Generation Methods]	Euro/Year
Electricity Investment - Stock[Coal]	"Desired Electricity – Stock"[Wind]-"Investments done - Stock"[Wind]	Euro
electricity price[Base]	SMOOTH((SUM(Hourly Electricity Price per Phase[Phases,Generation Methods!])/4) , 0.25)	MWh/hour
Electricity Production[Base]	SUM(Total Electricity Production[Phases,Generation Methods!])	MWh/hour
Electricity Production Capacity[Coal]	Electricity Production Capacity Installation[Coal]-Electricity Production Capacity Retirement[Coal]	MW
Electricity Production Capacity Installation[Coal]	Electricity Production Capacity under Construction[Coal]/Electricty Production Capacity Construction Delay[Coal]	MW/year
Electricity Production Capacity Lifetime[Coal]	40	year
Electricity Production Capacity Lifetime[Gas]	30	year
Electricity Production Capacity Lifetime[Nuclear]	40	year
Electricity Production Capacity Lifetime[Wind]	15	year

Electricity Production Capacity Orders[Coal]	investments in capacity adoption[Generation Methods]	MW/year
Electricity Production Capacity Retirement[Coal]	(Electricity Production Capacity[Coal]/(Electricity Production Capacity Lifetime[Coal]*Lifetime factor[Coal]))+((-1*Mothballing Power Plants[Coal])*Electricity Production Capacity[Coal])	MW/year
Electricity Production Capacity under Construction[Coal]	Electricity Production Capacity Orders[Coal]-Electricity Production Capacity Installation[Coal]	MW/year
Electricity Production per Generation Method[Coal]	(((Total Electricity Production[Peak,Wind]*876)+(Total Electricity Production[Shoulder,Wind]*7008)+(Total Electricity Production[Base,Wind]*876))/1e+006)*Capacity Factor[Wind]	TWh
Electricity Production TREND[Base]	TREND(Total Net Energy Demand[Phases],5, (Time-INITIAL TIME))	Dmnl
Electricty Production Capacity Construction Delay[Coal]	5	year
Electricty Production Capacity Construction Delay[Gas]	2	year
Electricty Production Capacity Construction Delay[Nuclear]	6	year
Electricty Production Capacity Construction Delay[Wind]	1	year
Energy to GDP Ratio in 2005[Base]	Initial Demand 2005[Phases]/(GDP in 2005/8760)	MWh/euro
ETS CO2 price	"ETS-Policy: CO2 Price"	euro/ton
ETS-Policy: CO2 Price	Look Up	euro/ton
EV Electricity Demand	(((kWh per kilometer*Average kilometers per year in the Netherlands)/1000)*(Number of EV's))/8760	MWh/hour
Export[Base]	IF THEN ELSE(Electricity Production[Phases]>=Total Net Energy Demand[Phases], (Electricity Production[Phases]-Total Net Energy Demand[Phases]) , 0)	MWh
Export Turnover[Base]	electricity price[Phases]*Export[Phases]	Euro
External financing[Coal]	IF THEN ELSE(IF THEN ELSE(Investment Priority Trend[Wind]>=0.0045,"Electricity Investment - Stock"[Wind]*((Investment Priority Trend[Wind]-Investment Priority[Wind])/ Investment Priority Trend[Wind]),0)>=0,IF THEN ELSE(Investment Priority Trend[Wind]>=0.0045,"Electricity Investment - Stock"[Wind]* ((Investment Priority Trend[Wind]-Investment Priority[Wind])/Investment Priority Trend[Wind]),0),0)	Euro
Fixed Cost[Coal]	(LCOE[Generation Methods]*Fixed Cost Factor per Technology[Generation Methods])*Electricity Production Capacity[Generation Methods]	Euro/Year
Fixed Cost Factor per Technology[Coal]	0.6823	Dmnl
Fixed Cost Factor per Technology[Gas]	0.2595	Dmnl
Fixed Cost Factor per Technology[Nuclear]	0.8773	Dmnl
Fixed Cost Factor per Technology[Wind]	1	Dmnl

Flexible Gas Production[Base,Coal]	IF THEN ELSE(Flexible Gas Production needed[Phases]<Available Flexible Gas Production 1[Phases,Generation Methods],Flexible Gas Production needed [Phases],Available Flexible Gas Production 1[Phases,Generation Methods])	MWh/hour
Flexible Gas Production Capacity[Base]	0.8	Dmnl
Flexible Gas Production needed[Base]	IF THEN ELSE((Total Net Energy Demand[Phases]>Demand forecast[Phases]),Total Net Energy Demand[Phases]-Demand forecast[Phases],0)	Mwh
Forecast minus Real Demand[Base]	Demand forecast[Phases]-Total Net Energy Demand[Phases]	MWh/hour
Forecast smooting time	10	year
Gas Price	Look Up	Euro/m3
Gas price 2005	0.12	euro/m3
Gas Production[Base,Coal]	IF THEN ELSE ((IF THEN ELSE((Demand forecast[Phases]-"SUM Available Production Capacity (Coal, Nuc & Wind)"[Phases])>=0, Demand forecast[Phases]-"SUM Available Production Capacity (Coal, Nuc & Wind)"[Phases], 0)) >= Available Production Capacity[Phases,Gas], Available Production Capacity[Phases,Gas], (IF THEN ELSE((Demand forecast[Phases]-"SUM Available Production Capacity (Coal, Nuc & Wind)"[Phases])>0, Demand forecast[Phases]-"SUM Available Production Capacity (Coal, Nuc & Wind)"[Phases], 0)))	Mwh/hour
GDP in 2005	6.57E+011	Euro
Gross Domestic Product	Yearly GDP	Euro
High Coal MC[Base,Coal]	IF THEN ELSE(Marginal Cost Calculation[Phases,Coal]>Marginal Cost Calculation[Phases,Gas], Marginal Cost Calculation[Phases,Coal]-Marginal Cost Calculation[Phases,Gas],0)	Euro/MWh
Horizon for Demand Forecast	1	year
Hourly Electricity Price per Phase[Base,Coal]	IF THEN ELSE((Total Electricity Production[Base,Wind]>=Total Net Energy Demand[Base]),Marginal Cost Calculation[Base,Wind],IF THEN ELSE (((Total Electricity Production[Base,Wind]+Total Electricity Production[Base,Nuclear])>=Total Net Energy Demand [Base]),Marginal Cost Calculation[Base,Nuclear],IF THEN ELSE (((Total Electricity Production[Base,Wind]+Total Electricity Production[Base,Nuclear]+Total Electricity Production [Base,Coal])>=Total Net Energy Demand[Base]),Marginal Cost Calculation[Base,Coal],IF THEN ELSE ((SUM(Total Electricity Production[Base,Generation Methods!])>=Total Net Energy Demand[Base]), (Direction Coefficient Marginal Cost[Gas]*(Total Net Energy Demand[Base]-(Total Electricity Production[Base,Wind]+Total Electricity Production[Base,Nuclear]+ Total Electricity Production[Base,Coal])))+Marginal Cost Calculation[Base,Gas]+High Coal MC[Base,Coal], (Direction Coefficient Marginal Cost[Gas]*(Total Net Energy Demand[Base]-(Total Electricity Production[Base,Wind]+Total Electricity	euro/Mwh

	Production[Base,Nuclear]+ Total Electricity Production[Base,Coal]))+Marginal Cost Calculation[Base,Gas]+High Coal MC[Base,Coal]+(0.0145*(Total Net Energy Demand[Base]- SUM(Total Electricity Production[Base,Generation Methods!])))))))	
Hours per Year	8760	hours
Hours per year per Phase[Base]	876	hours
Hours per year per Phase[Shoulder]	7008	hours
Hours per year per Phase[Peak]	876	hours
Import[Base]	IF THEN ELSE(Total Net Energy Demand[Phases]>=Electricity Production[Phases], (Total Net Energy Demand[Phases]-Electricity Production[Phases]) , 0)	MWh
Import Cost[Base]	electricity price[Phases]*Import[Phases]	Euro
Import Factor	Look Up	Dmnl
Initial Demand 2005[Base]	7829	MWh
Initial Demand 2005[Shoulder]	10902	MWh
Initial Demand 2005[Peak]	14376	MWh
Initial Electricity Production Capacity under Construction[Wind]	149	MW
Initial Marginal Cost 2005[Coal]	18.8	Euro/Mwh
Initial Marginal Cost 2005[Gas]	40.8	Euro/Mwh
Initial Marginal Cost 2005[Nuclear]	9.6	Euro/Mwh
Initial Marginal Cost 2005[Wind]	4.8	Euro/Mwh
Input[Coal]	Investment Priority[Generation Methods]	Dmnl
Input Trend[Coal]	ZIDZ(Input[Generation Methods]-Average Input[Generation Methods],Forecast smoothing time*Average Input[Generation Methods])	Dmnl
Investment[Coal]	ALLOCATE BY PRIORITY("Electricity Investment - Stock"[Generation Methods], Investment Priority[Generation Methods], ELMCOUNT(Generation Methods), Investment Priority Width, Investment Budget)	Euro/year
Investment as Percentage of Total Output[Coal]	(Electricity Investment[Generation Methods]/(Yearly GDP*1e+009))*100	Dmnl
Investment Budget	Investment Budget increase – SUM(Investment Budget Decrease[Generation Methods!])	Euro
Investment Budget Decrease[Coal]	IF THEN ELSE(Investment Budget>=SUM(Investment[Generation Methods!]), SUM(Investment[Generation Methods!]), Investment Budget-SUM(Investment[Generation Methods!]))	Euro/year

Investment Budget increase	Investment Budget per Year	Euro/year
Investment Budget per Year	IF THEN ELSE(Profit>0,Investment Percentage*Profit,0)	Euro/year
Investment Cost[Coal]	2.90E+006	Euro/MW
Investment Cost[Gas]	1.40E+006	Euro/MW
Investment Cost[Nuclear]	3.00E+006	Euro/MW
Investment Cost[Wind]	1.50E+006	Euro/MW
Investment Percentage	0.06	Dmnl
Investment Priority[Coal]	1/(LCOE[Generation Methods]/(Affinity factor[Generation Methods]))	Dmnl
Investment priority forecast horizon	10	year
Investment Priority Trend[Coal]	Input[Generation Methods]*(1+Input Trend[Generation Methods]*Investment priority forecast horizon)	Dmnl
Investment Priority Width	VMIN(Investment Priority[Generation Methods!])	Dmnl
Investments done - Stock[Coal]	investments in capacity adoption[Generation Methods]	euro/year
investments in capacity adoption[Coal]	IF THEN ELSE(Investment[Wind]>=0,(Investment[Wind]+("SDE+ Subsidy"[Wind]*S Value 22)+ External financing[Wind])/(Investment Cost[Wind]*Average Capacity Factor[Wind]),0)	MW/year
kWh per kilometer	0.2	kWh/km
LCOE[Coal]	(95.6*((Coal Price/Coal Price 2005)))+CO2 Cost[Coal]	Euro/MWh
LCOE[Gas]	(64.4*((Gas Price/Gas price 2005)))+CO2 Cost[Gas]	Euro/MWh
LCOE[Nuclear]	96.1*((Uranium Price/Uranium Price 2005))	Euro/MWh
LCOE[Wind]	140.3	Euro/MWh
Lifetime factor[Coal]	1	Dmnl
Lifetime factor[Gas]	1	Dmnl
Lifetime factor[Nuclear]	4	Dmnl
Lifetime factor[Wind]	Look Up	Dmnl
Marginal Cost[Coal]	(Initial Marginal Cost 2005[Coal]*((Coal Price)/Coal Price 2005))+CO2 Cost[Coal]	Euro/MWh
Marginal Cost[Gas]	(Initial Marginal Cost 2005[Gas]*((Gas Price)/Gas price 2005))+CO2 Cost[Gas]	Euro/MWh
Marginal Cost[Nuclear]	Initial Marginal Cost 2005[Nuclear]*((Uranium Price)/Uranium Price 2005)	Euro/MWh
Marginal Cost[Wind]	Initial Marginal Cost 2005[Wind]	Euro/MWh
Marginal Cost Calculation[Base,Coal]	IF THEN ELSE((Cumulative Production Coal[Phases,Coal]-Cumulative Production Nuclear[Phases,Nuclear])>=(Total Net Energy Demand[Phases]-Cumulative Production Nuclear[Phases,Nuclear]),(Marginal Cost[Coal]+(Direction Coefficient Marginal Cost[Coal]*((Cumulative Production Coal[Phases,Coal]- Cumulative Production Nuclear[Phases,Nuclear])))),Marginal Cost[Coal]+(Total Electricity Production [Phases,Coal]*Direction Coefficient Marginal Cost[Coal]))	Euro/MWh

Maximum electricity Production by Technology[Base,Coal]	Capacity Factor[Peak,Generation Methods]*Electricity Production Capacity[Generation Methods]	MWh/hour
Net Energy Demand[Base]	Energy to GDP Ratio in 2005[Phases]*((Yearly GDP)/Hours per Year)*Smoothed Price Multiplier	MWh/hour
Number of EV's	Look Up	Cars
Oil price	Look Up	dollar/barrel
Percentage Capacity[Coal]	Electricity Production Capacity[Coal]/Total Capacity	Dmnl
Population	Look Up	people
Population Growth	(Population/Dutch Population 2005)	people/year
Price Multiplier	Average to Normal Ratio^Causality on Energy Price	Dmnl
Production Factor[Coal]	1	Dmnl
Production Factor[Gas]	0	Dmnl
Production Factor[Nuclear]	1	Dmnl
Production Factor[Wind]	1	Dmnl
Production Factor 2[Coal]	0	Dmnl
Production Factor 2[Gas]	1	Dmnl
Production Factor 2[Nuclear]	0	Dmnl
Production Factor 2[Wind]	0	Dmnl
Production percentage per production technology[Coal,Base]	Total Electricity Production[Phases,Generation Methods]/Electricity Production[Phases]	Dmnl
Profit	(SUM(Yearly Turnover[Phases!])+SUM(Export Turnover[Phases!]))-(Total Cost+SUM(Import Cost[Phases!]))	euro/year
Projected Electricity Production Requirements[Base]	IF THEN ELSE((Electricity Production TREND[Phases]*Total Capacity)<0, 0, (Electricity Production TREND[Phases]*Total Capacity))	MW/year
Projection Period for Electricity Capacity Expansion	5	year
SDE+ Availability[Wind]	"SDE+ Subsidy"[Generation Methods]	euro/year
SDE+ Subsidy[Wind]	Look Up	Euro/year
Share of Electricity Production Capacity by Technology[Coal,Base]	Electricity Production Capacity[Coal]/Total Capacity	Dmnl
shortage[Base]	IF THEN ELSE((Total Net Energy Demand[Phases]-SUM(Total Electricity Production[Phases,Generation Methods!]))>0,Total Net Energy Demand[Phases]- SUM(Total Electricity Production[Phases,Generation Methods!]),0)	MWh/hour
Smoothed Price Multiplier	SMOOTH(Price Multiplier, Demand Adjustment Time)	Dmnl

Smoothing time	1	year
SUM Available Production Capacity (Coal, Nuc & Wind)[Base]	SUM("Available Production Capacity (Coal, Nuc & Wind)"[Phases,Generation Methods!])	MW/hour
Sum Desired Generation development[Base,Coal]	(Desired Electricity production development[Generation Methods]-Desired Electricity production Development with Nuclear[Nuclear,Phases])	MW/year
Sum Desired Production Capacity[Base]	SUM(Available Production Capacity[Phases,Generation Methods!])	MW/year
SUM Electricity Production Capacity Retirement[Base]	SUM(Electricity Production Capacity Retirement[Generation Methods!])	MW/year
surplus[Base]	IF THEN ELSE((Total Net Energy Demand[Phases]-SUM(Total Electricity Production[Phases,Generation Methods!]))<0, (Total Net Energy Demand[Phases]- SUM(Total Electricity Production[Phases,Generation Methods!]))*-1,0)	MWh/hour
Total Available Production Capacity[Coal]	SUM(Available Production Capacity[Phases!,Generation Methods])/3	MW/hour
Total Capacity	SUM(Electricity Production Capacity[Generation Methods!])	MW
Total Capacity Construction	SUM(Electricity Production Capacity under Construction[Generation Methods!])	MW/year
total CO2 emissions	SUM(CO2 Emissions by Production Technology[Generation Methods!,Phases!])	ton/year
Total Cost	SUM(Variable cost[Phases!,Generation Methods!])+SUM(Fixed Cost[Generation Methods!])*8760	Euro/year
Total Development Nuclear	SUM(Desired Electricity production Development with Nuclear[Nuclear,Phases!])	MW/year
Total electricity demand (without decentralization)[Base]	(876*Net Energy Demand[Peak])+(7008*Net Energy Demand[Shoulder])+(876*Net Energy Demand[Base])	MWh
Total Electricity Production[Base,Coal]	"Available Production Capacity (Coal, Nuc & Wind)"[Phases,Generation Methods]+Flexible Gas Production[Phases,Generation Methods]+ (Gas Production[Phases,Generation Methods])	MWh/hour
Total Net Energy Demand[Base]	(IF THEN ELSE((((Net Energy Demand[Phases]+EV Electricity Demand)*Population Growth)-Decentralization[Phases])>0,(((Net Energy Demand[Phases]+ EV Electricity Demand)*Population Growth)-Decentralization[Phases]),0))	MWh/hour
Total Variable Cost[Base]	(SUM(Variable cost[Base,Generation Methods!])*876)+(SUM(Variable cost[Shoulder,Generation Methods!])*7008)+ (SUM(Variable cost[Peak,Generation Methods!])*876)	Euro/year
total yearly electricity demand	((Total Net Energy Demand[Peak]*876)+(Total Net Energy Demand[Shoulder]*7008)+(Total Net Energy Demand[Base]*876))/1e+006	TWh/year
total yearly electricity production	((Electricity Production[Base]*876)+(Electricity Production[Shoulder]*7008)+(Electricity Production[Peak]*876))/1e+006	TWh/year
Total Yearly Export	((Export[Base]*876)+(Export[Shoulder]*7008)+(Export[Peak]*876))	MWh/year
Total Yearly Import	((Import[Base]*876)+(Import[Shoulder]*7008)+(Import[Peak]*876))	MWh/year
Total Yearly Turnover	SUM(Yearly Turnover[Phases!])	

Uranium Price	Look Up	euro/kg
Uranium Price 2005	11	euro/kg
Variable cost[Base,Coal]	Marginal Cost[Coal]*Total Electricity Production[Phases,Coal]	euro/year
Variable Cost percentage[Base,Coal]	((Variable cost[Peak,Generation Methods]*876)+(Variable cost[Shoulder,Generation Methods]*7008)+(Variable cost[Base,Generation Methods]*876))/ (SUM(Total Variable Cost[Phases!]))	Dmnl
Wind Electricity Production[Base]	((Total Electricity Production[Peak,Wind]*876)+(Total Electricity Production[Shoulder,Wind]*7008)+(Total Electricity Production[Base,Wind]*876))	MWh/year
Wind Electricity Production Percentage[Base]	Wind Electricity Production[Phases]/Yearly Electricity Production[Phases]	Dmnl
Wind percentage[Base,Coal]	Available Production Capacity[Phases,Wind]/SUM(Available Production Capacity[Phases,Generation Methods!])	Dmnl
Wind Speed Maximum	20	m/s
Wind Speed Minimum	4	m/s
Wind Speed Peak	10	m/s
Wind Speed variety	7.274	m/s
yearly average electricity price	((electricity price[Peak]*876/8760)+(electricity price[Shoulder]*7008/8760)+(electricity price[Base]*876/8760))	euro/MWh
Yearly Electricity Production[Base]	((SUM(Total Electricity Production[Peak,Generation Methods!])*876)+(SUM(Total Electricity Production[Shoulder,Generation Methods!])*7008)+ (SUM(Total Electricity Production[Base,Generation Methods!])*876))	MWh/year
Yearly GDP	Look Up	Euro
Yearly Turnover[Base]	electricity price[Phases]*Hours per year per Phase[Phases]*Electricity Production[Phases]	Euro/year
Load Energy Storage [Phases]	Input Energy Storage[Phases]-Output Energy Storage[Phases]	MWh
Output Energy Storage[Phases]	(IF THEN ELSE(shortage[Phases]>=Load Energy Storage[Phases],Load Energy Storage[Phases],Load Energy Storage[Phases]-shortage [Phases]))*Turn on and off	MWh
Input Energy Storage[Phases]	IF THEN ELSE(surplus[Phases]>=Available Energy Storage Capacity[Phases],Available Energy Storage Capacity[Phases],surplus[Phases])	MWh
Available Energy Storage Capacity[Phases]	IF THEN ELSE(Electricity Storage Capacity[Phases]>=Load Energy Storage[Phases],Electricity Storage Capacity[Phases]-Load Energy Storage[Phases],0)	MWh

Appendix B.2. – Social variables explanation

In this appendix the social variables – with the Dmnl units in Appendix B.1. – are further explained.

Variable	Explanation
Affinity	The affinity deals with the social aspects within an investment process. When the affinity is high - in the model close to 1 or even above - then it is most likely that a certain generation method will receive an investment, if other variables influencing the investment environment are also positive. When the affinity is low - close to 0 - then it is less likely that the generation method receives investments.
Affinity factor	The affinity factor contains all the important aspects for making an investment. The CO2 price and the capacity factor are taken into account in this factor as well.
Average Capacity Factor	The Capacity factor is the ratio of the actual output of a power plant over a period of time, to the potential output of the power plant.
Average Input	The average input functions as an input variable for a Trend analysis function in Vensim - System Dynamics software. This formula will be described in more detail in appendix B.4.
Average to Normal Ratio	This variable is a factor calculated based on the average energy price in 2005 divided by the average energy price per year. This factor is then used in the electricity demand part of the System Dynamics model.
Capacity Utilization	A percentage that determines how much of the available generation capacity is actually used for electricity production
Causality on Energy Price	This factor corresponds as the causality factor between the energy price and the electricity demand.
Direction Coefficient Marginal Cost	This factor influences the marginal cost of generation capacity in the power plant. It is assumed that marginal cost of power plants of the same generation method are not the same. Through the Direction coefficient the marginal cost rises as more electricity production is demanded from more expensive generation capacity, that are mostly bid as last in the power exchange. More information on the determination of this factor is given in appendix B.3.
Electricity Production TREND	A factor used as input for the trend analysis formula in Vensim - the System Dynamics software. More information on this formula is given in appendix B.4.
Import Factor	This factor deals with the lower electricity prices that get imported from Germany. This influences the electricity in the Netherlands. It lowers the average electricity prices in the Netherlands. More information on this factor is given in appendix B.3.
Input	Input factor for trend analysis function in Vensim - System Dynamics software
Input Trend	Input factor for trend analysis function in Vensim - System Dynamics software
Investment Priority	A factor which is determined through the LCOE and the affinity factor. This factor is eventually used to determine whether an investment in a certain generation method should be made.
Investment Priority Trend	Input factor for forecast function in Vensim - System Dynamics software
Investment Priority Width	Input factor for forecast function in Vensim - System Dynamics software
Lifetime factor	A factor that counteracts the retirement of generation capacity. This is called into place to counteract the retirement of wind generation capacity that is just installed. Since the lifetime of wind mills are approximately 15 years and the most

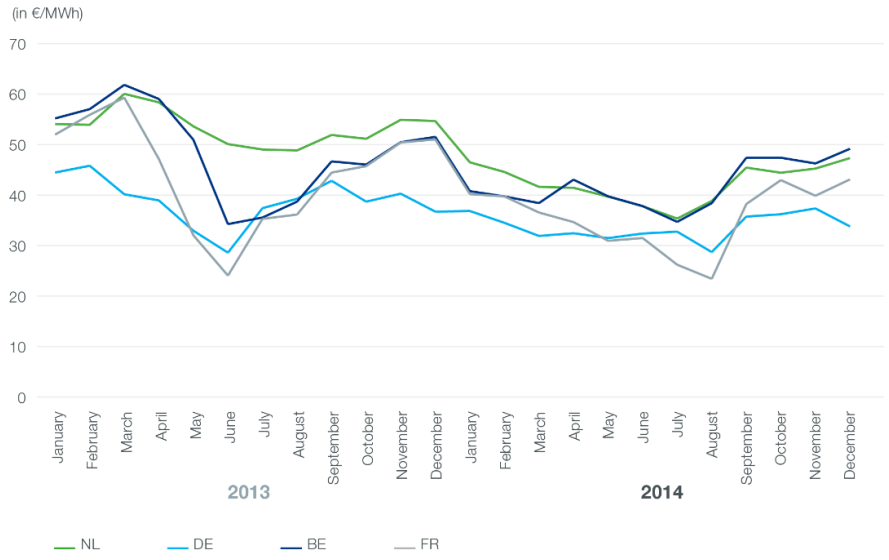
	of the wind energy is installed after 2005 - meaning that the wind mills should not retire around 2010. This factor slowly grows to 1 as later on the retirement of wind mills should function as the other generation methods.
Price Multiplier	The factor calculated from the causality factor for energy price and electricity demand. This multiplier times the electricity demand provides the expected development of electricity demand towards 2030 with the energy price as the factor influencing it.
Production Factor	This factor contains a 0 or 1 value. This is called into place to turn certain generation methods on or off, when especially flexible power plants are required or the other way around.
Production Factor 2	This factor contains a 0 or 1 value. This is called into place to turn certain generation methods on or off, when especially flexible power plants are required or the other way around.
Smoothed Price Multiplier	Smoothens the price multiplier - which contains the causality between energy price and energy demand. This factor is based on research of Davies & Simonovic (2009).

