Influence of capacity markets on the development of electrical energy storage

An Agent-Based simulation study into the long term effects of a capacity market on electrical energy storage.
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Acknowledgements

Before you lies the result of my graduation project of the past 7 months. However this project cannot only be seen as the final result of these 7 months of work but even more as the result of 7 years studying at the faculty of Technology, Policy and Management of the TU Delft and I am very proud to present this final work of my study to you all.

During my study I got interested in answering questions regarding the world’s energy system and how this would look like in the future. With the ever-increasing demand for energy, the depletion of fossil fuels and growing environmental concerns due to the use of fossil fuels, I think the question of how we are going to assure the energy supply in the future is one of the biggest challenges we face at the moment. Because of this I am very happy that with my graduating project I was able to contribute to these questions, even though it was only for a very small part.

Although solely my name stands on the cover, this work would not have been possible without the contribution of many others. At first I want to start with thanking the committee members of my graduating committee.

At the start of my graduating process I was looking for a project on the subject of the long term strategy of the Dutch/European electricity markets regarding sustainability and via Paulien Herder I got the idea to use the Delft Plan as a starting point. I want to thank her for this great idea that fitted exactly the description of my desired graduation project! Besides I want to thank her for all the valuable feedback!

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Sophie Kerckhoffs
Delft, September 2015
Summary

In the past years some powerful drivers have led to the call for a change of our energy system. Drivers such as the dependence of imported oil and gas, the depletion of this oil and gas, and the rise of atmospheric concentrations of CO\(_2\) have led to the promotion of Renewable Energy Sources (RES). The European Union has established the 20-20-20 targets, which are “mandatory targets consistent with a 20% share of energy from renewable sources by 2020”. However this growing share of RES in the electricity markets in combination with the liberalized energy markets in Europe, raise concerns about the security of supply in future electricity markets. The reasons for this are the variability and unpredictability of RES. The TU Delft in combination with Roland Berger have developed the so called Delft Plan. In this Delft Plan a vision is presented how the Netherlands can anticipate on these complex system changes in the electricity markets. The Delft Plan aims at a fully sustainable energy system in 2050. The concepts conversion, transport, system integration and electrical energy storage (EES) are important to guarantee security of supply in this fully sustainable energy system.

EES capacity is one of the measures that is mentioned in The Delft Plan that can provide the needed flexibility to cope with the variability and unpredictability of RES, however, the amount of installed EES capacity grows much slower compared to the amount of installed RES capacity. In other words, RES are growing much faster than the development of new EES capacities can follow to provide the needed flexibility. Another measure of safeguarding the security of supply at this moment, is flexible capacity that could be provided by thermal generators. To secure investments in thermal generators several European countries envision the institutionalization of a capacity market in electricity markets with a growing share of RES. Capacity markets can be defined as a quantity based capacity mechanism where administratively an obligation exists for the demanding parties to buy supply capacity so a certain reserve margin of generation can be met.

Therefore, a capacity market can be seen as an institutional measure that can provide flexibility to electricity markets and EES can be seen as a technical measure that can provide flexibility to electricity markets. Because of these qualities it can be argued that they can be seen as substitute measures for each other. This creates the risk that the need for EES capacity decreases when a capacity market is introduced, leading to a decrease in investments in EES capacity. On the other hand it can be argued that with the introduction of a capacity market, investments in EES increase. Capacity markets provide payments for capacity and this capacity can also be delivered by EES. Such payments can be particularly important for EES, which may rely to a greater extent than traditional generators on payments for societal benefits.

It is unsure what the influence is of a