Appendix B.3. – Detailed explanation on social factors

In this appendix further explanation is given for the following social factors; Import factor (influencing the electricity price), the direction coefficient of Marginal Cost and External investments.

The import factor for electricity prices

The import factor on electricity prices is called into place to represent the, in general, lower electricity prices in Germany. The System Dynamics model focuses on the on the Dutch electricity system and the electricity systems of neighbor countries have not been taken into account. As the electricity price from neighbor countries are important to take into account when simulating an electricity system, a factor has been called into place. From the graph – on the right – could be concluded that the electricity prices in Germany are structurally about 20% less. Therefore, the assumption is made that the electricity prices in the Netherlands are influences by this 20% and thus this factor is decided to be 0.8. This import factor is added to the System Dynamics model influencing the power exchange by multiplying the output with 0.8. The model would be



Average Electricity Prices in the Netherlands, France, Belgium and Germany (TenneT, 2015)

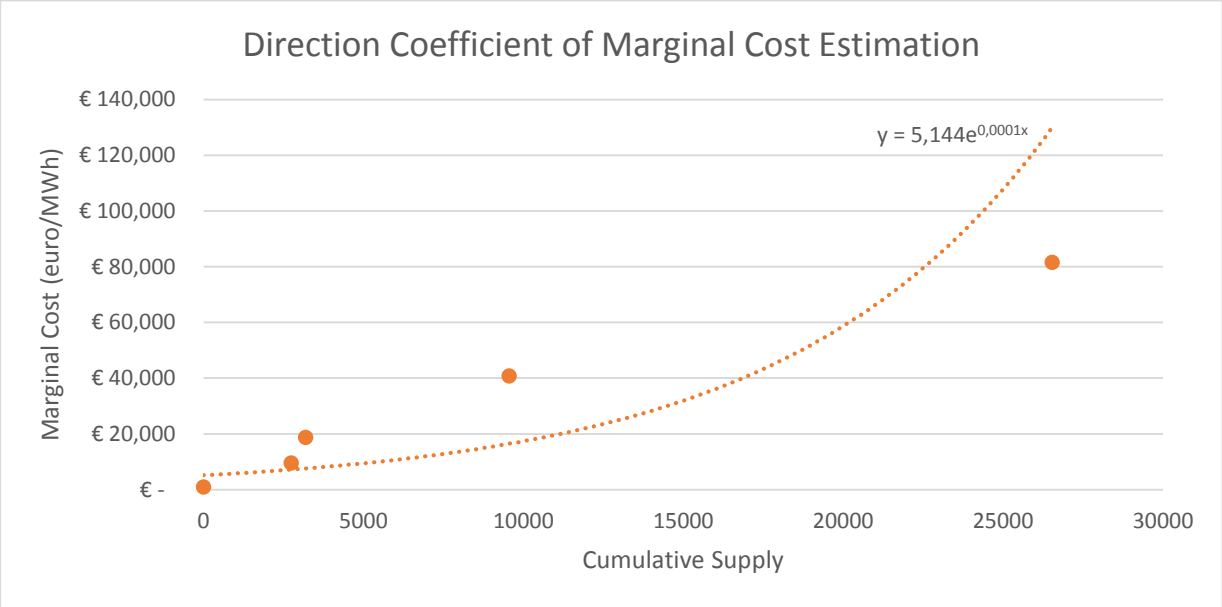
more realistic if the electricity prices would be simulated just as the Dutch power exchange. However, to add this to the model would make this research too complex, as a whole other electricity system should have been added.

The direction Coefficient for Marginal Cost

The direction coefficient of the marginal cost is called into place, as the marginal cost of two different power plants – within the same generation method – do not generate electricity for the same marginal cost. This direction coefficient is designed to create more dynamics in the power plant – like in the real world – by linearly increasing the marginal cost when more electricity production is required. The most expensive power plants are simply used to produce the residual electricity – as power plants with low marginal cost are more competitive.

To determine the direction coefficient of the marginal cost of Dutch power plants, data of 2011 was used as the marginal cost of this year are known. The data is provided in the table below. The table shows the lowest marginal cost of wind to the highest marginal cost of gas. In combination with the supply data, a trend line is determined (see graph below). The formula of this trend line is used to determine the direction coefficient between every single step of the merit order. The input for this direction coefficient formula is the average electricity supply per step of the merit order.

2011	Wind	Nuclear	Coal	Gas	Total
Cumulative MWh	1	2746	3196	9564	26543
Marginal Cost (euro/MWh)	€ 1.00	€ 9.60	€ 18.80	€ 40.80	€ 81.6
Average electricity supply (MWh)	1373	2971	6380	18054	
Direction Coefficient (y = 5.144e^0.0001x)	0.00059	0.000692	0.000972	0.003129	



The final formula for each merit order step – containing the direction coefficient – is as following:

$$Marginal\ cost\ per\ step = Direction\ coefficient * MWh(per\ generation\ method) + lowest\ marginal\ cost$$

External Financing

The validation phase of the research showed that not enough investment budget came available each year, resulting in not as many investments compared to the real data. Therefore, external financing has been added to create a more realistic investment part in the System Dynamics model.
The investment priority variable in the model is an important factor to determine whether investments need to be done or not. The investment priority is a factorized variable which indicates the quality of the investment environment. The closer the value to one, the better the investment environment.
By executing a short calibration during the validation phase, the external investment showed to behave best – compared with real data – when a boundary for the investment priority was drawn at 0.0045. This means that when the investment priority goes above 0.0045 of a generation method, the investment environment is positive – meaning that investments in this generation method are made through external financing. When it is below this value of 0.0045, no external investments are made to a certain generation method. This means that the investment environment is negative for a certain generation method.

Mothballing – the opposite of investments – closing power plants earlier – is done when investment environment are negative and when power plants become too expensive. One of the factors influencing the investment priority are the cost of production. As these factors are connected and most likely influence the determination whether to execute mothballing, low investment priority values are connected to the mothballing process. This means that mothballing will take place when the investment priority is below 0.0045. It is implemented to the model in such a way that the closer the investment priority is to zero, the more MW will be closed down. The exact formula is provided in appendix B.1.
The mothballing simulation results show to come close to the real mothballing that will take place in 2016 and 2017, which was agreed in the Dutch energy agreement in becoming more sustainable (Europese Unie, 2013)

Appendix B.4. – Vensim Formulas

In this appendix three Vensim formulas are described in more detail. The ALLOCATE BY PRIORITY formula, which is used to allocate the investment budget to the different generation methods, will be described. Then the Trend Analysis will be explained, which was used for the external investment part of the model. Last, the forecasting formula is described, which is used for electricity demand forecasting.

ALLOCATE BY PRIORITY (Vensim, 2015)

This function is used to allocate a scarce supply to a number or requests based on the priority of those requests. The basis function is:

$$ALLOCATE\ BY\ PRIORITY(Request, Priority, Size, Width, Supply)$$

The formula is fulfilled when the supply is bigger than the sum of request over the size elements. In case of the investment allocation. The investment budget is the supply, which needs to be divided over the generation methods – the size. Based on trend analysis and investment priority it is determined how much new generation capacity of the different generation capacities is needed. When the supply is fulfilled, the allocation formula stops.

The *size* are the number of subscripts – the number of generation methods between which it should be allocated. The investment *priority* is determined through the deviation of 1 by the Levelized Cost of Electricity. The higher the LCOE, the lower the investment priority. This output is then multiplied by the affinity factor.
To the *width,* is the way the allocation takes place connected. The allocation could take place in two ways. In the first scenario, the requested demand with the lowest priority is first fulfilled and then the requested demand with the second highest priority is fulfilled and so on. This scenario is triggered when the VMIN function is used over the priority.
The second scenario of allocation is that the supply is allocated through a ratio. In this way, each request gets a certain supply – depending on height of the investment *priority.* For this scenario the VMAX formula is used.

As investments work in such a way that the best scenario wins, it is decided to use the VMIN function. In this way, the one with the highest priority gets the supply – thus investment – first.

Trend Function (Vensim, 2015)

This trend function in Vensim provides a simple trend estimate for a variable. It returns the average fractional growth rate (negative for decline) in the input.

$$Trend\ Analysis = TREND(input, average\ time, initial\ trend)$$

In the SD-model the trend analysis is used for determining the future investment environment. The input to this formula is het investment priority – which should be analyzed. The average time is one year, as changes in the investment priority need to be picked up by the model as soon as possible. The initial trend – which is the period of time over which the trend should be determined – is calculated by Time minus INITIAL TIME in Vensim. The initial time in case of this model is 2005. Every time step towards 2030, this initial trend is determined, and has the maximum value of 25 years.

Forecasting Function (Vensim, 2015)

The FORECAST function is Vensim provides a simple trend extrapolation forecast of the future value of a variable based on its past behavior. The function returns a forecast of the value input will take on at Time + Horizon.

$$Demand\ Forecast = FORECAST(input, average\ time, horizon)$$

This function is used to make a demand forecast of the demand. The input variable in case of the model is the Total Net Energy Demand per phase – as the forecast is used to make a planning on which production capabilities to use in each phase (Base, Shoulder, Peak). The average time over which the historical data of demand should be looked at, is in case of the model 1 year. The time horizon for trend extrapolation is also one. This is done to make the model as flexible as possible for sudden changes. If the value would be chosen higher than one, the forecast would too slowly adapt to sudden changes.

Appendix C – List of External variables

- Initial Electricity Capacity under Construction
- Electricity Production Capacity Construction Delay
- Electricity Production Capacity Lifetime
- Direction Coefficient Marginal Cost
- Import Factor
- Initial Marginal Cost
- Coal Price 2005
- Average Yearly Coal Price
- Uranium Price 2005
- Average Yearly Uranium Price
- Gas Price 2005
- Average Yearly Gas Price
- Wind Speed Variety
- Average Yearly Electricity Price
- Oil Price
- Causality on Electricity Price and Electricity Demand
- Dutch Population 2005
- Yearly Dutch population
- Initial Yearly Electricity Demand 2005 (per phase)
- Gross Domestic Product (GDP) of the Netherlands in 2005
- Decentralized Electricity Production
- Electric Vehicle (EV) Electricity Demand
- CO2 price in 2005 of the Emissions Trading Scheme (ETS)
- Yearly CO2 Price
- CO2 Emission per generation method (Coal and Gas power plants)
- Hours per Year per Phase (for the Load Duration Curve; Base: 876 hours, Shoulder: 7008 hours, Peak: 876 hours)
- Investment Percentage
- SDE+ Subsidy

Appendix D – Model Assumptions

As mentioned before, John Sterman stated that models are always wrong because they are just a simplification of reality (Sterman, 2000). This means that certain assumptions needed to be made in order to model the Dutch electricity system. Below the assumptions are stated, with an explanation on why the assumption needed to be.

Assumption	Explanation
Always electricity for import and export available from neighbor countries	The system boundaries of this research were chosen to be the geographical boundaries of the Netherlands. However, electricity systems (of different countries) are connected to each other. The different electricity systems work together to stabilize the electricity grids. A surplus in one electricity system could help to solve a shortage in another system. More realistically, the electricity systems of neighbor countries of the Netherlands would be simulated as well to determine the available electricity for export or the required electricity import. Besides, simulations of electricity systems of neighbor countries would determine the electricity prices in the different countries - which influence each other's electricity prices. However, simulating these neighbor countries' electricity systems would make the model too complex for this research as the size of the SD-model would double when adding another electricity system. To reduce complexity, it is assumed that electricity is always available to import and electricity could always be exported when a surplus occurs.
Electricity prices are 20% lower in Germany, so this lower the electricity prices in the Netherlands with 20%	As the electricity system of neighbor countries is not simulated in the model, electricity prices of neighbor countries are not determined as well. Data on electricity prices of different countries show that the electricity price in Germany is structurally about 20% lower than in the Netherlands (explained in Appendix B.3.). This means - as it is assumed that export and import electricity are always available - that it would lower the Dutch electricity prices with 20% as well. This because electricity prices from Germany compete well with the generation capacity in the Netherlands. Obviously, in the real world, this is much more complex since the amount of available electricity for import and the number of times this is available plays an important role. Since no simulations of the neighbor countries' electricity systems are made, the real influence of electricity import cannot be determined. Therefore it is assumed that using an import factor over the electricity prices would be a simplified and well-working substitution. However, research needs to be done to check this assumption.
Four generation methods have been chosen (Coal, Gas, Nuclear and Wind)	To reduce complexity it is also assumed that the generation capacity for electricity in the Netherlands only consists of four generation methods. To reduce complexity the different generation technologies for gas electricity production have for example not been taken into account. Various gas electricity generation technologies exist, which differ in efficiency and characteristics. An open-cycle gas turbine is for example more expensive in LCOE then Combined Cycle electricity production. To reduce complexity, gas electricity production has been generalized. The determined direction coefficient to create a difference in marginal cost between produce MWs of the same generation methods, has a positive influence on this assumption. This because the difference in marginal cost of different generation technologies have been taking into account. Solar electricity production is a sustainable source that has not been taken into

	account. First of all the research is focused on wind energy, but for simulating the electricity system solar electricity should be taken into account. However, it is assumed that solar electricity production is done off grid - decentralized. In this way, this assumption could be justified.
6% of the profit is used for investment budget	Energietrends 2013 stated that 6% of the turnover of energy utility companies in the Netherlands are used as investment budget (Energie-Nederland, 2013). This investment budget is not only for generation capacity adoption though, it is also used for other investment purposes, for example office equipment. Besides, the cost aspects of the power plants should be taken into account. The turnover could be high, but if cost are even higher in the real world there would not be room for investments. Therefore, the investment budget in the model is determined through the profits. It is assumed that this same percentage - of 6% - determines the investment budget. The determined investment budget over the profit functions as budget for generation capacity investments (adoption).
The Load Duration Curve is split up in three phases - Base, Shoulder and Peak	In order to take into account outliers in electricity demand - which are important when modeling electricity prices - three phases have been determined. For this research it is assumed that three phases is sufficient for taking into account the outliers. In the real world, the Load Duration Curve consists of 8760 phases (all hours per year), but this is not realistic to model in System Dynamics as the software has its limits in the amount of subscripts that can be used. Further research needs to be done to analyze what the effects are of dividing the Load Duration Curve into more phases. A sensitivity analysis on the size of the phases has been executed (appendix F.4.), but this shows that it is not extremely sensitive to size changes of the phases.
The direction coefficient influencing the marginal cost of electricity production of the same generation technology is linear	To create more dynamics in the power exchange and as different generation technologies of the same generation method have different cost, a direction coefficient influencing the marginal cost is determined (Appendix B.3.). In order to reduce complexity in the modeling functions, it is assumed that the growth in marginal cost grows linearly per extra MW (y=ax+b, a = direction coefficient, x = MWs, b = lowest marginal cost, y = dynamic marginal cost). In the real world, the marginal cost of the same power plant are the same and thus does it grow discontinuously. However, for this model it is assumed that it is sufficient if the marginal cost grow linearly with the generation method.
External financing	For external financing, it is assumed that external investment budget is available as long as the investment environment is positive. In the validation phase it has been checked that if the investment priority value is above 0.0045, it matches well with the real data on investments. The R2 and MAE/mean metrics of the installed capacity of the different generation methods proof that as well. When the value is below 0.0045, there is a poor investment environment. In this situation it is assumed that mothballing - closing down power plants earlier - will take place of the 'inefficient' power plants. The worse the investment environment, the higher the percentage of mothballing and thus the more mothballing will take place.
Interest of to external financiers for their external	Though, it is assumed that these interest are covered by a part of the other spending of the investment budget of energy utility companies (6% of the turnover).

investment are not part of the SD-model Marginal cost for electricity production in the US are the same as in the Netherlands The social aspects within investment decisions are all covered in the affinity factor in the SD-model.	No data was found on the marginal cost of electricity production in the Netherlands. Though, data was found about the marginal cost of electricity production in the USA. It is assumed that the USA has the same electricity production technologies as the Netherlands installed and therefore it is assumed that the marginal cost of electricity production is the same. The process of investment decision is very complex in such a way that many social aspects influence the decisions. Besides, negotiations on the investments could take place which are highly unpredictable. Not having stated yet, that political factors also play an important role within investment decision making. The affinity factor tries to generalize these social factor into one factor. Even when more research is done on this aspect, it is mostly likely not possible to generalize this to one factor. Though, to take into account some social factors, the affinity factor has been added to the system. It contains the affinity for a certain generation method in general. Also, cost aspects like the CO2-cost and the LCOE influence the affinity factor.

Appendix E – Scenarios

In this appendix, the scenarios towards 2030 of the external forces will be shown. The scenarios are the factors that had a lookup function in Appendix B.

Variable	Scenario	Explanation
Affinity[Coal]	(2005,1),(2030,0.5)	Taking into account that before sustainability agreements were signed - like the Kyoto-protocol in 1997 - CO2 emissions were not seen as such an important factor (United Nations Convention on Climate Change, 2014). Therefore, the starting value of affinity for coal in 2005 is assumed to be one, since it has become more and more important to reduce CO2 emissions for companies over the years.
Affinity[Gas]	(2005,1),(2015,1.1),(2030,0.9)	For gas counts the same as for coal capacity, however gas electricity production is more sustainable than coal as it is generally twice as efficient to produce electricity from gas. Besides, gas is the flexible generation method that could produce electricity when electricity cannot be generated from sustainable sources. Therefore, the affinity for gas stay constant around the value one.
Affinity[Nuclear]	(2005,1),(2011,0.1),(2020,1.2),(2030,1)	From the political discussion on adopting more nuclear power could be derived that the affinity for nuclear energy around 2005 was relatively high - which means a starting value of 1 has been chosen. After the nuclear disaster of the nuclear power plant in Fukushima Japan, the affinity for nuclear energy declined rapidly. Germany even decided - based on this event - to close down all nuclear power plants - thus a low affinity value in 2011. Though, as sustainability will become more and more important, the political discussion will flare up again. Therefore, the affinity value goes back to one towards 2030.
Affinity[Wind]	(2005,1.4),(2016,1.4),(2030,1.5)	After the Kyoto-protocol, the desire for sustainable sources increased (United Nations Convention on Climate Change, 2014). Wind energy production was one of these interesting sustainable sources. Around 2005, the adoption of wind electricity was slow as it was still too expensive, though the desired has always been active. Therefore the affinity of wind electricity production is stable around 1.5.
Average electricity price	(2005,125),(2006,133),(2007,130),(2008,133), 2009,145),(2010,125),(2011,130),(2012,135),	The scenario of the development of electricity prices that consumers have to pay towards 2030 is based on a scenario from the Dutch government on grid management (netbeer Nederland). (CE Delft, 2014)

	(2013,133),(2014,139),(2030,260)	
Coal Price	([(0,0)-(3000,10)],(2005,2.12),(2006,2.06),(2007,2.33),(2008,3.75),(2009,2.65),(2010,2.8),(2011,3.22),(2012,3.21),(2013,2.82),(2030,3)	This scenario is based on a report of the Department of Energy and Climate Change - based on the report of DECC fossil fuel price projections 2013. (Department of Energy & Climate Change, 2013)
Decentralized Electricity Production	([(2005,0)-(2030,0.5)],(2005,0),(2010.12,0.0614035),(2012.34,0.116228),(2015.09,0.14693),(2018.76,0.164474),(2022.51,0.179825),(2025.26,0.186404),(2026.71,0.197368),(2030,0.2)	This scenario is based on a report of the national statistics department of the Netherlands. This report states historical data on centralized and decentralized electricity production. In combination of predictions of decentralized electricity production, in the report of CE Delft - Scenario-ontwikkeling energievoorziening 2030, this scenario is set up (CE Delft, 2014).
ETS-Policy: CO2 Price	(2005,22.5),(2006,18),(2007,21.5),(2008,25),(2009,13.7),(2010,15.4),(2011,11.5),(2012,9),(2013,5.5),(2014,6.3),(2020,46),(2030,186)	This scenario is based on a research of the European Union which is reported in the following report: European Commission – EU ETS emission Trading Scheme (ETS): Response to consultation on the auction time profile (Neuhoff & Schopp, 2012)
Gas Price	(2005,0.12),(2006,0.125),(2007,0.1294),(2008,0.134),(2009,0.1492),(2010,0.1269),(2011,0.142),(2012,0.1518),(2013,0.138),(2014,0.14),(2030,0.2)	This scenario is based on predictions of the Department for Energy and Climate Change (DECC). (Department of Energy & Climate Change, 2013)
Import Factor	(2005,1),(2010,0.8),(2014,0.8),(2030,1)	Currently the difference between electricity prices from the Netherlands and Germany is about 20%. It is expected that the European grid will become more and more integrated in the future leading to electricity prices that become more equal. Therefore, the import factor grows to 1 towards 2030. It is also assumed that the difference in electricity prices is caused by the higher installed capacity of sustainable sources in Germany and it is also assumed that the difference between sustainable capacity in the Netherlands and Germany around 2005 was not that high. Therefore, the value around 2005 is also one - as there is no difference.
Lifetime factor[Wind]	(2005,1.8),(2015,1.5),(2020,1.2),(2030,1.2)	This factor was added to the model to reduce the retirement of wind mills - as most of the wind capacity is still relatively new and thus do not need to be closed

		down yet. Towards 2030 this value will decline to 1 as by that time wind mills that have been installed before 2005 should be replaced already.
Number of EV's	([(2005,0)-(2030,4e+006)],(2005,0),(2015,20000),(2020,200000),(2025,1e+006),(2030,1.35088e+006))	The scenario for the development of EV is based on a target for the Dutch government to have adopted 1 million electric vehicle by 2023. It is assumed that the Dutch government will focus on achieving this target and that after 2023 the adoption will keep growing. (Rijksoverheid, 2014)
Oil price	([(2005,0)-(2030,200)],(2005,54.52),(2006,65.14),(2007,72.39),(2008,97.26),(2009,61.67),(2010,79.5),(2011,111.26),(2012,111.67),(2013,108.67),(2014,80),(2015,65),(2030,116.5))	The future development of the oil prices is based on a report of the IEA (Department of Energy & Climate Change, 2013)
Population	([(2005,0)-(2030,2e+007)],(2005,1.632e+007),(2006,1.6346e+007),(2007,1.6358e+007),(2008,1.6405e+007),(2009,1.6485e+007),(2010,1.6575e+007),(2011,1.6656e+007),(2012,1.673e+007),(2013,1.678e+007),(2014,1.682e+007),(2030,1.707e+007))	The expected growth of population is determined based on data from a 'future database' of the University of Denver (University of Denver, 2015)
SDE+ Subsidy[Wind]	([(0,0)-(3000,2e+008)],(2005,1.75e+008),(2006,1.75e+008),(2006.06,0),(2007.94,0),(2008,1.75e+008),(2030,5e+008))	The subsidy is based on historic values on the SDE+ subsidies given out before 2015 and based on a advice (report) of the Dutch government stating that the SDE+ subsidy should grow with 22% towards 2030 in order to reach the sustainability targets. It is assumed that the Dutch government will follow this advice. (Algemene Rekenkamer, 2015)
Uranium Price	([(2005,0)-(2030,50)],(2005,11),(2006,18),(2007,50),(2008,32),(2009,21),(2010,20),(2011,28),(2012,33),(2030,50))	The expected uranium price development is based on data from the NUEXCO exchange on monthly uranium spot prices (NUEXCO Exchange, 2013)
Yearly GDP	(2005,6.57e+011),(2006,7.3e+011),(2007,7.73e+011),(2008,7.89e+011),(2009,7.62e+011),(2010,7.76e+011),(2011,8.25e+011),(2012,8.2e+011),(2013,8.29e+011),(2014,8.35e+011),(2015.57,8.64035e+011),(2017.32,8.59649e+011),(2019.71,9.21053e+011),(2021.46,9.6052	The expected growth of the GDP is determined based on data from a 'future database' of the University of Denver (University of Denver, 2015)

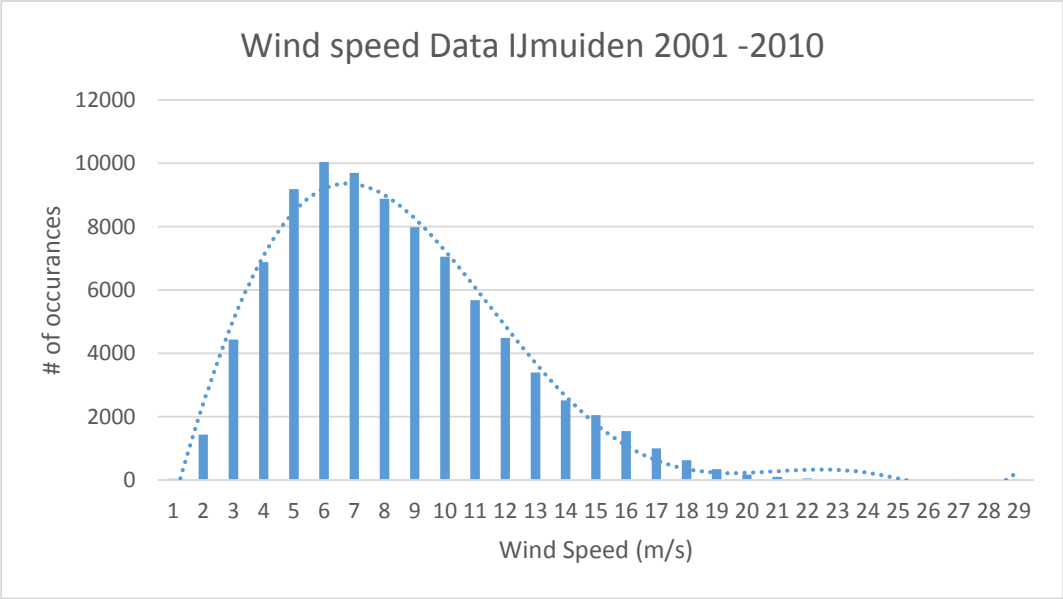
Electricity Storage Capacity[Phases]	6e+011),(2023.69,9.16667e+011),(2025.99,9.38596e+011),(2027.5,9.86842e+011),(2030,1.019e+012)) ([(0,0)-(3000,3000)],(2005,0),(2015,0),(2030,13975))	Determined based on the expected adoption of Electricity Vehicles towards 2030 and an assumed amount of capacity available for energy storage. Besides an assumption of 2000 MW capacity of energy storage has been made, which is 10% of the total installed capacity in 2030

Appendix F – Uncertainties

In this appendix the uncertainty factors of the scenarios are described. These factors are used in the Monte Carlo simulations of the System Dynamics model. First the determination of the wind speed variation is described. Where after the uncertainties of the rest of the external forces are described.

Appendix F.1. – Wind Speed Variation and capacity factor

The variation of the availability of wind influences the electricity prices. Therefore, it is of great importance to simulate the variations of wind as happens in the real world. In order to research the variation of wind speed, ten years of wind speed data of Ijmuiden – The Netherlands – has been researched.
It shows that the variation of wind follows a normal distribution shape (see graph below). Based on this, it is decided to follow the normal distribution for wind variation.



Based on this information it is determined that the Average wind speed is 7.27 m/s and the standard deviation is 3.68 m/s. When varying the wind speed according to the normal distribution in the System

Dynamics model, it is decided to varying it with a maximum of one sigma. The minimum wind speed is therefore 3.59 m/s and the maximum wind speed 10.59 m/s. Wind speeds in this region occur the most.

$$P_W = \begin{cases} 0 & als\ v < v_{min}\ of\ v > v_{max} \\ \left(\frac{v}{v_{piek}}\right)^3 P_{max} & als\ v_{min} < v < v_{piek} \\ P_{max} & als\ v_{piek} < v < v_{max} \end{cases}$$

The yield of wind capacity is not the same for every wind speed. A part of a model on wind turbines – from Pieter Bots – has been added to the System Dynamics model to determine the yield of wind capacity for various wind speeds (Pieter Bots, 2015). The formula that is used for this determination is shown below. The Vmin is 4 m/s, the Vpeak = 10 m/s and the Vmax = 20 m/s. Based on this formula the capacity factor of wind could be determined. As this is a factor of the actual electricity production compared with the maximum potential electricity production. Based on this formula and the average wind speed, the average capacity factor is 38.49%.

Appendix F.2. – Uncertainties of the other external forces

Literature research has led to little results on uncertainty data of external forces – like GDP and population growth. Therefore it is assumed that the rest of the external uncertainty have the same uncertainty factor as used in the multivariate sensitivity analysis – 10% uncertainty according a random uniform distribution. Research needs to be done to determine these uncertainty factor, this would provide a more realistic exploration model for future electricity prices in the Netherlands.

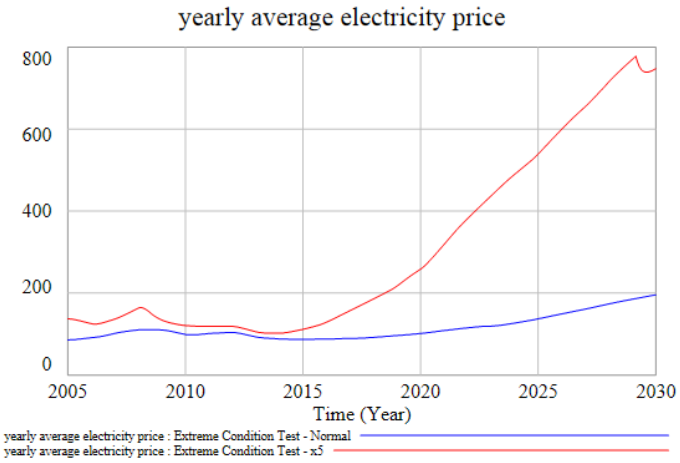
It can be discussed that certain external factors should have a larger variation than other external factors. However, it could also be discussed that certain external factors strengthen or weaken each other. As this information is also not known, it has been decided to choose the same uncertainty factor for all the unknown external forces. Future research should find what these uncertainty factors should be.

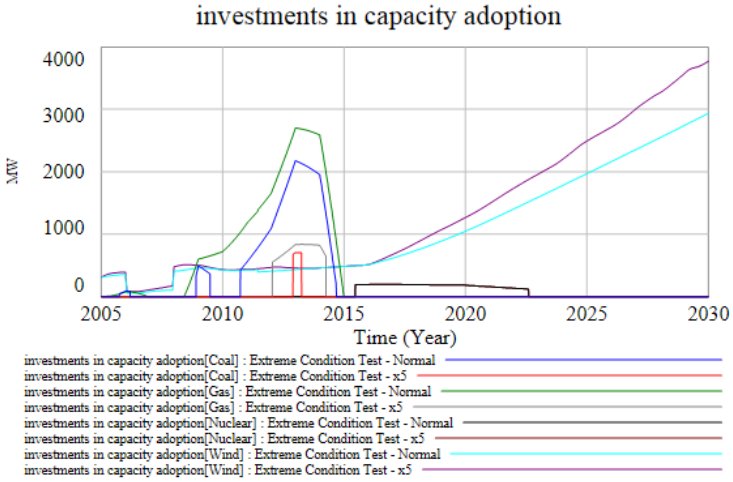
Appendix G – Validation

Appendix G.1. – Extreme Condition Test: Hypotheses and Results

If CO2-price is extremely high, Electricity price will be high leading to high investments in low carbon electricity production (Wind and Nuclear).

To test this hypothesis the CO2-price is multiplied by five. The results are as following:

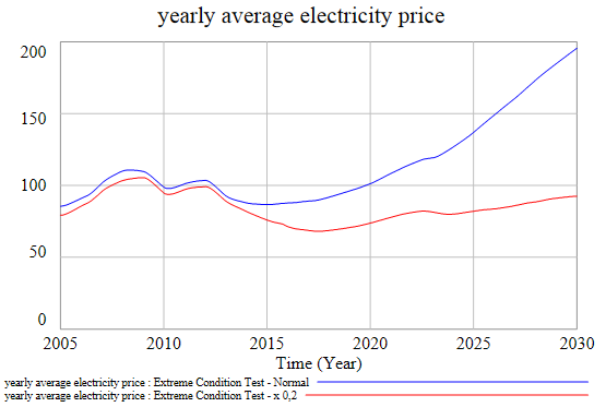


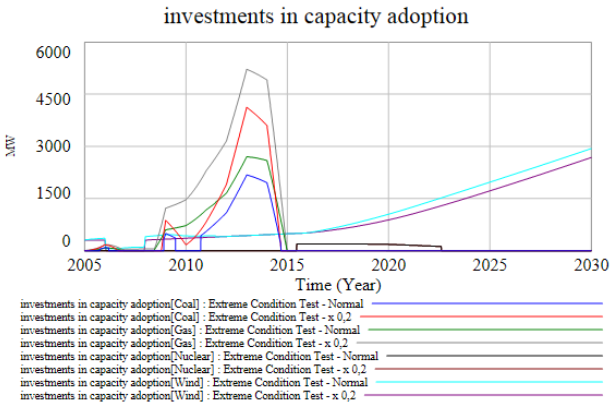


Due to the high CO2 price, which together with the fuel and maintenance cost determines the marginal cost, the marginal cost are high and thus the electricity price (euro/MWh) as well. As the CO2 price is high, investments in CO2 polluting sources become less interesting. Therefore more investments in wind energy are made as the marginal cost of this source is not sensitive for CO2 price changes. Investments in new coal capacity becomes almost zero (from the green line in the normal situation to the red line in the hypothesis-situation). Investments in new gas capacity is also significantly lower (from the green line to the grey line). The wind capacity investments increases (from light blue to purple).

IF CO2-PRICE IS EXTREMELY LOW, ELECTRICITY PRICE WILL BE LOW LEADING TO LITTLE INVESTMENTS IN LOW CARBON ELECTRICITY PRODUCTION (WIND AND NUCLEAR) AND HIGHER INVESTMENT IN CARBON INTENSIVE ELECTRICITY PRODUCTION (COAL AND GAS).

To test this hypothesis, the CO2-price is divided by five. The results are as following:

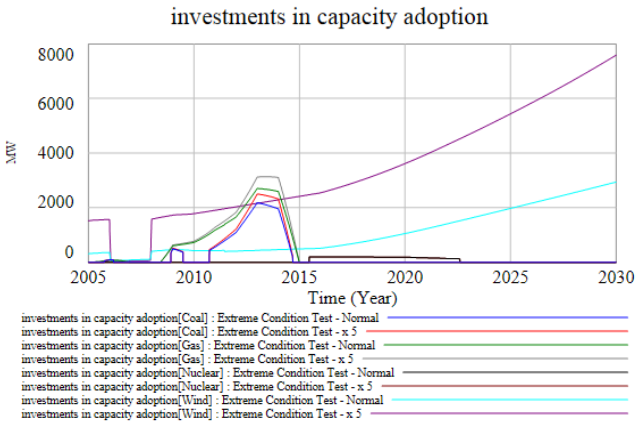


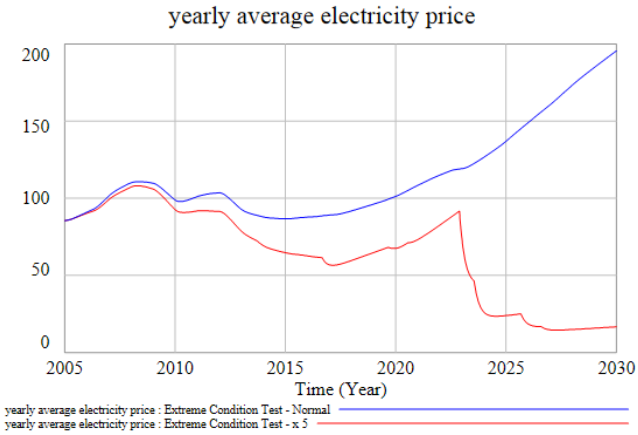


Contrarily to the situation with a high CO2 price, less investments are made in wind energy and more in gas and coal capacity with a low CO2 price. The grey line (for gas investments) and the red line (for coal investments) are much higher and the purple line of wind energy investments is lower than normal. Due to the lower marginal cost – caused by a lower CO2 price – the electricity price is also lower than normal.

IF THE AFFINITY OF GENERATION TECHNOLOGIES ARE HIGH, HIGH INVESTMENT IN THE GENERATION TECHNOLOGIES WILL BE MADE

To test this hypothesis the affinity is multiplied by five. The results are as following:

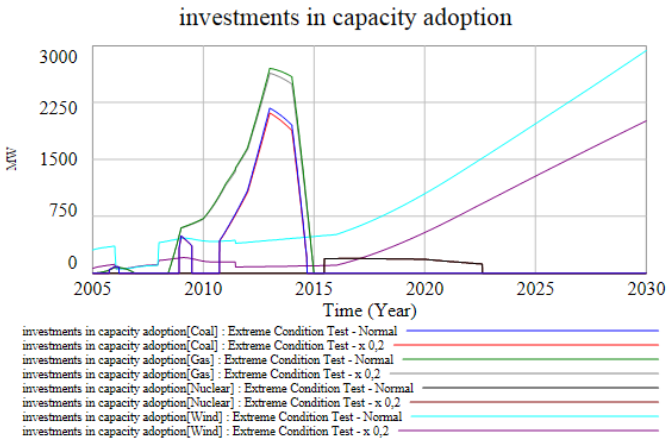


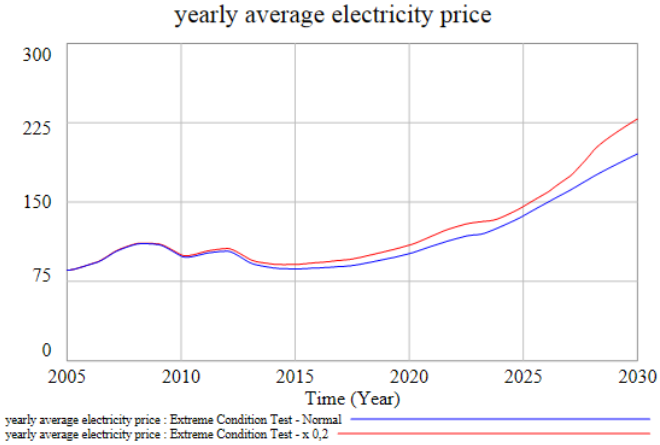


Multiplying the *affinity* of the generation methods, leads to an extremely high affinity for wind energy investments. Also more investments are made in gas and coal electricity production but this is not significant compared to wind energy production investments. Due to the high adoption of wind energy, the *yearly average electricity price* drops as more electricity with a lower marginal cost becomes available.

IF THE AFFINITY OF GENERATION TECHNOLOGIES ARE LOW, LITTLE INVESTMENTS WILL BE MADE

To test this hypothesis the *affinity* is divided by five. The results are as following:

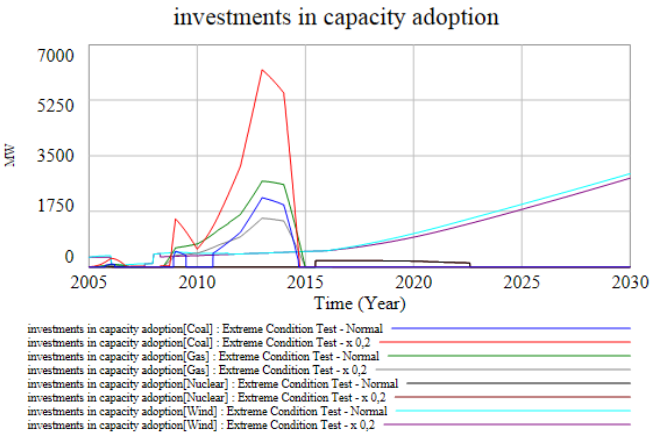




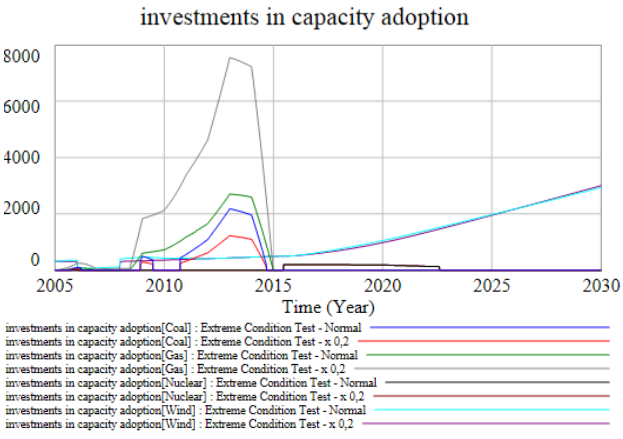
Dividing the *affinity* leads to lower investments in adoption of new capacity. It mostly affects the investments in wind energy production. Gas and coal investments are lower but not significantly. Due to the lower investments, the *yearly average electricity price* increases as more electricity needs to be produced by flexible gas power plants – with relatively high marginal cost.

IF ENERGY PRICE (GAS, URANIUM AND COAL) ARE LOW, ELECTRICITY PRICES ARE LOW AND INVESTMENTS IN NON-RENEWABLE ELECTRICITY PRODUCTION WILL BE LOW

To test this hypothesis the energy prices (gas, uranium and coal) have been divided by five. The results are as following:

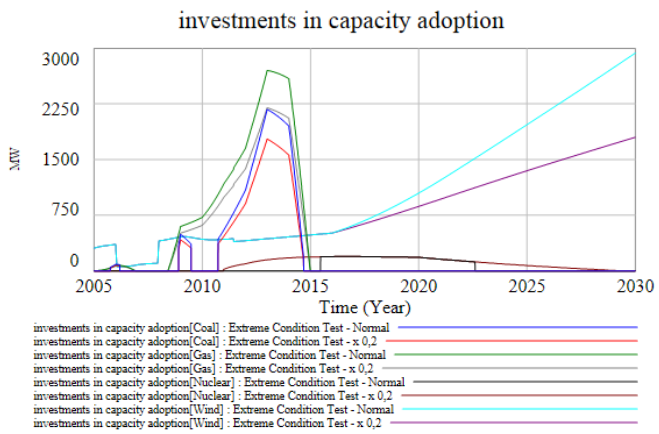


Extremely low Coal price



Extremely low Gas price

Dividing the energy prices of (gas, uranium and coal) by five, leads to more investments of the generation method with the low energy price. This is due to the fact that a decline of energy prices results in a decline of the LCOE of that generation method. This leads to an increase of the investment priority and thus more



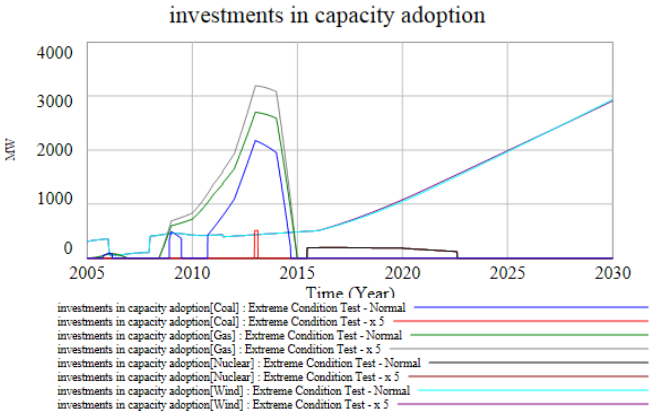
Extremely low Uranium price

investments in that generation method. An interesting fact is that the decline of uranium prices have the most effect on the investments in wind energy.

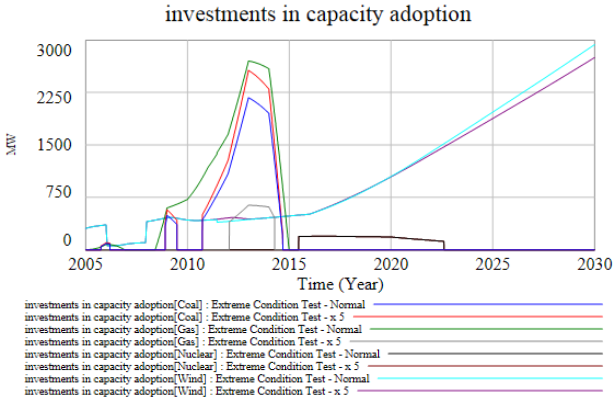
The decline of gas prices have the most effect on the average yearly electricity price – this because the marginal cost of gas electricity production determines most of the time the electricity price.

If energy prices (Oil, Gas, Uranium and Coal) are high, more investments will be made in wind energy production

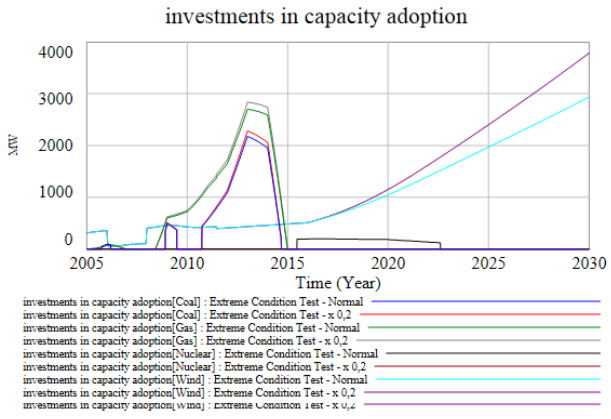
To test this hypothesis the energy prices (gas, uranium and coal) have been multiplied by five. The results are as following:



Extremely high Coal price



Extremely high Gas price

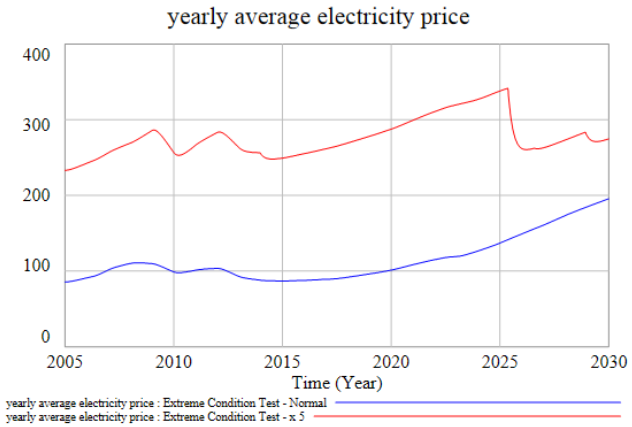


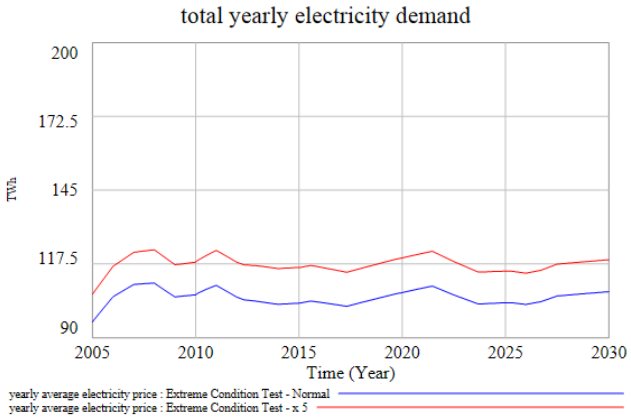
Extremely high Uranium price

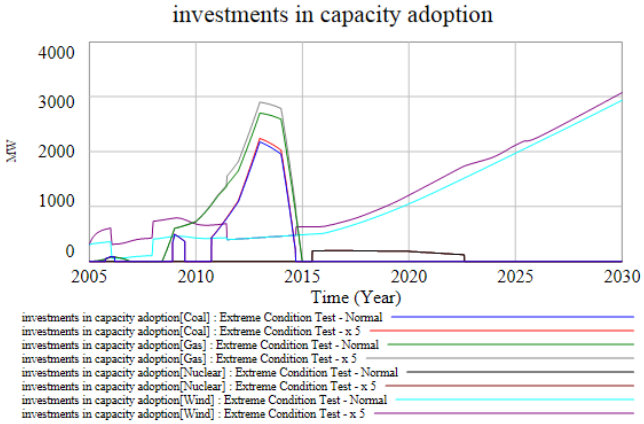
Multiplying the energy prices of (gas, uranium and coal) with five, leads to less investments of the generation method with the high energy price. This is due to the fact that a rise of energy prices results in a rise of the LCOE of that generation method. This leads to a decrease of the investment priority and thus less investments in that generation method. When declinging the energy prices, the uranium price has the most effect on the wind energy investments. The rise of gas prices have the most effect on the average yearly electricit yprice – this because the marginal cost of gas electricity productio ndetermines most of the time the electricity price.

IF GDP IS EXTREMELY HIGH, THEN THE ELECTRICITY DEMAND WILL BE HIGH AND THE ELECTRICITY PRICE AND INVESTMENTS IN NEW ELECTRICITY PRODUCTION CAPACITY WILL INCREASE

To test this hypothesis the *GDP* is multiplied by five. The results are as following:



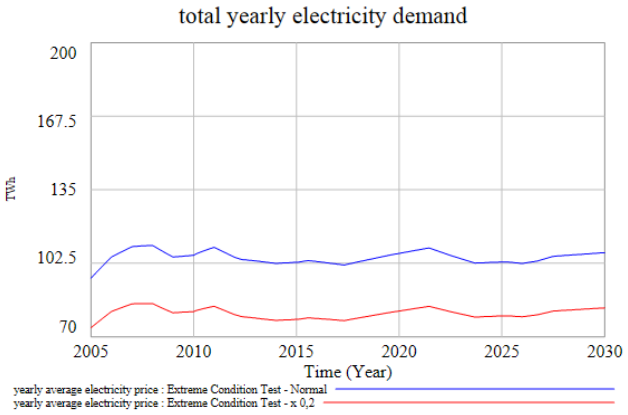


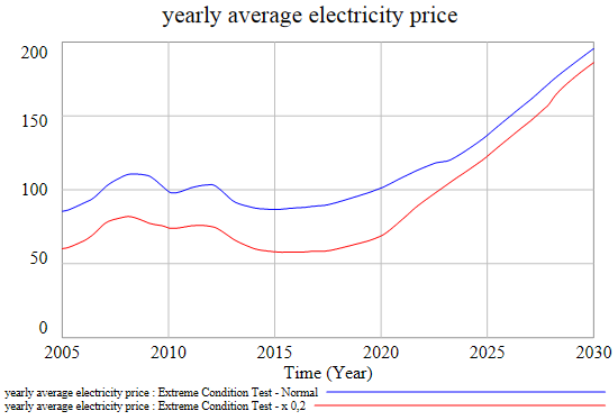


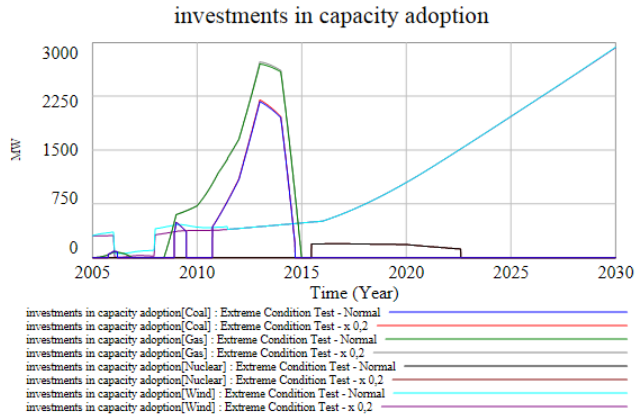
Multiplying the *GDP* with a factor five, leads to a much higher electricity demand and results in the adoption of installed capacity for all different generation methods. As the electricity demand is high and not enough available electricity production capacity is available, the electricity price will be high. Towards 2030 the electricity price decreases again as by then more electricity production capacity is available.

IF GDP IS EXTREMELY NEGATIVE, THEN THE ELECTRICITY DEMAND WILL BE LOW AND THE ELECTRICITY PRICE AND INVESTMENTS IN NEW ELECTRICITY PRODUCTION CAPACITY WILL DROP

To test this hypothesis the *GDP* is divided by five. The results are as following:



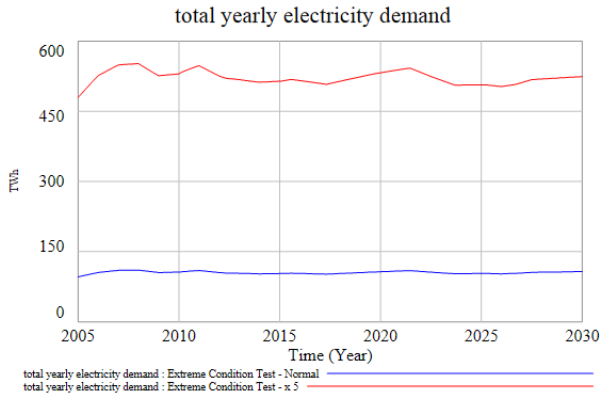


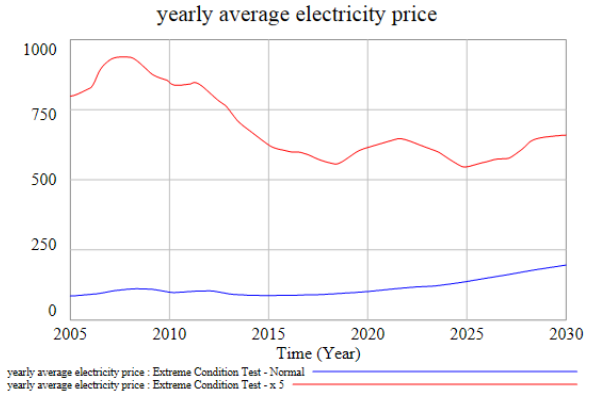


Dividing the *GDP* by five, leads to a low electricity demand and the electricity prices are approximately 40% lower. Even though the electricity demand is low, still the same investments are done – which is unexpected. In the model, the desired adoption of installed capacity is lower than in the normal situation, but even with the lower desired adoption the same investments are done. An explanation for this could be that in the normal situation the full desired adoption of installed capacity could not be done as insufficient financial resources are available.

IF THE DUTCH POPULATION IS HIGH, THE ELECTRICITY DEMAND AND THE ELECTRICITY PRICES WILL BE HIGH

To test this hypothesis the *Dutch Population* is multiplied by five. The results are as following

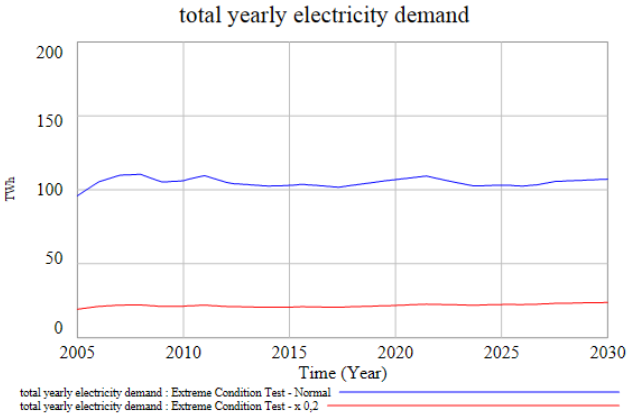


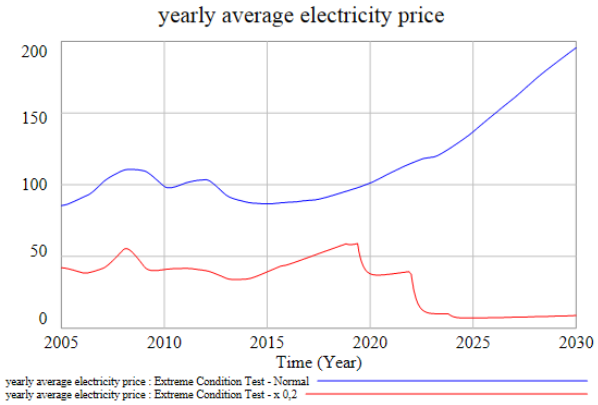


Multiplying the *Dutch Population* by five leads to an extremely high *total yearly electricity demand*. This high demand influences the *yearly average electricity price*, which starts at approximately 800 euro per MWh. Due to the high *yearly average electricity price*, an high *Investment Budget* is available which leads to high investments in capacity adoption. Thereby, the shortage of electricity becomes smaller, which leads to a lower *yearly average electricity price* in 2030 (approximately 600 euro per MWh) than in 2005.

IF THE DUTCH POPULATION WOULD BE LOWER, THE ELECTRICITY DEMAND AND THE ELECTRICITY PRICES WILL BE LOW.

To test this hypothesis the *Dutch Population* is divided by five. The results are as following:

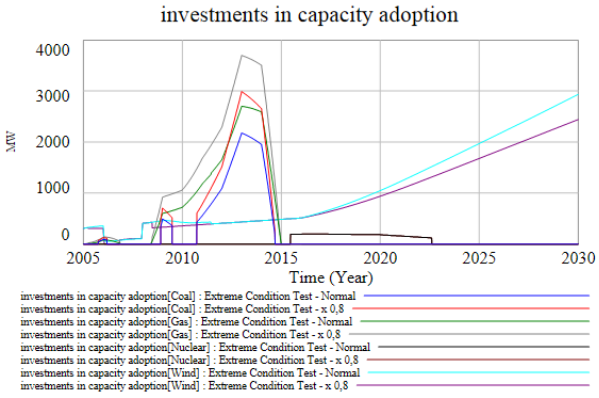


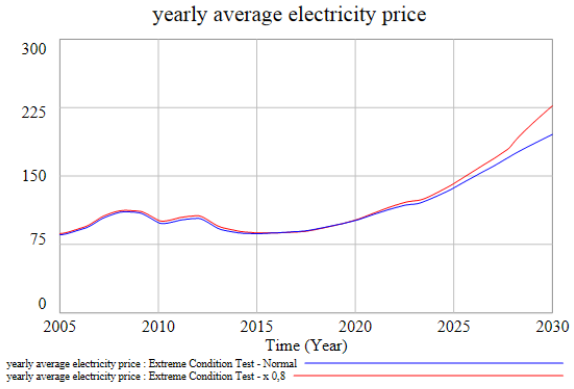


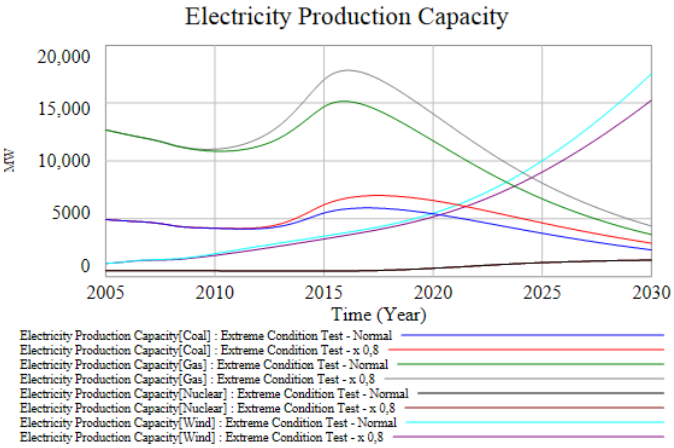
Dividing the *Dutch Population* by five, leads to an extremely low *total yearly electricity demand.* Due to the low demand and the relatively high *Available Production Capacity*, the *yearly average electricity price* is lower. As investments in wind capacity are continue to be made because of the SDE+ subsidy, the overcapacity grows towards 2030. This leads to an even lower *yearly average electricity price.*

IF THE WIND SPEED IS LOW, THEN INVESTMENTS IN WIND ENERGY WILL DROP AND ELECTRICITY PRICES BECOME MORE STABLE.

The test this hypothesis the *Wind Speed* is multiplied by 0.8. The results are as following:



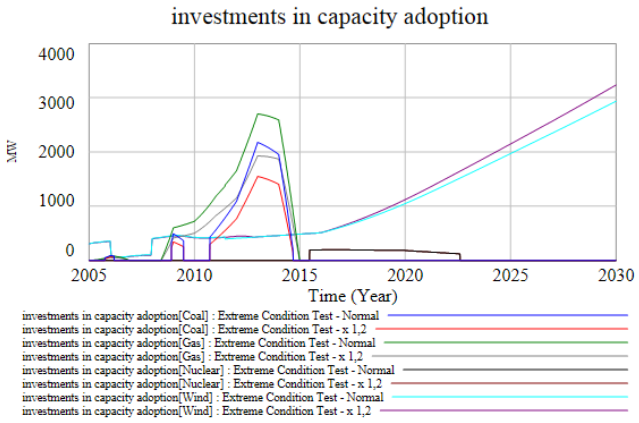


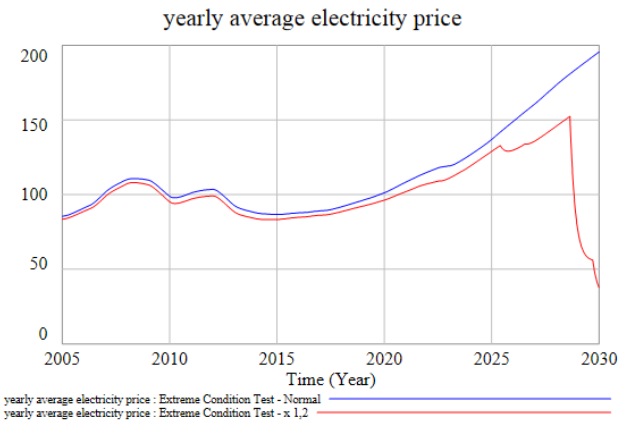


Dividing the *Wind Speed* by five, leads to lower *Available Production Capacity.* This means that the shortage that this lower wind production capacity causes, should be compensated by gas electricity production (flexible production method) or by importing electricity from neighbor countries. As lower wind production capacity leads to shortages at some point, the *yearly average electricity price* increases faster over time than in the normal situation. The lower *Wind Speed* also affects the investments in new production capacity. Less investments in wind production capacity are made. Though more electricity production capacity in carbon intensive production methods are done.

IF THE WIND SPEED IS HIGH, THEN INVESTMENTS IN WIND ENERGY WILL SOAR AND ELECTRICITY PRICES WILL DECREASE

To test this hypothesis the *Wind speed* is multiplied by 1.2. The results are as following:

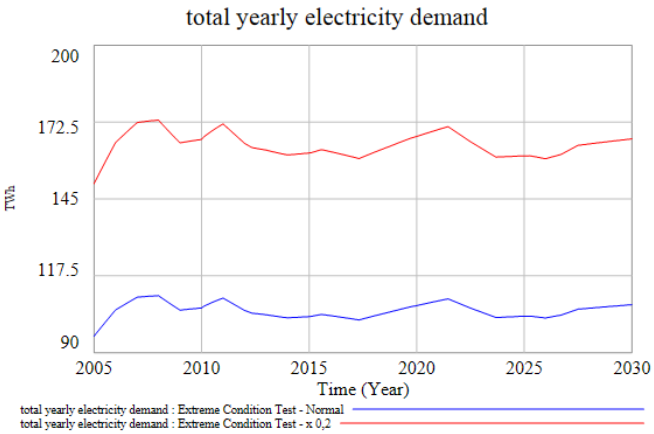


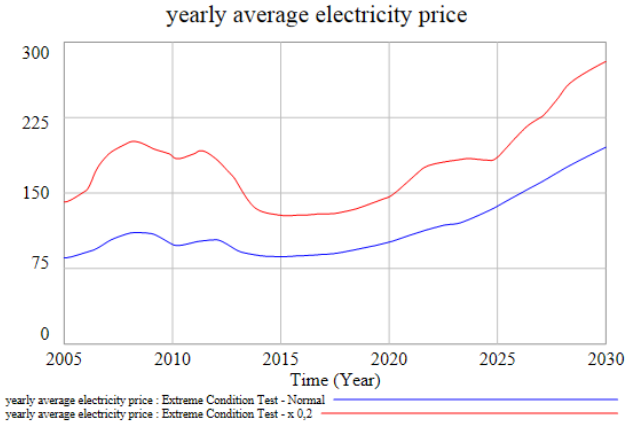


Multiplying the *Wind Speed* leads *to* higher *investments in capacity adoption* in wind. Lower investments are done in carbon intensive electricity production methods. The *yearly average electricity price* is lower than in the normal situation because more and cheaper wind electricity becomes available to the power exchange. Around 2028 the electricity decreases extremely fast. This is the point where most of the electricity demand could be supplied by cheaper electricity methods instead of electricity generated by gas or coal power plants. This is caused by the higher investment in wind energy that are done due to the higher *Wind Speed.*

IF ENERGY PRICES (THAT CONSUMERS PAY) DECREASES, THE ELECTRICITY DEMAND WILL GO UP AND ELECTRICITY PRICES WILL INCREASE

To test this hypothesis the *energy price* (that consumers pay) is divided by five. The results are as following:

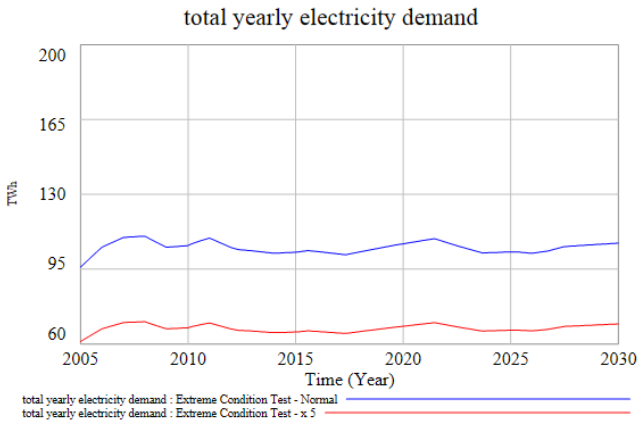


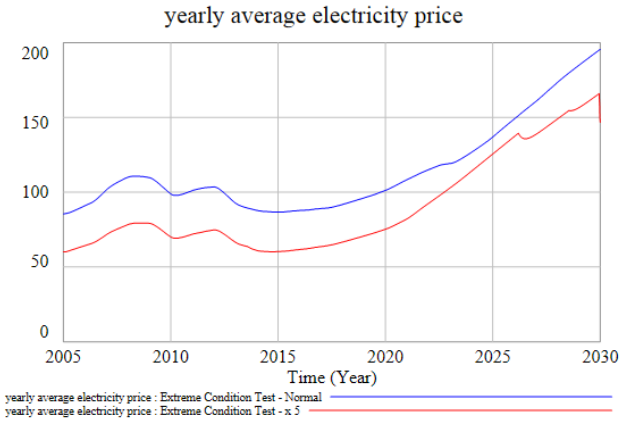


Dividing the energy prices – that consumers pay: oil, gas, electricity – is divided by five, leads to a very high *total yearly electricity demand*. As the demand increases and the electricity production capacity is the same in 2005, the *yearly average electricity price* is higher. Due to the higher electricity price, there is more room for investments. Though the electricity price stays higher than normal, as more electricity should be imported and produced by relatively expensive production methods – gas power plants to meet the high electricity demand.

IF ENERGY PRICES (THAT CONSUMERS PAY) INCREASE, THE ELECTRICITY DEMAND WILL GO DOWN AND ELECTRICITY PRICES WILL DECREASE

To test this hypothesis the *energy price* (that consumers pay) is multiplied by five. The results are as following:



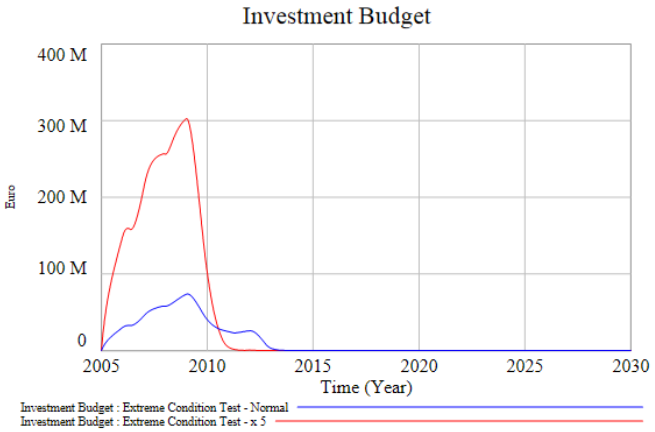


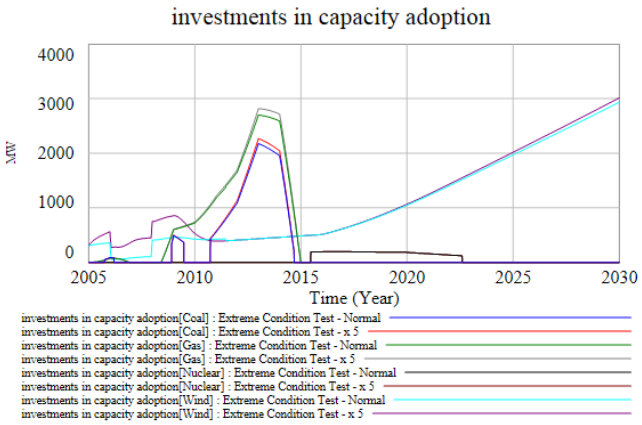
Multiplying the energy prices – that consumers pay: oil, gas, electricity – is multiplied by five, leads to a very low *total yearly electricity demand.* Due to the low electricity demand and the relatively high

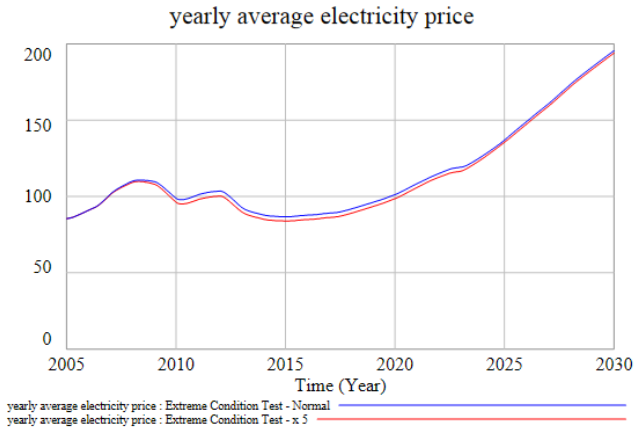
electricity production capacity, the *yearly average electricity price* is lower than in the normal situation. Because of the low electricity price, the *investment budget* is lower which leads to less investments in production. But since there is a overcapacity due to the low electricity demand, investments are not vital anyways.

IF THE INVESTMENT PERCENTAGE INCREASES, THE INVESTMENTS IN CAPACITY ADOPTION WILL INCREASE AND THE ELECTRICITY PRICE WILL DECREASE

To test this hypothesis the *investment percentage* is multiplied by five. The results are as following:



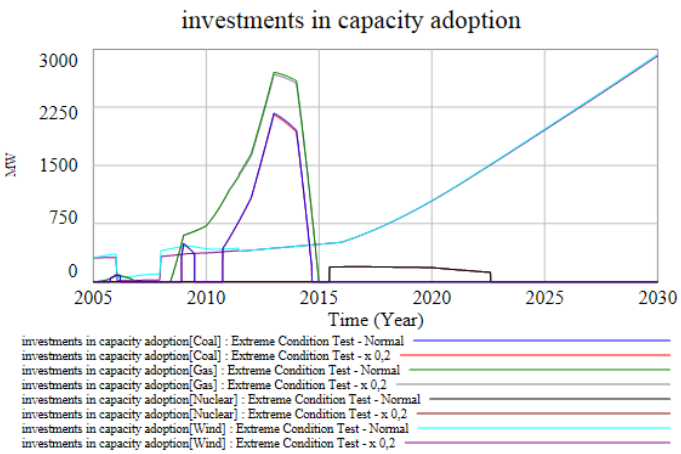


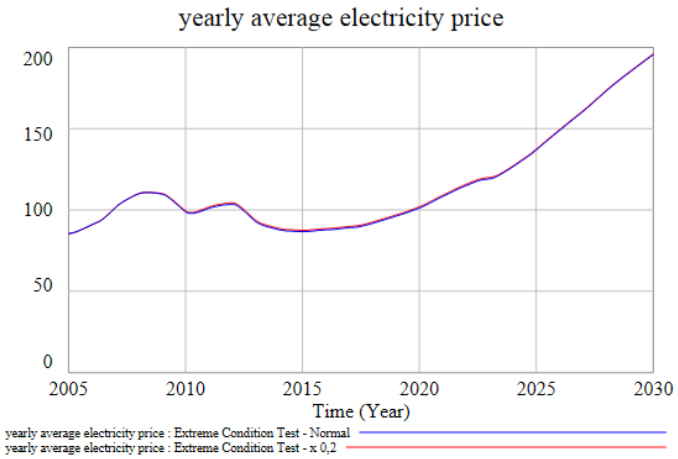


Multiplying the i*nvestment percentage* by five, leads to an *Investment Budget that* is five times higher. As the *Investment Budget* is not very high, since not much profit is made, not many *investment in capacity adoption* are done. Slightly more investments are done in Coal, Gas and Wind *electricity production.* Hereby more electricity production capacity becomes available which leads to a slightly lower *yearly average electricity price.*

IF THE INVESTMENT PERCENTAGE DECREASES, THE INVESTMENTS IN CAPACITY ADOPTION WILL DECREASE AND THE ELECTRICITY PRICE WILL INCREASE

To test this hypothesis the *investment percentage* is divided by five. The results are as following:





Dividing the *investment percentage* by five, leads to an *Investment Budget* that is five times lower than in the normal situation. Thereby, the *investments in capacity adoption* is lower. Though, since the *Investment Budget* in the normal situation is already low, an even lower *Investment Budget* does not have that much effect on the *investments in capacity adoption.* Since the difference is almost nothing, the change in *yearly average electricity price* is also almost nothing, but it is slightly higher.

Appendix G.2. – Sensitivity Analysis Results

Univariate Sensitivity Analysis

The external variables in the SD-model have been part of a sensitivity analysis which is conducted with a 10 percent increase and decrease for each variable. The sensitivity analysis exists of 1000 simulation runs with the random uniform distribution. The sensitivity analysis is given with confidence bounds are given for the KPI's of the system (See chapter 5). The KPI's are the main aspects of the electricity system and the sensitivity analysis provides insight on the sensitivity of changes of external variables on these KPI's. If the KPI's are not shown below, it indicates that the KPI's are not (or barely) numerically sensitive to changes of changes of the external variable.

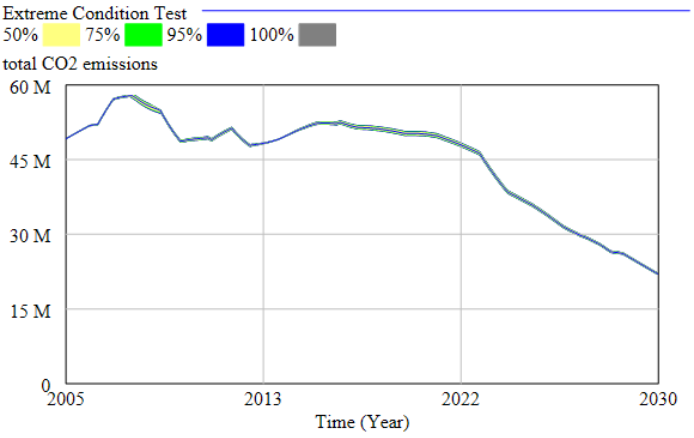
The first part of the sensitivity analysis consists of a univariate analysis, which is a sensitivity analysis with a single external variable being changed. In the second part, a multivariate sensitivity analysis is executed, where the influence of changes of multiple external variables on the electricity system is tested.

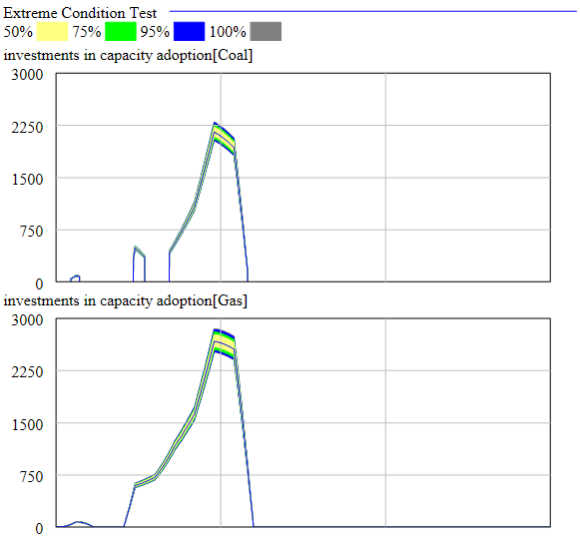
Electricity Production Capacity Construction Delay

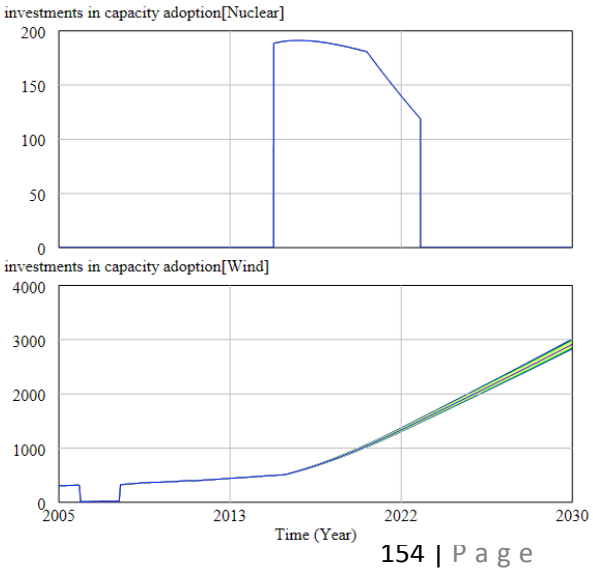
The sensitivity analysis of this external variables did not affect the electricity system significantly. This external variable influences the time it takes to build new capacity of a certain generation technology. As there is overcapacity from 2005 on in the electricity system, delay in construction or a faster construction does not affect the electricity prices and other KPI's significantly.

Electricity Production Capacity Lifetime

The external variable *Electricity Production Capacity Lifetime* influences the two KPI's of the electricity system. It influences the *Average Electricity Price* and the *Yearly CO2 Emissions*. The lifetime variable influences the *Yearly CO2 Emissions* as a shorter lifetime (or earlier retirement) of carbon intensive generation technology, provides an opportunity to faster replace these carbon intensive technologies with more sustainable generation technologies. The



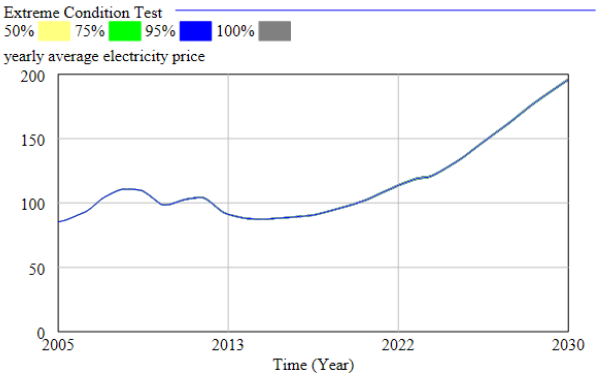


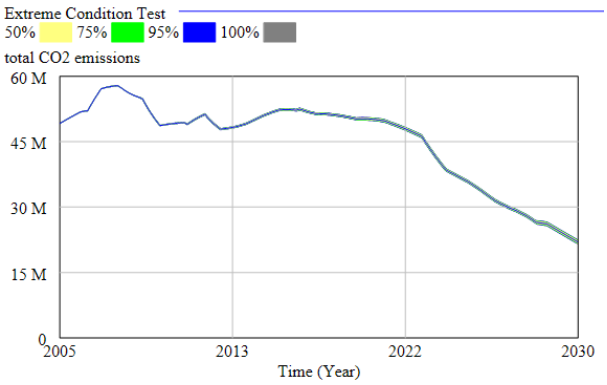


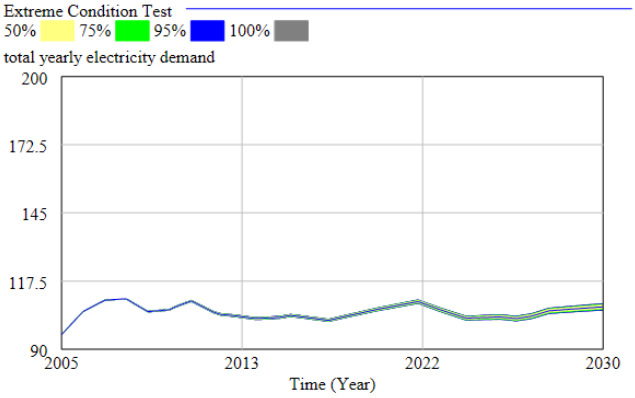
change of the electricity production mix influences the *Average Electricity Price.*

Direction coefficient Marginal Cost

The *Direction Coefficient Marginal Cost* is introduced in the SD-model as the marginal cost of different generation technologies are not the same. Generally, the generation methods with the lowest marginal cost of the same generation technology are bid earlier in the merit order (APX electricity market) than the ones with higher marginal cost. Changes of the *Direction Coefficient of Marginal Cost* influences the differences between the lowest marginal cost and the highest marginal cost of the same generation technology. Therefore, the sensitivity analysis on this external variable influences the *Average Electricity Price.* Other KPI's are not sensitive to changes of this external variable.

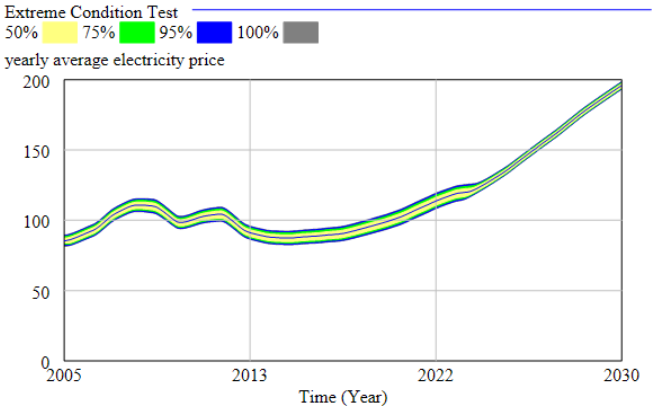






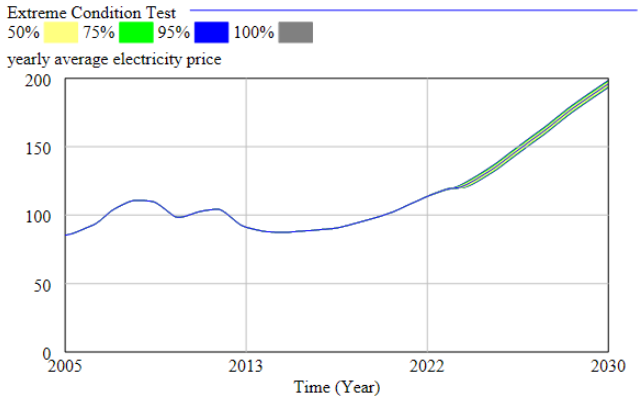
Initial Marginal Cost

The *Initial Marginal Cost* influences the power exchange (APX electricity market) and the prices that are bid to the market in 2005. The initial value influences the bids in the power exchange in after 2005 as well, as the yearly marginal cost are connected to the initial marginal cost value. The *initial Marginal Cost* influences the *Average Electricity Price* slightly. After 2024 the sensitivity is lower than earlier, this is caused by a higher available wind capacity. Wind capacity has a lower initial marginal cost, so a percentile changes has less influences than on high initial marginal cost. The *Initial Marginal Cost* does not influence other KPI's of the electricity system.



Average Yearly Coal Price

The *Average Yearly Coal Price* influences the marginal cost of coal power plant electricity generation. Besides the price of coal influences the adoption of coal technology, because a high coal price leads to less investments. Since the *Investment Budget* is zero most of the time and since the *investment priority* of coal is lower than the priority for wind, the *investment in capacity adoption* variable is not sensitive for changes.



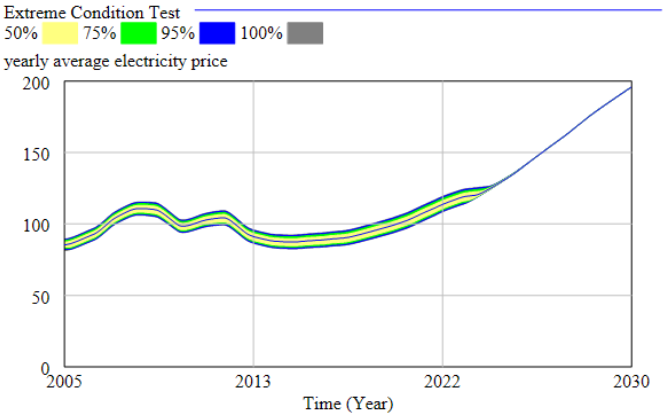
The *Yearly Average Electricity Price* is sensitive for the *Average Yearly Coal Price* – only after 2024 though. This because after 2024, the price of coal determines the market prices whereas before 2024 the electricity price is determined through the price of gas. This means that it also influences the available *investment budget* after 2024.

Average Yearly Uranium Price

The *Average Yearly Uranium Price* does not influence the KPI's of the electricity system. No investments in nuclear power plants are made within the model as there is not enough investment budget available. Besides, the price of uranium does not influence the electricity price as electricity from nuclear plants are always sold in the electricity market (of the SD-model) and more electricity than only wind and nuclear electricity is demanded.

Average Yearly Gas Price

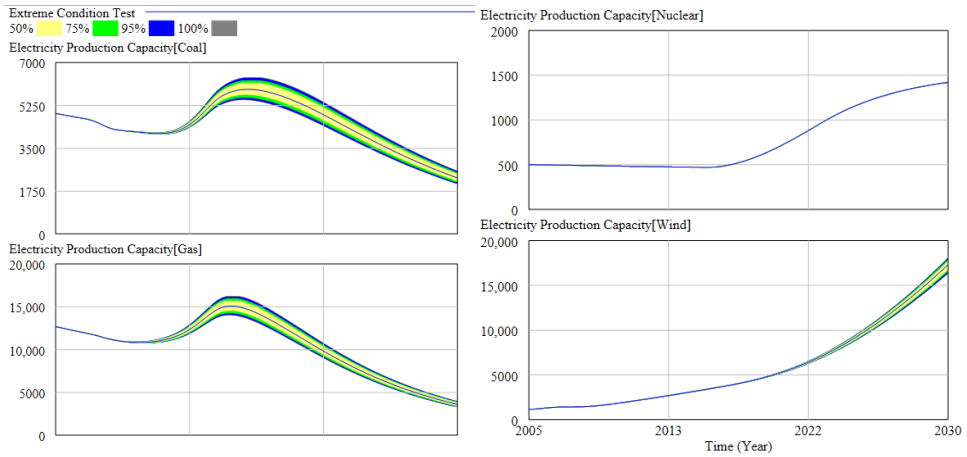
The *Average Yearly Gas Price* has an influence on the KPI's of the electricity system. First of all, the *Yearly Average Electricity Price* is sensitive to changes in the gas price until 2024. This because the marginal cost of gas power plants determine the electricity price until 2024. After 2024, it is the marginal cost of coal that influence the electricity price. Since the average electricity price is sensitive to the gas price, the I*nvestment Budget* is as well. An increasing electricity price leads to a higher *Investment Budget*, and the other way around.

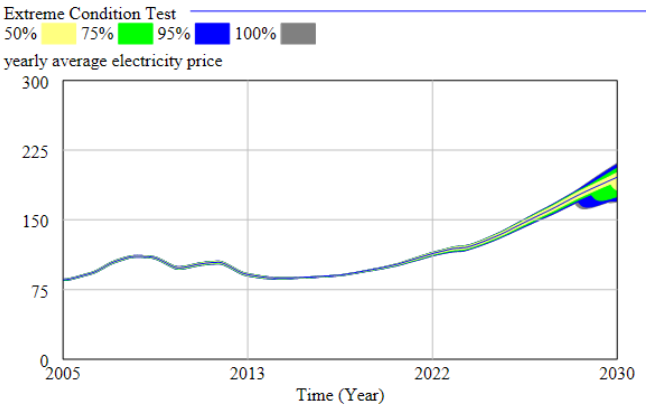


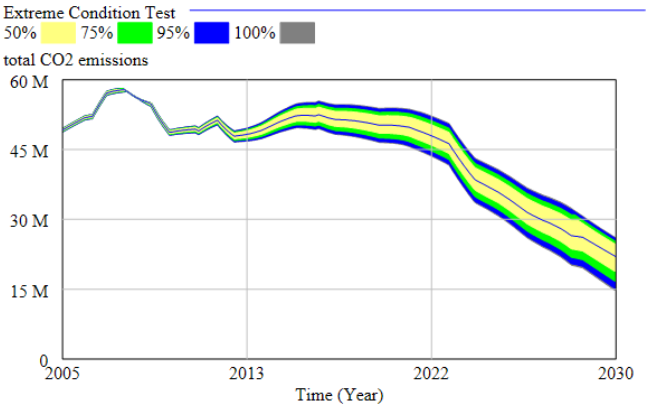
The gas price influences investments made in wind electricity production, as there is more room for investments when the electricity price is higher.

Wind Speed Variety

The *Wind Speed Variety* influences the capacity factor – how efficient a MW installed capacity could be transferred to an electrical MW – of wind electricity production at first. This influences the *Electricity Price* as a lower wind capacity factor leads to less electricity production and especially when there is a high demand for electricity the price becomes higher. The wind electricity production is highly sensitive to the wind speed and therefore has a large influence on the *CO2 emissions*. More wind electricity production means that less carbon intensive power plants are required to deliver the demanded electricity.

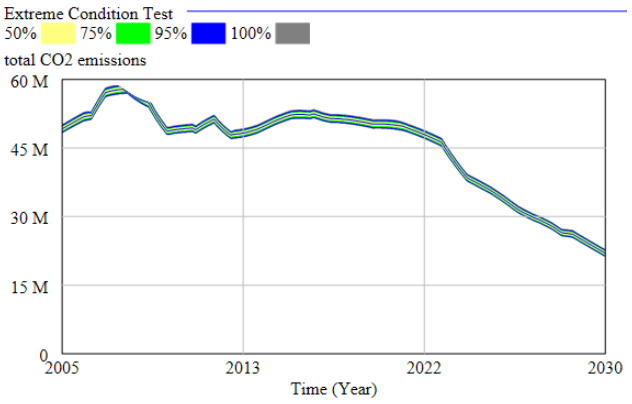


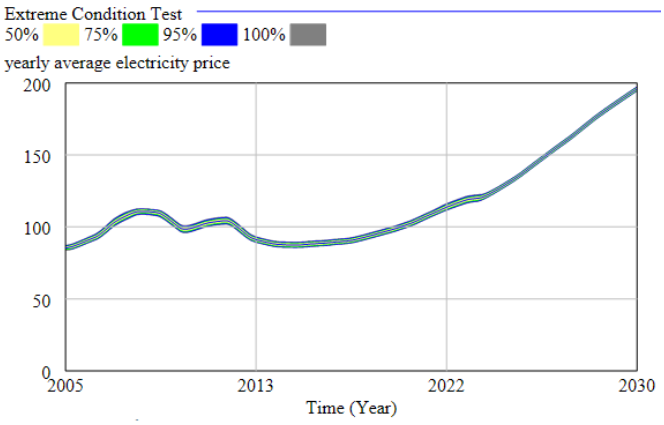


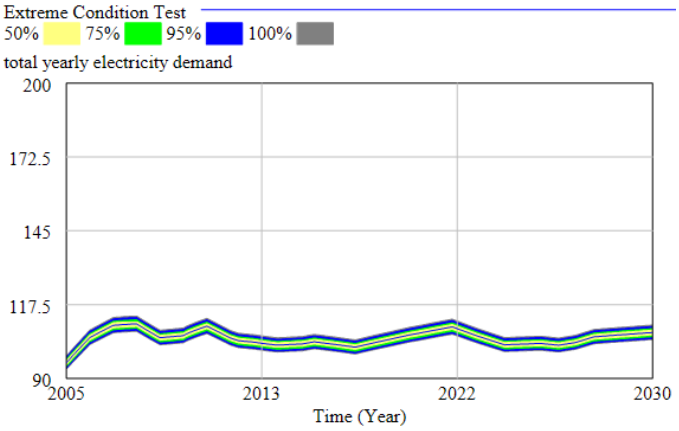


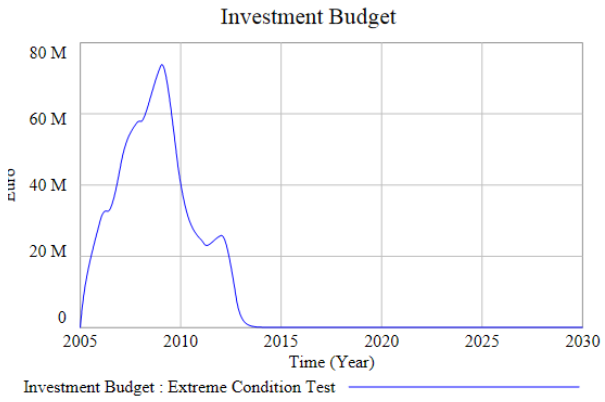
Average energy price for Consumers

The *Average Energy Price for Consumers* influences the *electricity demand*, as a higher energy price leads to a lower electricity demand. The sensitivity analysis of the *electricity demand* clearly shows the how sensitive the demand is for electricity price changes. The *electricity price* (output of the power exchange and the SD-model) is slightly sensitive to the *energy prices for consumers,* as the changes in demand have influence on the electricity price. A lower electricity demand also leads to lower *CO2 emissions* as less electricity production is needed.





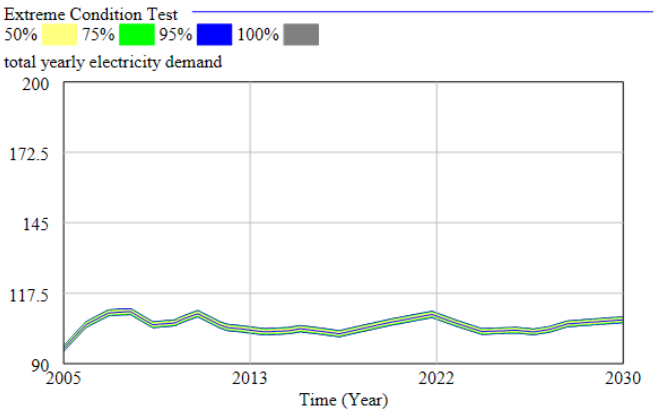




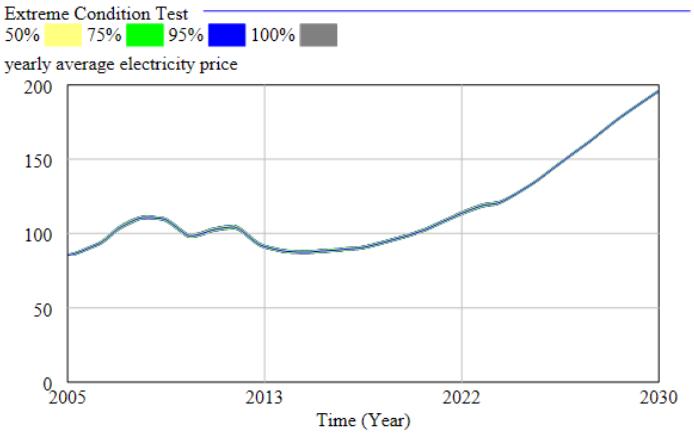
Investment Percentage of profit

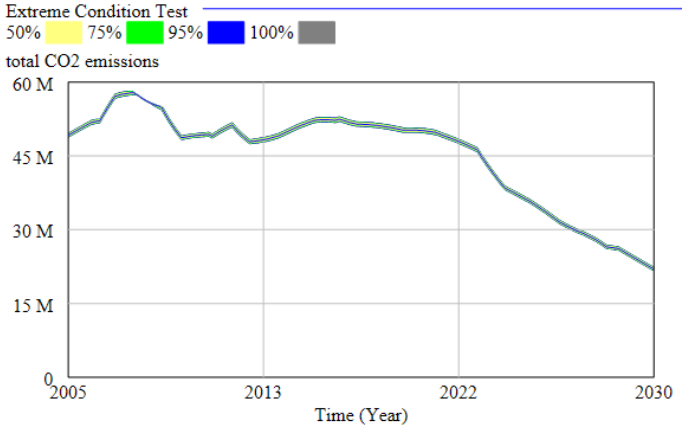
The *Investment Percentage* of the profit made by energy utility companies that leads to an *investment budget* used for adopting new installed capacity. When electricity prices are too low to cover the cost, no profit will be made which means that no *Investment Budget* becomes available. Only in the first 8 years there is investment budget available, but in terms of megawatts of capacity that could be installed this is nothing. The sensitivity of a small *Investment Budget* is therefore very small.

Oil Price



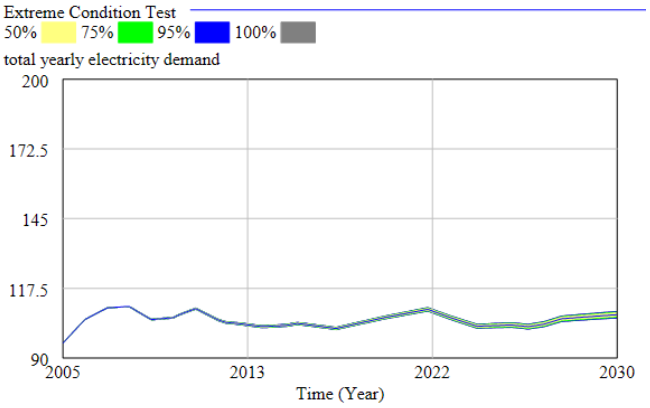
The *Oil Price* influences the electricity demand side of the model. The rise of oil prices directly leads to higher cost of consumers and thus less spending money available for other things. The rise of energy prices is negatively correlated to the demand of electricity. The oil prices are connected to gas prices, which means that a rise of oil prices will lead to a rise of gas prices. Eventually this will mean that the production of electricity (using gas power plants) will be more costly and thus electricity prices will become higher as well. As can be seen in the graphs below is that the oil prices have the most effect on the electricity demand. A ten percent increase and decrease of oil prices will not influence the electricity prices that much. Also the CO2 emissions will not increase or decrease that much with a changing oil price.

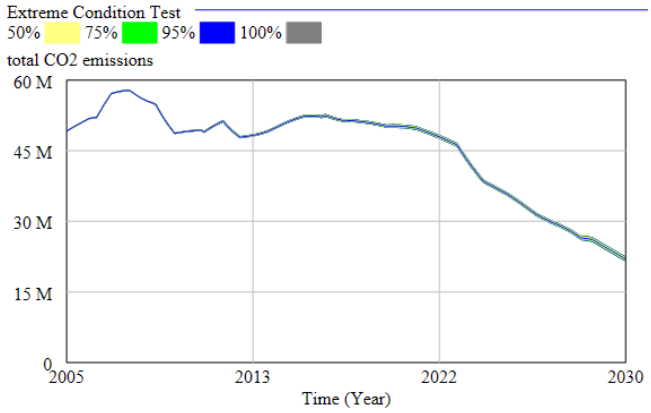




Causality on Energy Price and Energy Demand

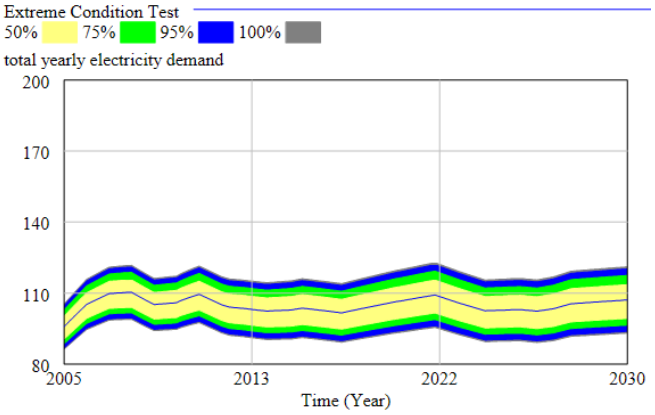
The *causality factor on Energy Price and Energy Demand* is factor that negatively correlates the energy prices with the energy demand. A rise in energy prices leads to lower electricity demand. The sensitivity analysis shows that it has more influence on the *total yearly electricity demand* towards 2030. On the *total CO2 Emissions*, the causality factor does not have that much influence. It is important to take this sensitivity into account for the model though, because the factor is not always exact -0.28.

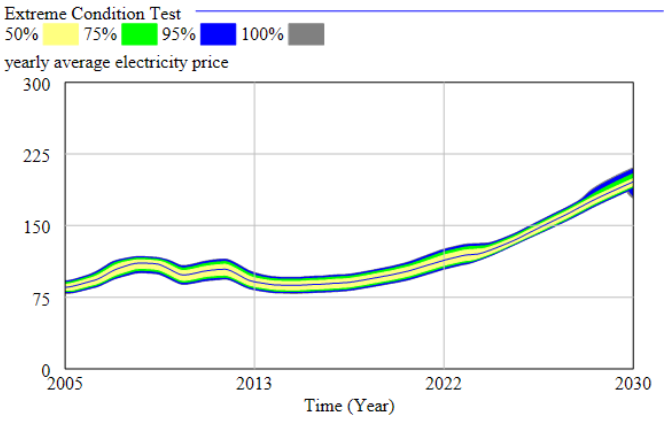


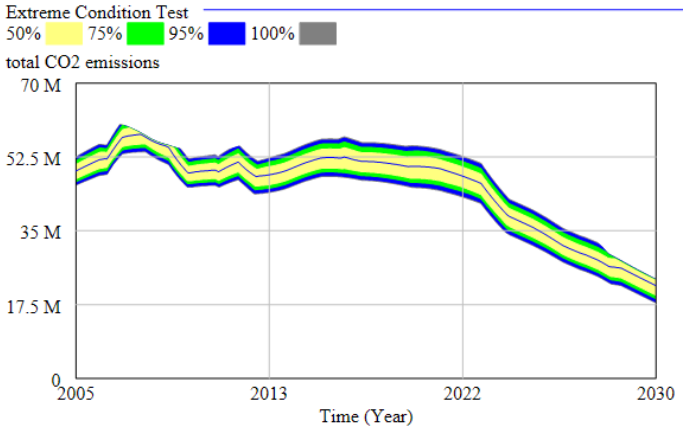


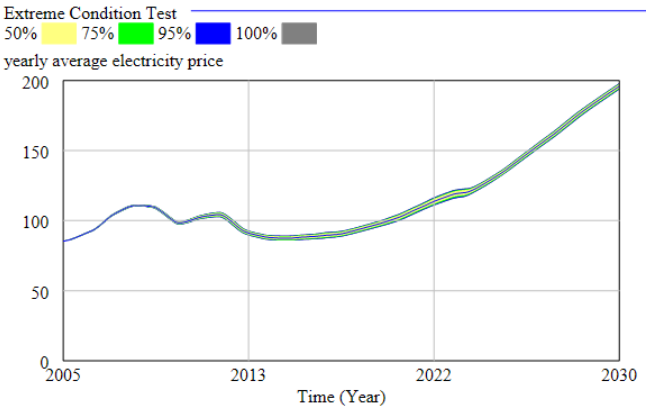
Dutch Population

The output of the model shows that it is very sensitive to changes of the population size. The Demand varies with approximately 10% – 15%. Since the demand is sensitive to changes, the CO2 emissions is as well. This because electricity demand influences the amount of electricity that is produced, which directly influences the total CO2 emissions. Also, changes in demand have a large influence on the yearly average electricity prices. For example, if more electricity is demanded, more expensive power plants should be turned on the meet the demand, and the other way around.



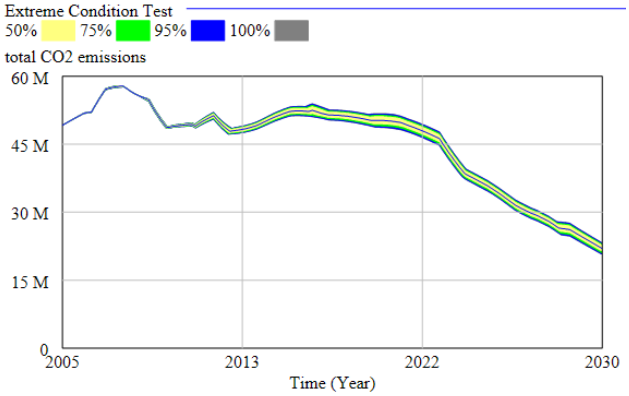


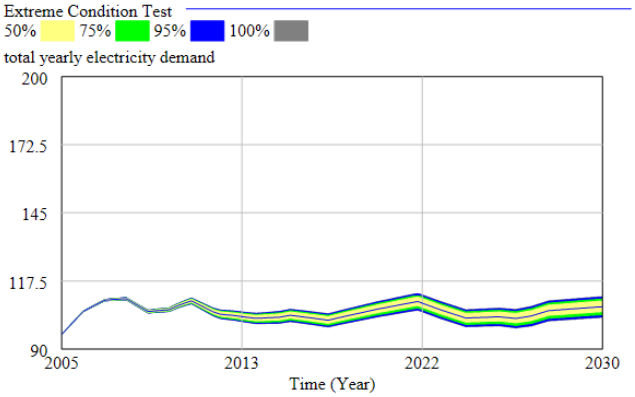




Decentralized Electricity Production

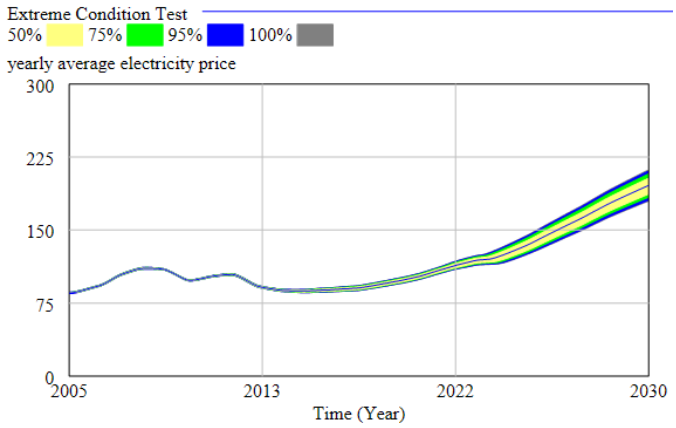
The *Decentralized Electricity Production* increases over time as decentralized renewable energy production becomes more accessible and financially interesting. This explains why the sensitivity of the *total yearly electricity demand* and the *total CO2 emissions* increase towards 2030. The *yearly average electricity price* is sensitive for decentralization, but not as much as much as the others.

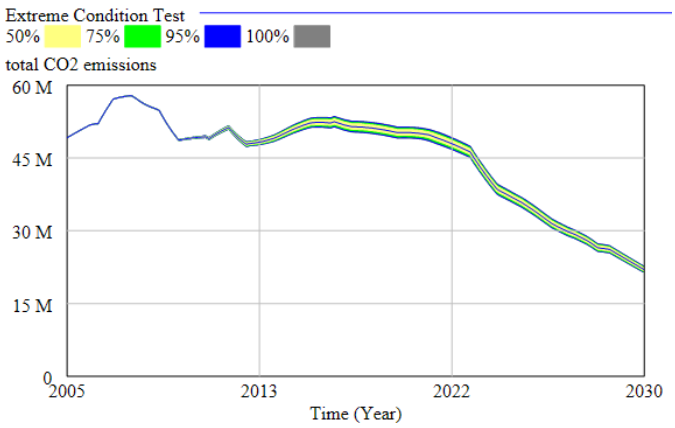




CO2 Variation

CO2 price changes have a large influence on the *yearly average electricity price*, especially towards 2030. It is highly uncertain how the CO2 price will evolve over time. Therefore, testing the sensitivity of the CO2 price changes is of high importance. It is assumed that the CO2-price will grow towards approximately 186 euro per ton CO2 in 2030. Since this factor is uncertain, a 10 percent increase and decrease of the scenario has been tested. Analysis shows that the *total CO2 emissions* are fairly sensitive for CO2 price changes.

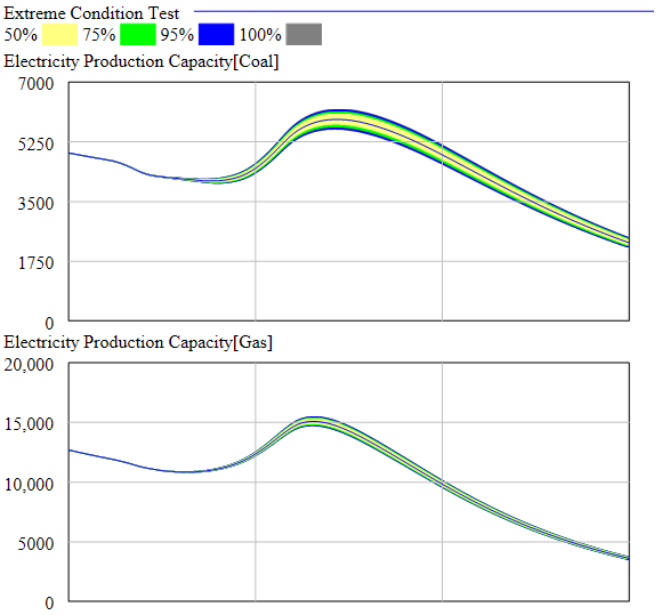


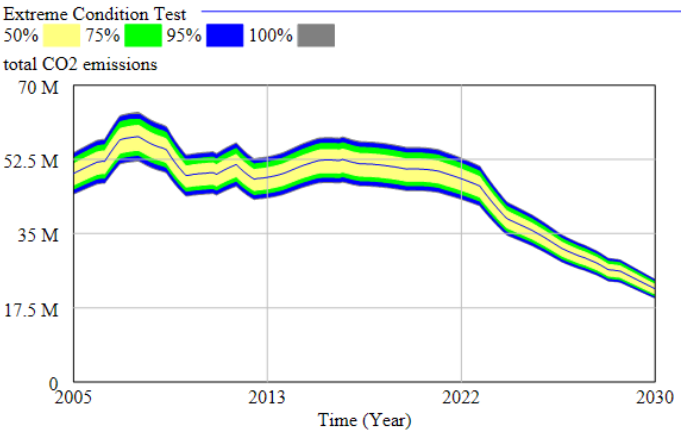


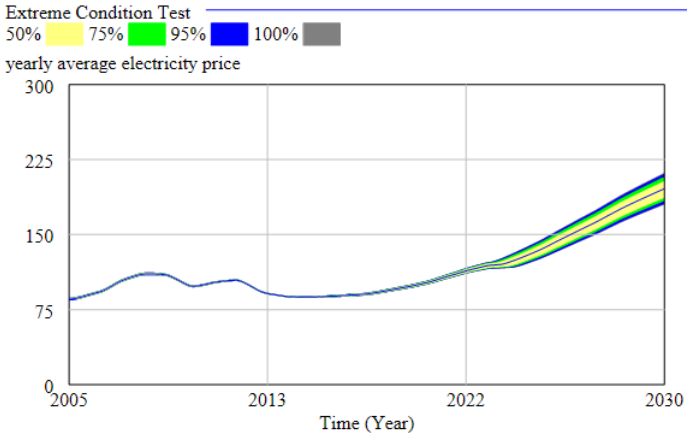
CO2 Emissions per production technology

Gas and Coal power plants emit CO2 of burning fossil fuels to generate electricity. The efficiency of the plants and how much CO2 per generated MWh is emitted differs from plant to plant. The average CO2 emissions for Coal per generated MWh is 850 kg and for gas power plants this number is approximately 350 kg. As this number varies from plant to plant, a sensitivity analysis is done.

It shows that the *total CO2 emissions* is highly sensitive for a changing efficiency of the power plants. It also, affects the adoption of carbon intensive power plants as the CO2 cost decreased when plants are more efficient and thus this leads to more investments, and the other way around. Especially towards 2030 the *yearly average electricity price* is sensitive for the efficiency of the power plants. This is due to the high CO2 price around 2030 – efficiency has more influence on the cost.

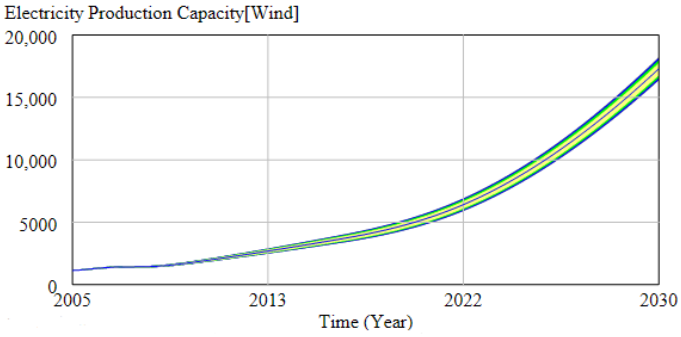


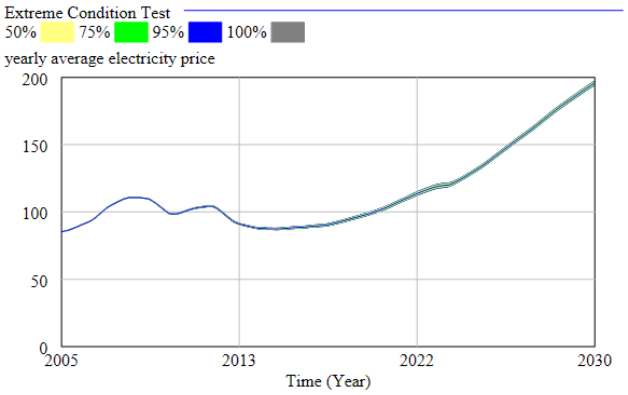


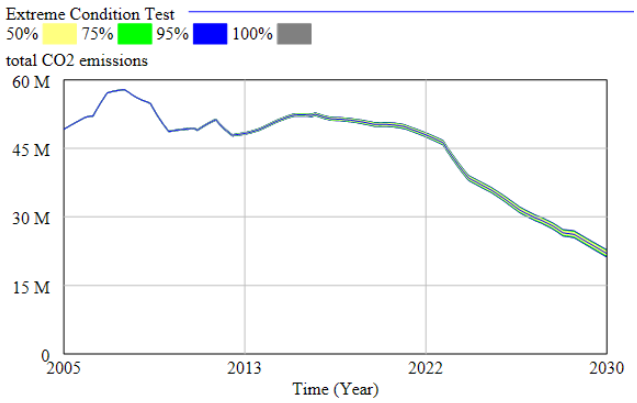


SDE+

The SDE+ subsidy is a policy from the Dutch government to stimulate sustainable development, and thus also the adoption of wind energy production capacity.It shows that the *Electricity Production Capacity* of wind is sensitive for changes in the SDE+ subsidy. The SDE+ subsidy increases towards 2030 and therefore it has an increased sensitivity on the *Electricity Production Capacity* adoption of wind energy. The subsidy does not influence the *yearly average electricity price* significantly. As the growing SDE+ subsidy leads to an increased adoption of wind energy, it influences the *total CO2 emissions* towards 2030 as well.



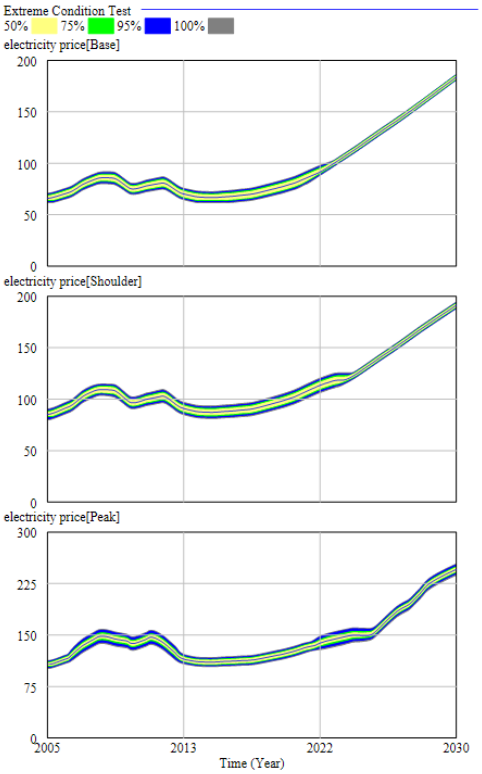

Extreme Condition Test
50% 75% 95% 100%
yearly average electricity price
200
150
100
50
0
2005
2013
2022
2030
Time (Year)


Extreme Condition Test
50% 75% 95% 100%
total CO2 emissions
60 M
45 M
30 M
15 M
0
2005
2013
2022
2030
Time (Year)

Multivariate Sensitivity Analysis

The external variables in the SD-model have been part of a sensitivity analysis which is conducted with a 10 percent increase and decrease of each external variable.

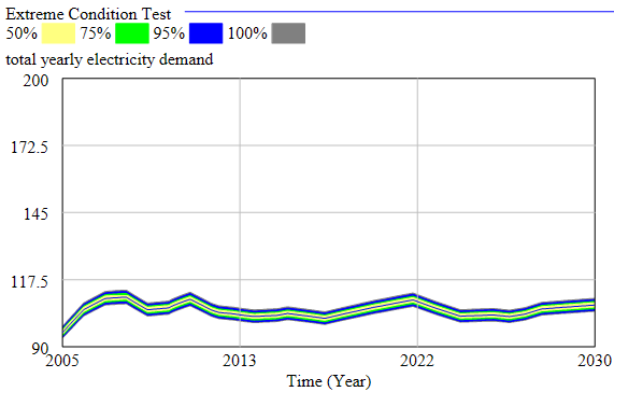
The second part of the sensitivity analysis consists of a multivariate analysis, which is an analysis of the sensitivity of the model when varying a group of external factors uncorrelated. The different groups of external forces that are tested in the multivariate analysis are the energy prices, megatrends, policies and all the external variables.



Energy Prices

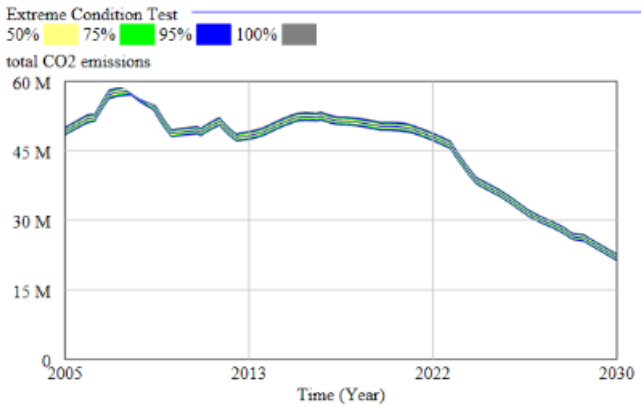
The prices of oil, gas, nuclear and coal influence both the electricity demand as well as the electricity supply. As the development of these external factors towards 2030 are highly uncertain, a sensitivity analysis on how changes of the different external factors influence the electricity system.

The *electricity price* per phase (base, shoulder and peak) are sensitive for the energy prices. Around 2022, the electricity price in the base and shoulder become less sensitive. This has to do with the increased available production capacity of wind energy. The adoption of wind electricity capacity has led to an available capacity of different generation methods that could supply sufficient electricity in the base and shoulder without using gas power plants. Therefore, the electricity price is not sensitive to gas price changes.



The *total yearly electricity demand* is sensitive for energy prices as an higher energy price leads to less spending money for consumers and thus reduction of energy usage to reduce cost.

Next to that, the energy prices influence the *total CO2 emissions.* This because higher energy prices lead to a lower electricity demand and thus less supply – from carbon intensive power plants – needed.

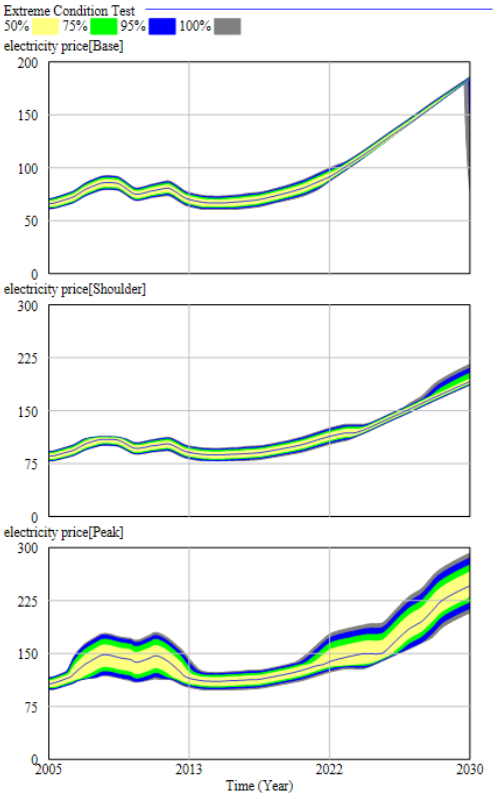


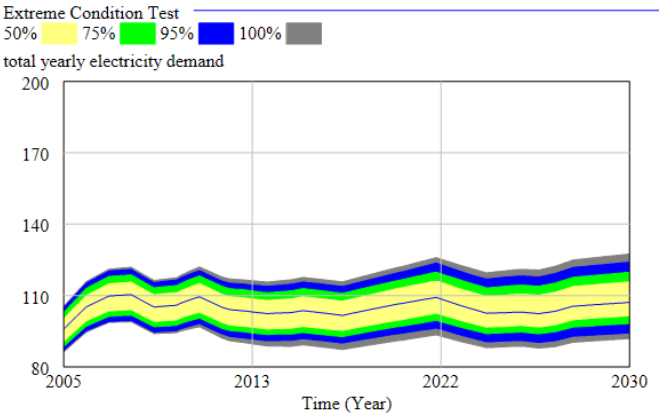
Megatrends

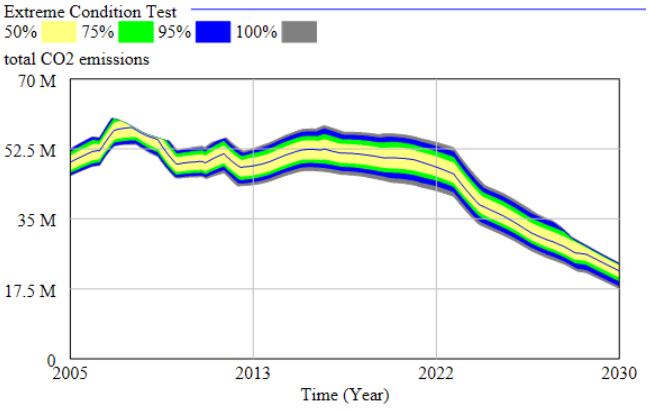
Megatrends are long term external factors that evolve according a certain pattern. An example is the worldwide population growth, a larger problem in developing countries like in China and India. Though, it is expected that the population will grow from 16.8 million in 2015 to 17.1 million in 2030. Next to population growth, factors like decentralization of electricity production and the adoption of Electric Vehicles that have been taken into account in the model.

These megatrends together show that the *total yearly electricity demand* is highly sensitive for megatrends. The *electricity price* shows that the peak price is much more sensitive for megatrends than the electricity price in the base and shoulder. The higher sensitivity is mostly caused by the population growth. This factor has a greater influence on the peak price, since producing more electricity peak is more expensive than in the base and shoulder. This is because for electricity production in the peak a higher percentage of the total capacity is already used and thus the more expensive power plants need to be used to generate the extra electricity in the peak.

Since the electricity demand is highly sensitive for megatrends, the *total CO2 emissions* are as well.

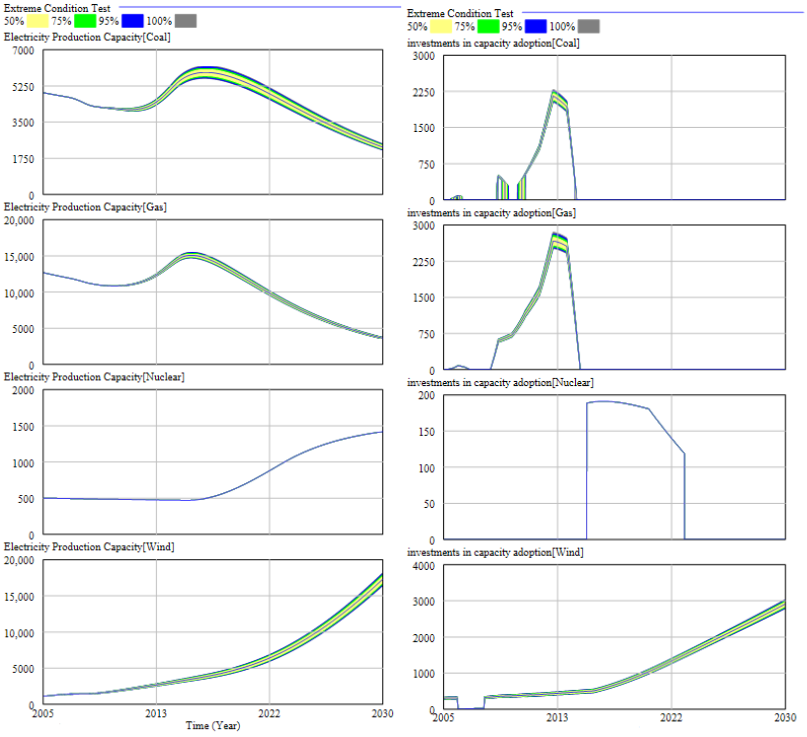






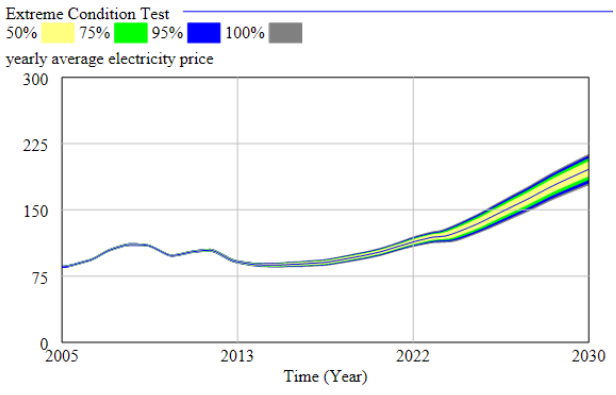
Policies

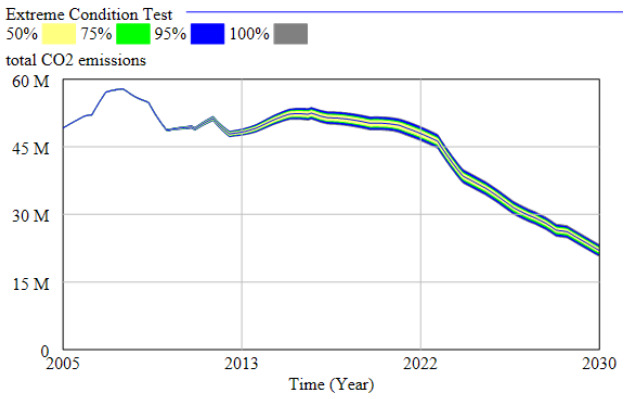
Two policies have been added to the simulation model, the CO2 price of the Emission Trading Scheme of the European Union and the SDE+ subsidy of the Dutch government.



It first of all shows that the adoption of wind energy capacity dependent and sensitive is for the SDE+ subsidy. Next to that the CO2 price influences investments in the coal intensive power plant capacity. An higher CO2 price reduces the attractiveness of coal and gas capacity, and the other way around.

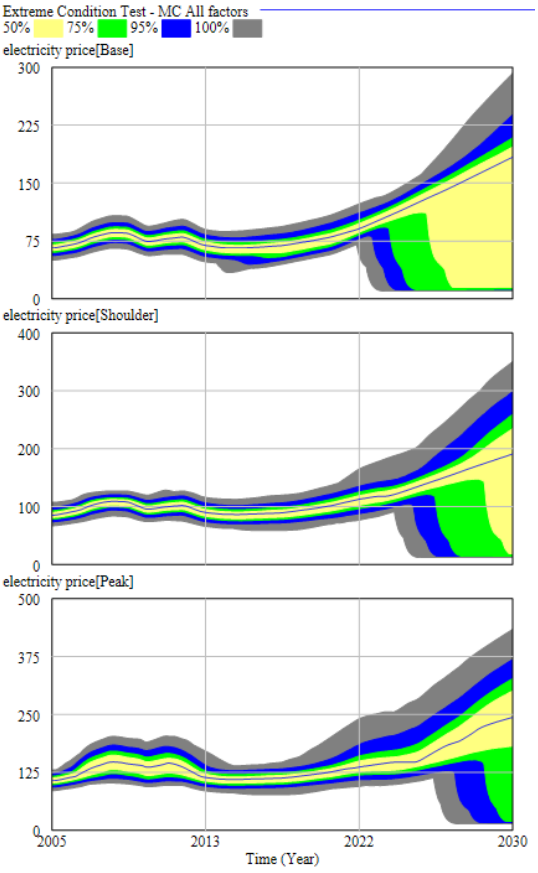
The CO2 price influences the *yearly average electricity price* as a higher CO2 price increases the marginal cost of carbon intensive generation capacity. Next to that, the high adoption of wind energy capacity towards 2030 (caused by SDE+ Subsidy), leads to an increased volatility of the electricity price. This volatility is caused by the unpredictability of wind speeds and the variation of wind energy generation yields. When yields are low, electricity should be generated with relatively expensive gas power plants. If yields are high, electricity could be generated by relatively cheap generation methods, leading to a drop of electricity prices.

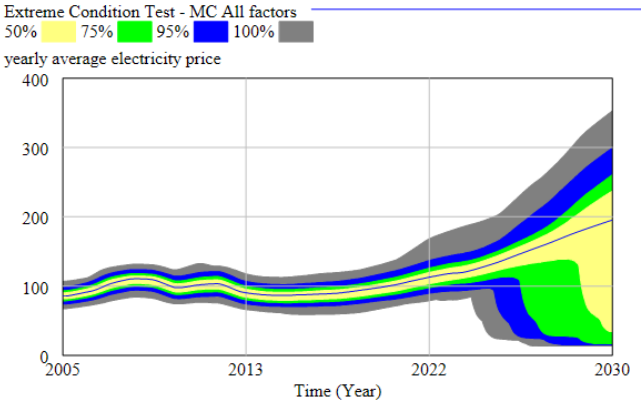


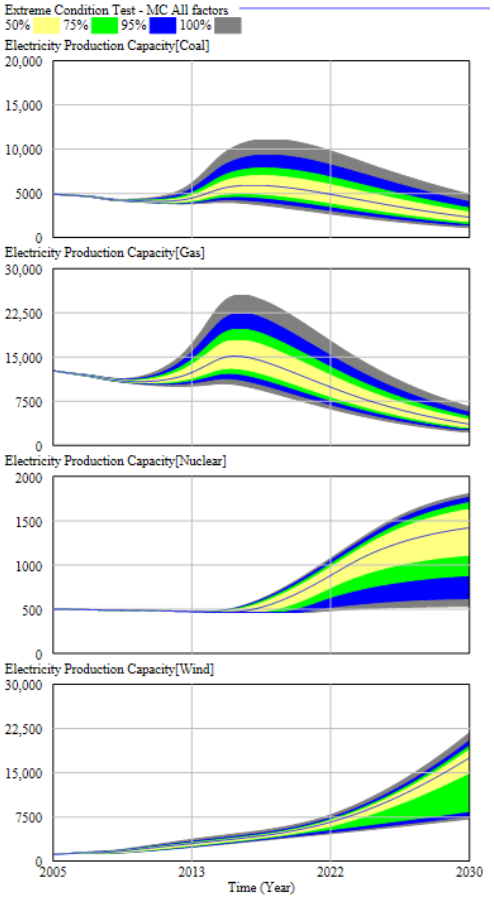


Sensitivity Analysis – All External Variables

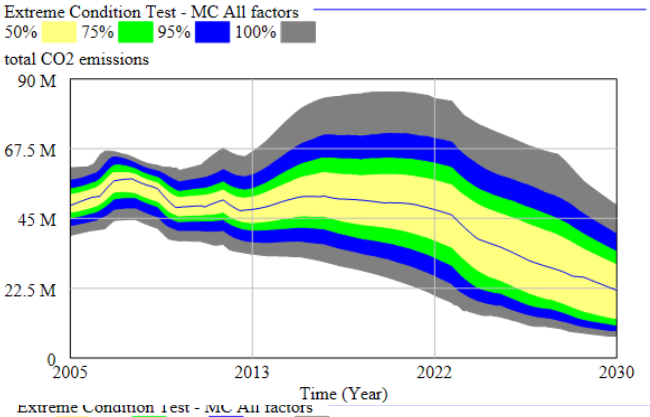
Varying all the external factors provides an interesting overview of the total sensitivity of important factors of the Dutch electricity system. The electricity price in the three phases shows a high volatility towards 2030. This is exactly what is expected to happen towards 2030, as the increased adoption of wind energy will have a high influence on the electricity price. The *electricity price* shows that the demanded electricity in the base phase, is the first phase where electricity could be fully supplied by wind energy. The down side of being able to fully supply the demanded electricity through wind energy capacity is that when there is no wind available, a large part of the installed capacity will not be available. Thereby more expensive power plants should produce the demanded electricity, causing a higher electricity price.

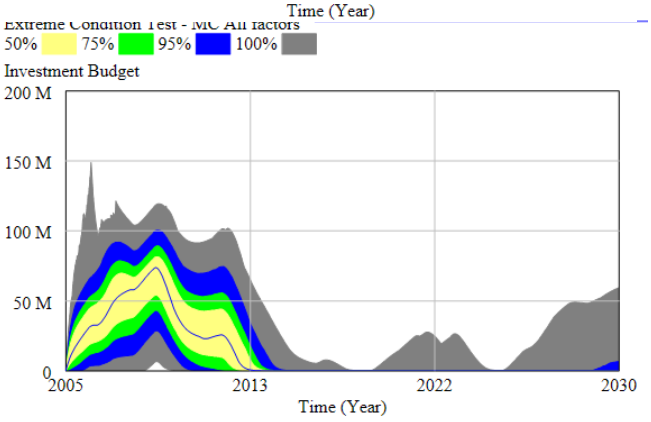






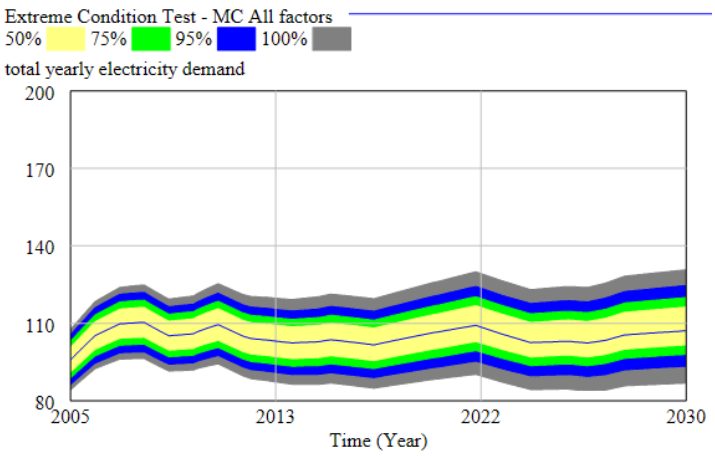
The graphs show a negative trend for generation capacity development for coal and gas, caused by expected high cost for CO2 emissions. Nuclear and wind generation capacity development have a positive trend towards 2030, leading to a downward trend for *total CO2 emissions.* Most of the capacity adoptions arise from external investments as the high cost of carbon





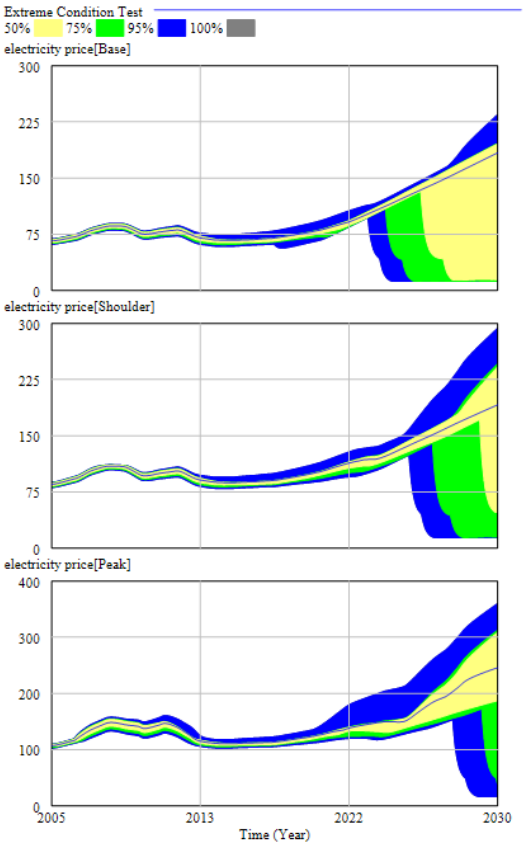
intensive electricity production negatively influences the profit whereby not much investment budget becomes available for capacity development.

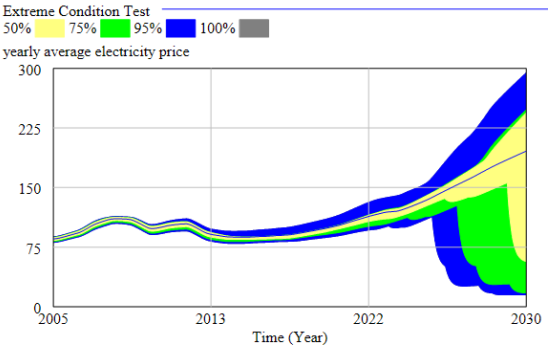
The average electricity demand does not grow much, which is caused by the decentralized electricity production trend. Uncertainty on how the decentralized electricity production will development leads to a high uncertainty, with an electricity demand between 90 – 130 TWh in 2030.

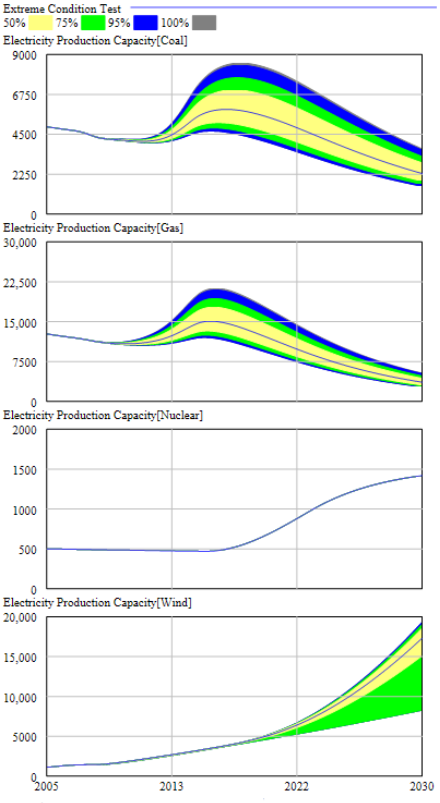


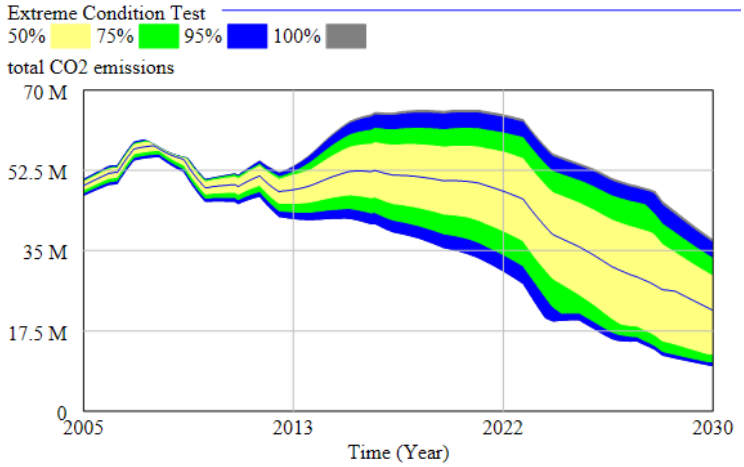
Wind variety and Electricity Price volatility

By only varying the wind speed, more insights can be provided on the sensitivity of the electricity system and the influence of this factor. As expected the Dutch electricity system is highly sensitive for this external force – especially after 2025 when a large volume of wind energy production capacity has been installed. The wind speed has the most influence on the electricity prices in the peak – high electricity demand phase. The highest and lowest price are respectively about 350 euro/MWh and 5 euro/MWh. Besides the electricity price, the wind speed has a large influence on the investments done. When wind speeds are high, the yield of wind electricity production is higher and thus an investment in this generation method is more interesting. Next to the effects on the electricity price and the investments, the wind speed influences the CO2 emissions as well. Wind speed directly influences the CO2 emissions as a higher yield of wind electricity production will replace gas electricity production – resulting in a reduction of CO2 emissions. An indirect influence that wind speed has on the CO2 emissions, is that higher wind speeds lead to more investments in wind electricity production – leading to a larger potential for sustainable electricity production.



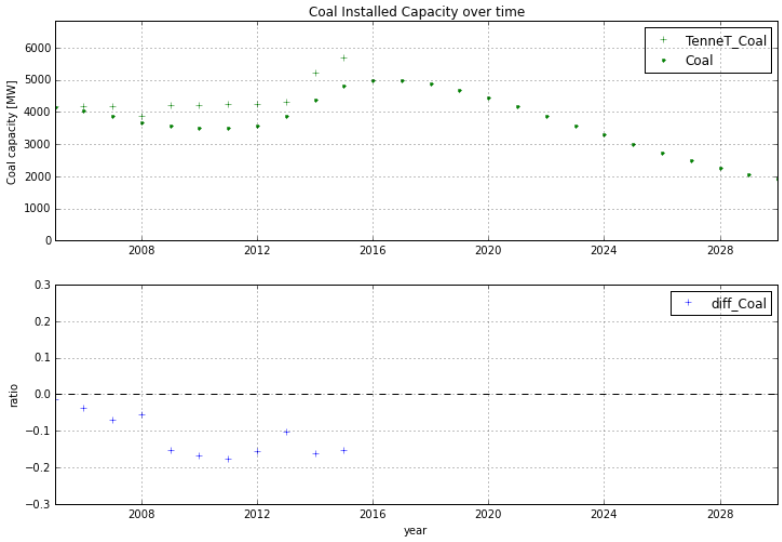




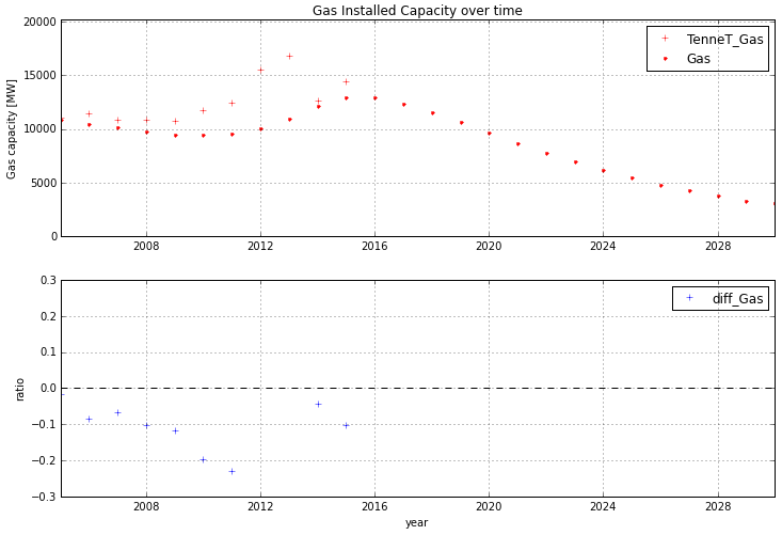


Appendix G.3. – R^2 and MAE/Mean Metric

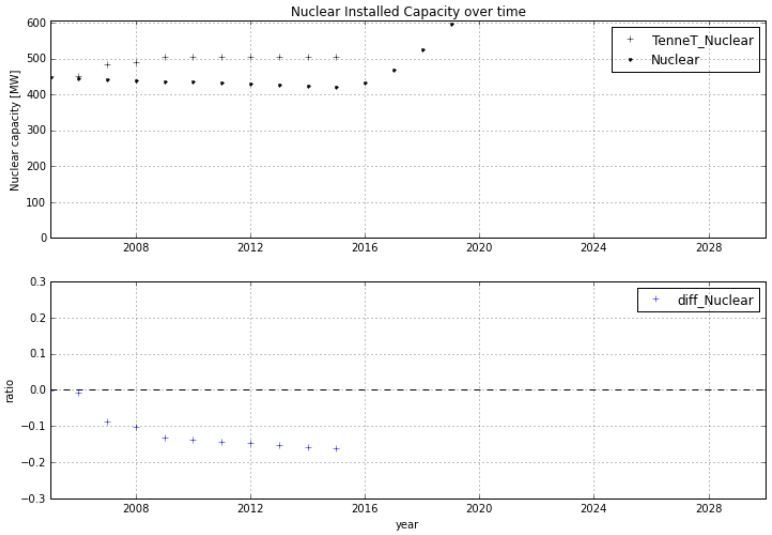
In this appendix the detailed results of the R^2 and MAE/Mean calculations are provided. Next to that the graphs showing the differences between real data and simulation data are given.



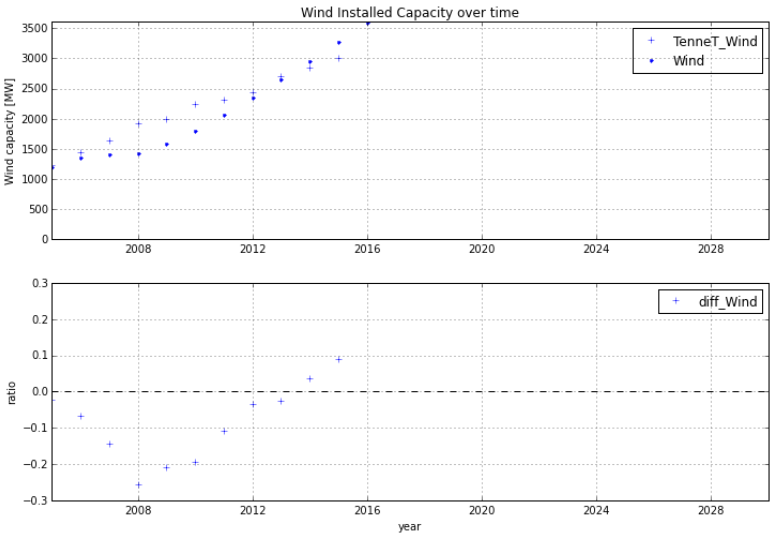
Installed Capacity - Coal		
Time	R2	MAE/mean
2005	-0.01	678
2006	-0.01	560
2007	-0.04	393
2008	0.90	429
2009	-0.16	10
2010	-0.36	91
2011	-0.49	132
2012	-0.30	24
2013	0.59	237
Total	**0.01**	**6.80%**



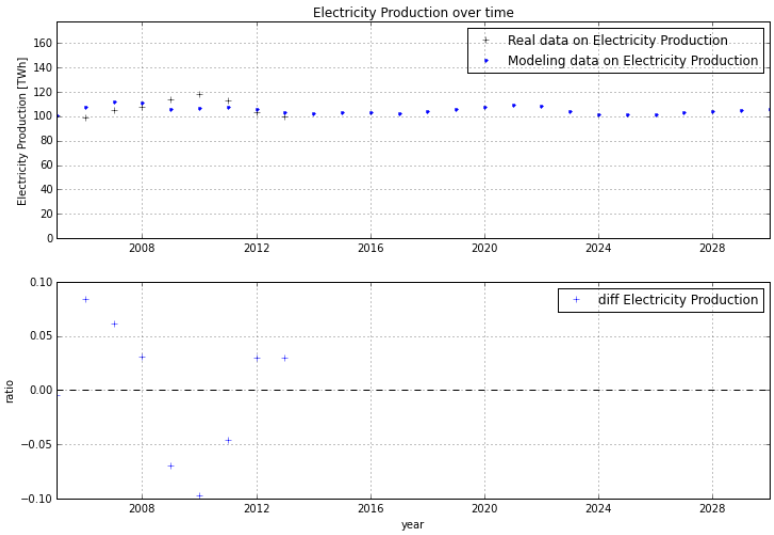
Installed Capacity - Gas		
Time	R2	MAE/mean
2005	-0.82	1442
2006	-0.31	610
2007	-0.07	804
2008	0.43	331
2009	0.77	152
2010	0.32	910
2011	-0.03	1410
2012	-0.04	3928
2013	2.92	4240
Total	**0.35**	**12.40%**



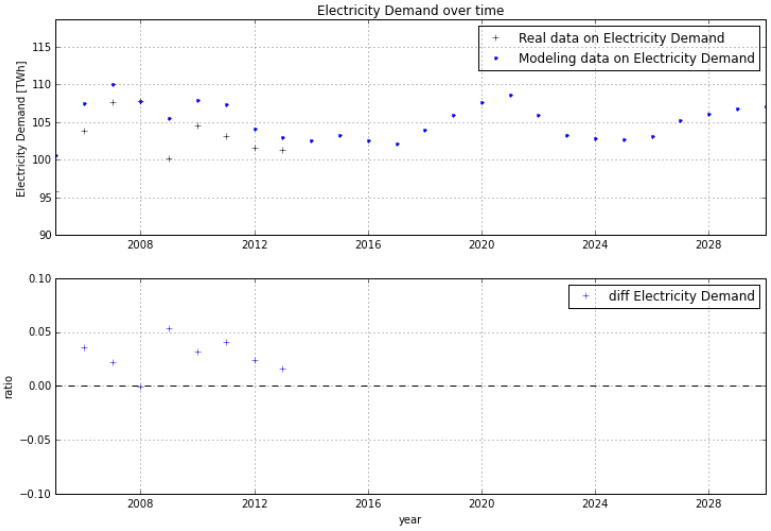
Installed Capacity - Nuclear		
Time	R2	MAE/mean
2005	-2.47	48
2006	-1.84	45
2007	-0.11	7
2008	0.03	1
2009	-0.01	18
2010	-0.25	21
2011	-0.50	24
2012	-0.75	27
2013	-0.99	30
Total	**-0.77**	**5.00%**



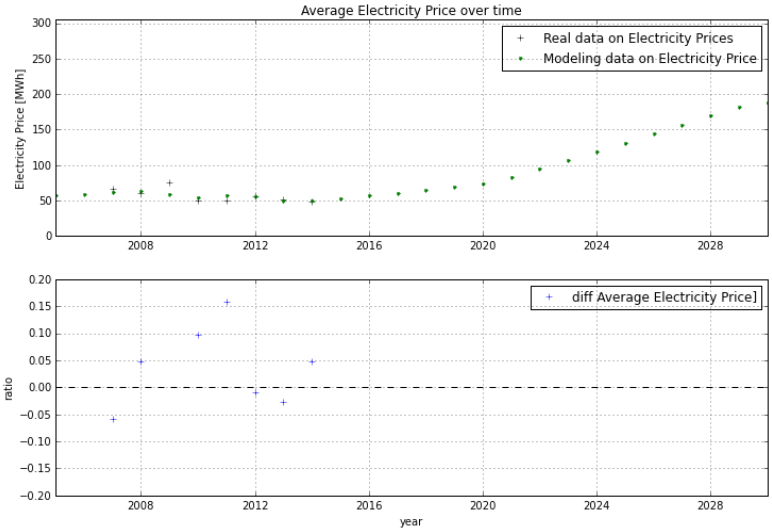
Installed Capacity - Wind		
Time	R2	MAE/mean
2005	1.79	28
2006	0.90	99
2007	0.52	237
2008	0.10	491
2009	0.00	415
2010	0.05	432
2011	0.41	249
2012	1.08	84
2013	2.65	67
Total	**0.83**	**11.70%**



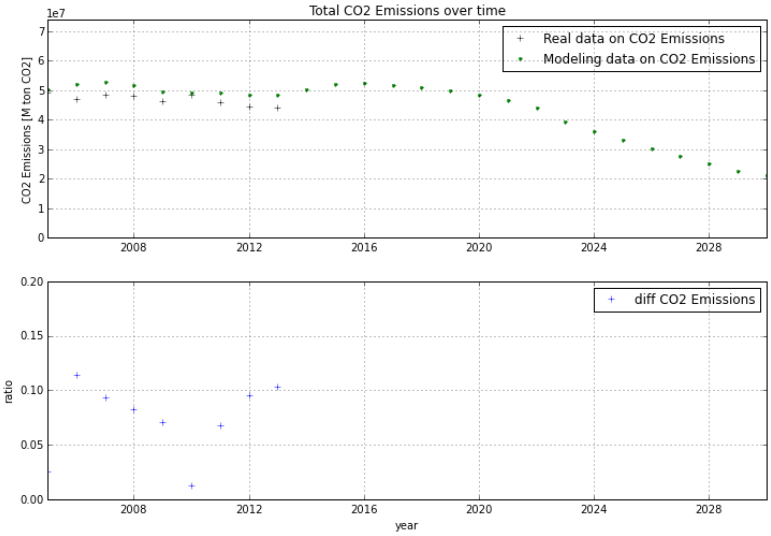
Installed Capacity - Electricity Production		
Time	R2	MAE/mean
2005	1.47	0.45
2006	-0.21	8.32
2007	-0.36	6.49
2008	0.24	3.30
2009	-0.19	7.94
2010	-0.08	11.49
2011	0.30	5.17
2012	0.10	3.05
2013	1.05	2.95
Total	**0.26**	**5.10%**



Installed Capacity - Electricity Demand		
Time	R2	MAE/mean
2005	3.44	4.71
2006	0.13	3.70
2007	1.80	2.40
2008	0.79	0.07
2009	0.09	5.37
2010	0.28	3.38
2011	0.03	4.20
2012	0.22	2.48
2013	0.43	1.65
Total	**0.80**	**3.00%**



Installed Capacity - Average Electricity Price		
Time	R2	MAE/mean
2005	No Data	No Data
2006	No Data	No Data
2007	0.84	3.87
2008	0.25	2.94
2009	0.76	16.79
2010	0.57	4.87
2011	0.08	7.86
2012	0.16	0.54
2013	1.32	1.43
Total	**0.57**	**9.30%**



Installed Capacity - CO2 emissions		
Time	R2	MAE/mean
2005	0.12	1267976
2006	-0.01	5372973
2007	1.37	4544479
2008	0.58	3962712
2009	0.16	3282232
2010	-0.62	606744
2011	0.27	3134460
2012	1.29	4223490
2013	1.65	4533849
Total	**0.53**	**7.30%**

Appendix G.4. – Load Duration Curve Sensitivity

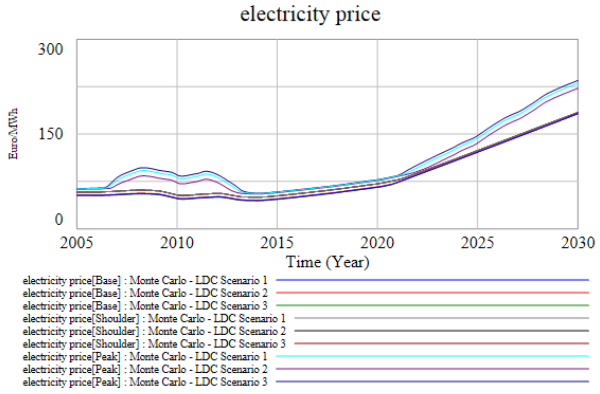
To be able to simulate outliers – which are important to take into account when simulating electricity prices – the load duration curve has been split up into three phases. These phases – named: Base, Shoulder and Peak – have a size of 10%/80%/10% respectively.

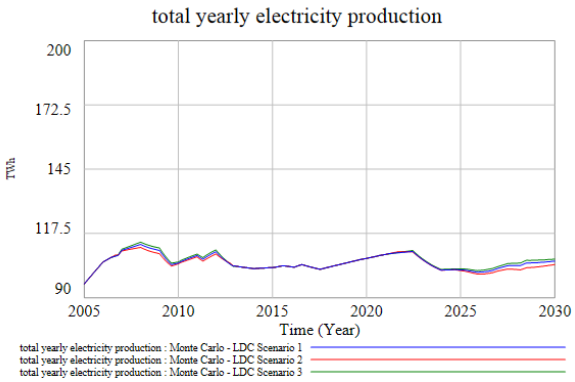
The sensitivity of changing the number of steps is not been researched in this thesis. However, the size of the phases has been reserached in a sensitivity analysis. Scenario 1 is the normal situation where the average electricity demand with a phase size of 10%/80%/10% for the Base, Shoulder and Peak respectively. Scenario 2 has a diviation of 20%/60%/20% and scenario 3 has a deviation of 5%/90%/5%.
The table below provides the initial Electricity Demand (MWh/hour) in 2005. As shown in the table, the peak initial electricity demand in scenario 3 is the highest. This is caused by the small size of the peak phase – in this way the outliers have more influence on the average of the phase. By simulating the three scenarios the sensitivity on the electricity system for this phase size could be tested.

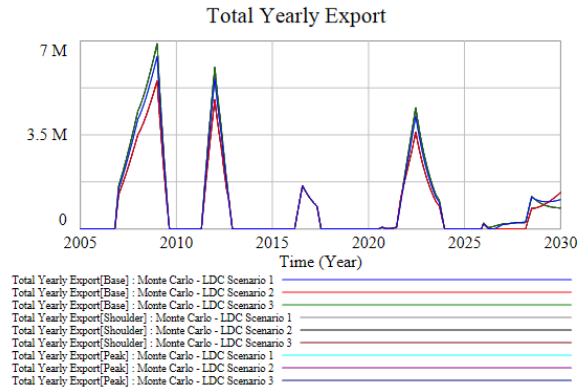
	Initial Electricity Demand (MWh/hour) in 2005		
	Base	Shoulder	Peak
Scenario 1 (10/80/10)	7829	10902	14376
Scenario 2 (20/60/20)	8127	10893	13900
Scenario 3 (5/90/5)	7604	10921	14640

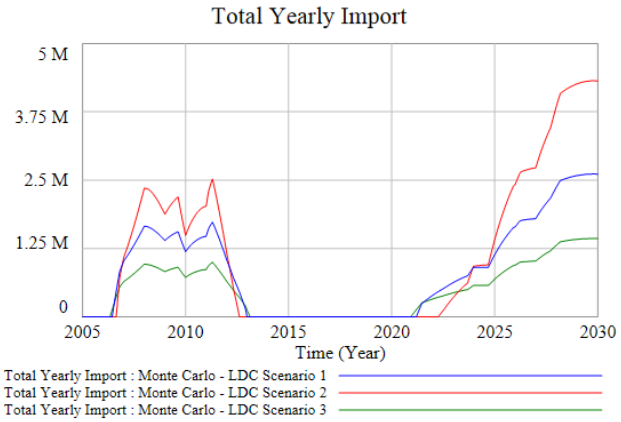
Initial Electricity Demand (MWh/hour) in 2005 per phase

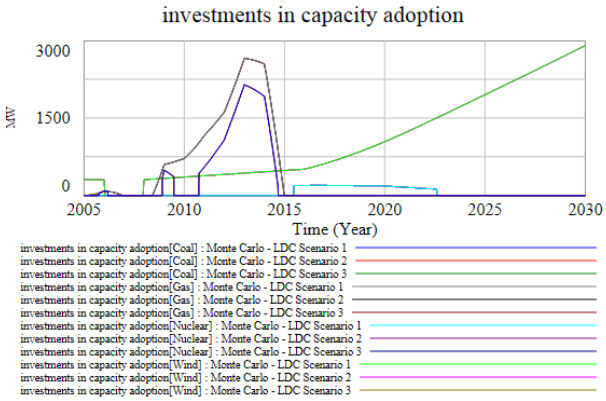
It shows that the electricity prices, the total yearly electricity production and the import and export are slightly sensitive for changing the phase size. CO2 emissions, Electricity Production Capacity, investments in capacity adoption are not sensitive to size changes of the phases (see graphs next page).

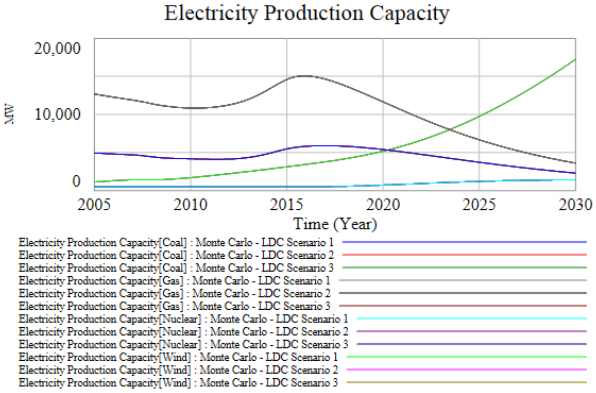


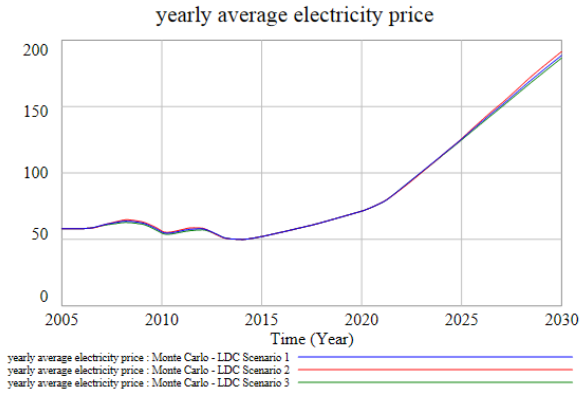


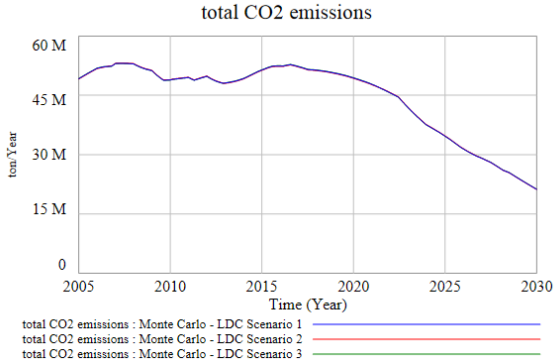





investments in capacity adoption
3000
1500
0
MW
2005
2010
2015
2020
2025
2030
Time (Year)
investments in capacity adoption[Coal] : Monte Carlo - LDC Scenario 1
investments in capacity adoption[Coal] : Monte Carlo - LDC Scenario 2
investments in capacity adoption[Coal] : Monte Carlo - LDC Scenario 3
investments in capacity adoption[Gas] : Monte Carlo - LDC Scenario 1
investments in capacity adoption[Gas] : Monte Carlo - LDC Scenario 2
investments in capacity adoption[Gas] : Monte Carlo - LDC Scenario 3
investments in capacity adoption[Nuclear] : Monte Carlo - LDC Scenario 1
investments in capacity adoption[Nuclear] : Monte Carlo - LDC Scenario 2
investments in capacity adoption[Nuclear] : Monte Carlo - LDC Scenario 3
investments in capacity adoption[Wind] : Monte Carlo - LDC Scenario 1
investments in capacity adoption[Wind] : Monte Carlo - LDC Scenario 2
investments in capacity adoption[Wind] : Monte Carlo - LDC Scenario 3


Electricity Production Capacity
20,000
10,000
0
MW
2005
2010
2015
2020
2025
2030
Time (Year)
Electricity Production Capacity[Coal] : Monte Carlo - LDC Scenario 1
Electricity Production Capacity[Coal] : Monte Carlo - LDC Scenario 2
Electricity Production Capacity[Coal] : Monte Carlo - LDC Scenario 3
Electricity Production Capacity[Gas] : Monte Carlo - LDC Scenario 1
Electricity Production Capacity[Gas] : Monte Carlo - LDC Scenario 2
Electricity Production Capacity[Gas] : Monte Carlo - LDC Scenario 3
Electricity Production Capacity[Nuclear] : Monte Carlo - LDC Scenario 1
Electricity Production Capacity[Nuclear] : Monte Carlo - LDC Scenario 2
Electricity Production Capacity[Nuclear] : Monte Carlo - LDC Scenario 3
Electricity Production Capacity[Wind] : Monte Carlo - LDC Scenario 1
Electricity Production Capacity[Wind] : Monte Carlo - LDC Scenario 2
Electricity Production Capacity[Wind] : Monte Carlo - LDC Scenario 3


yearly average electricity price
200
150
100
50
0
2005
2010
2015
2020
2025
2030
Time (Year)
yearly average electricity price : Monte Carlo - LDC Scenario 1
yearly average electricity price : Monte Carlo - LDC Scenario 2
yearly average electricity price : Monte Carlo - LDC Scenario 3


total CO2 emissions
60 M
45 M
30 M
15 M
0
ton/Year
2005
2010
2015
2020
2025
2030
Time (Year)
total CO2 emissions : Monte Carlo - LDC Scenario 1
total CO2 emissions : Monte Carlo - LDC Scenario 2
total CO2 emissions : Monte Carlo - LDC Scenario 3

Appendix H – Data

In this appendix the remaining data is provided in the table below. This data is used for the validation chapter. The comparison study on the modeling data and the real data was based on the data provide in this appendix.

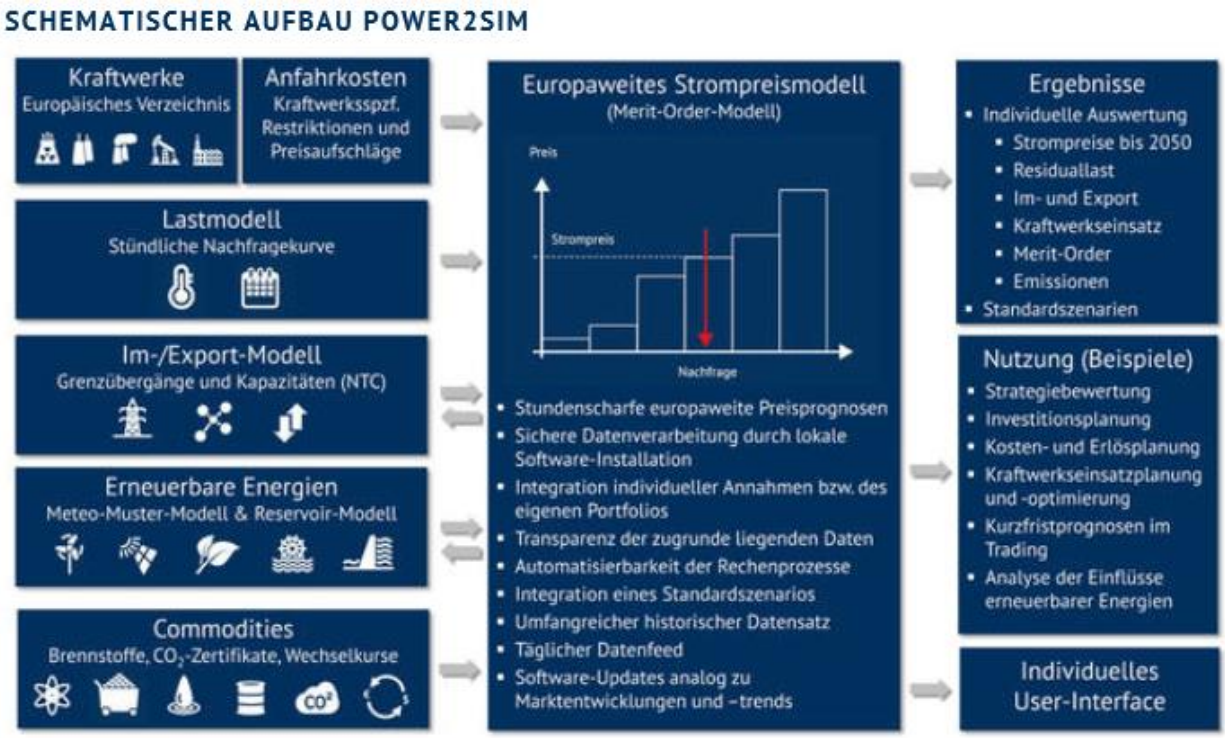
	Electricity price	CO2 emissions	Electricity Demand	Electricity production	Installed Capacity (MW)				
	Euro/MWh	Ton	TWh	TWh	*Coal*	*Gas*	*Nuclear*	*Wind*	Total
2005	-	49230390	95.84	101	4182	11031	450	1224	16887
2006	-	46878821	103.81	99	4182	11465	450	1453	17550
2007	65.93	48470561	107.7	105	4175	10852	485	1641	17153
2008	60.34	47996566	107.8	108	3880	10847	490	1921	17138
2009	76.2	46261193	100.2	114	4208	10750	504	1994	17456
2010	50.33	48611887	104.5	118	4228	11759	504	2237	18728
2011	49.57	46131594	103.1	113	4238	12456	504	2316	19514
2012	55.98	44474154	101.6	103	4233	15498	504	2433	22668
2013	51.88	44029934	101.3	101	4319	16793	504	2713	24329
2014	48.43	-	-	-	5224	12654	504	2852	21234
2015	-	-	-	-	5684	14476	504	3004	23668

(TenneT Holding B.V., 2015)

Appendix I – Schematic overview of alternative energy model designs

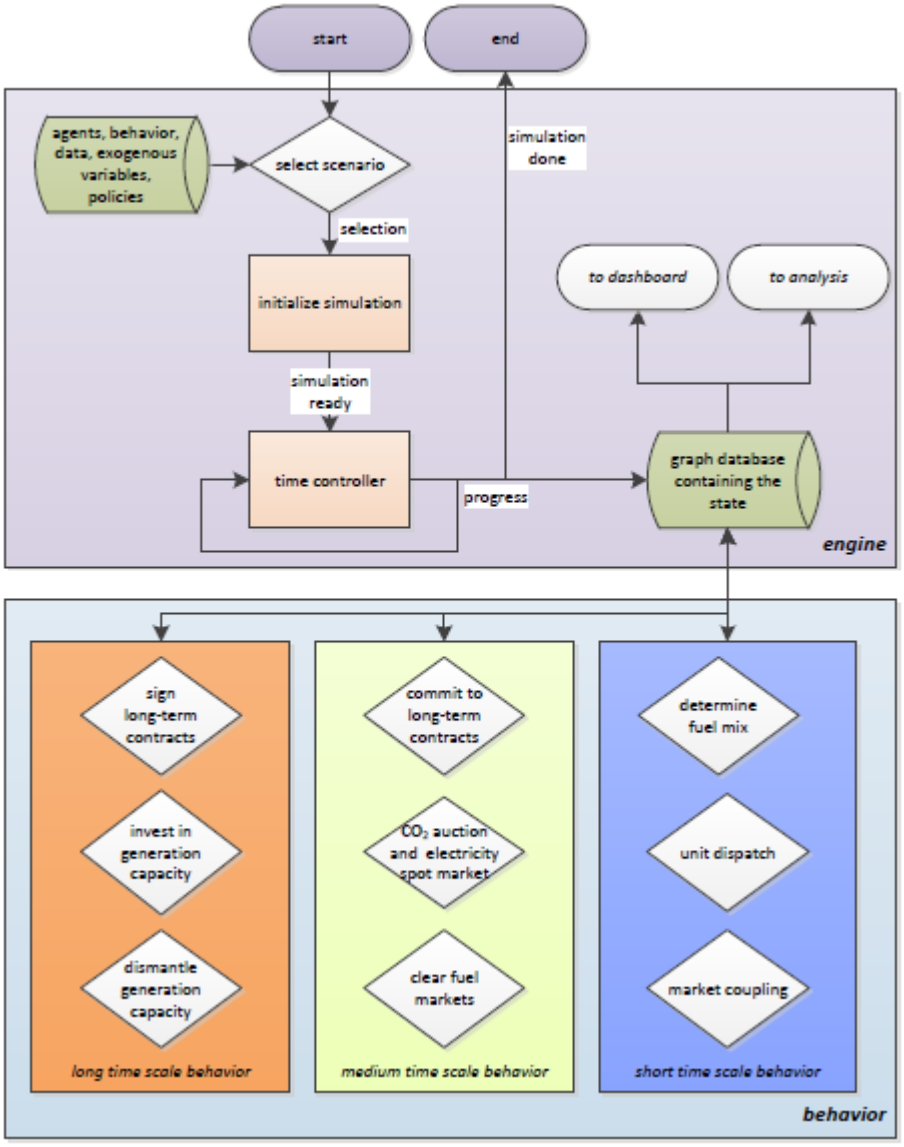
In this chapter a schematic overview of the designs of the alternative energy models – which were used for the comparison study in chapter 7 – are shown in this appendix. First the design of the Power2Sim model is shown, then the EMLAB design and as last the Plexos design.

Appendix I.1. – Power2Sim



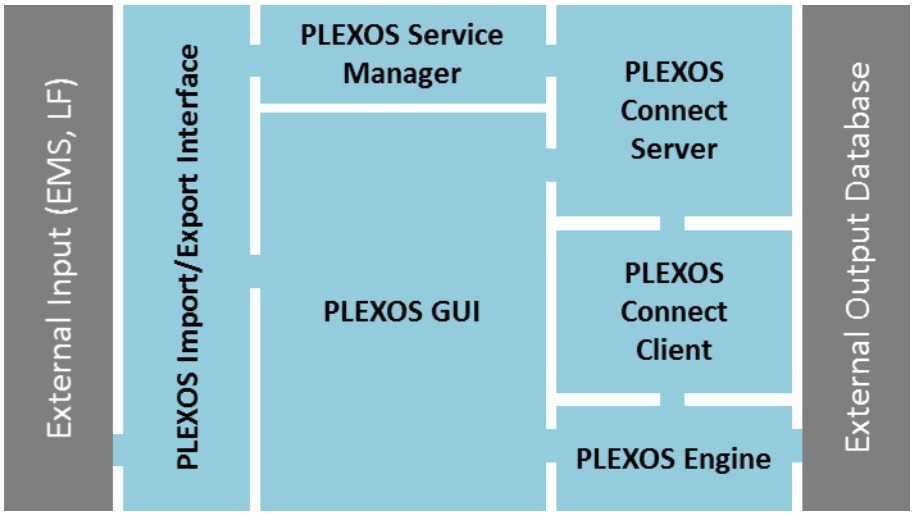
(Energy Brainpool, 2015)

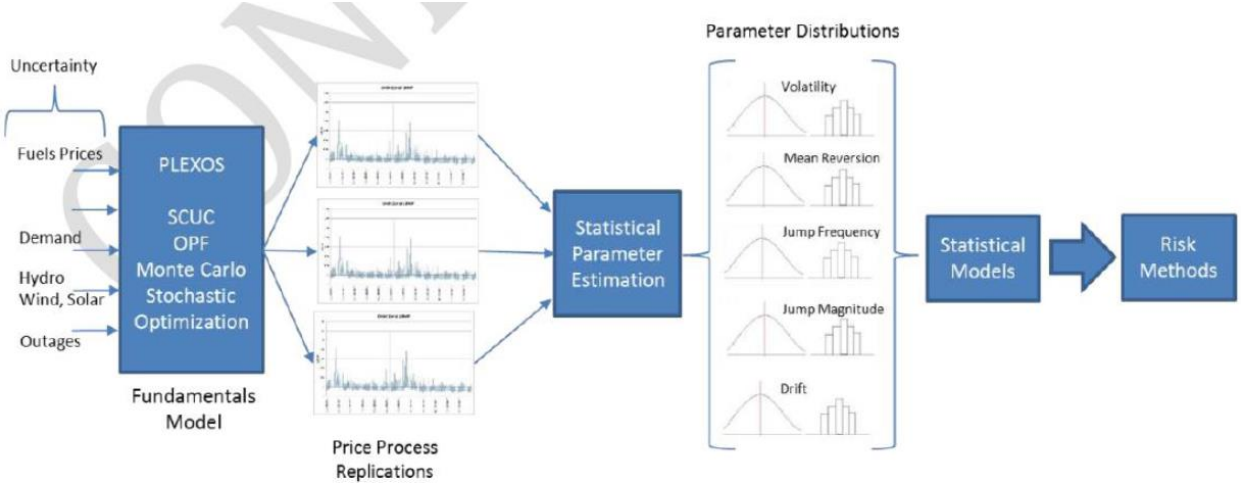
Appendix I.2. – EMLab



(Delft University of Technology, 2015)

Appendix I.3. – Plexos Energy Exemplar





(Energy Exemplar, 2015)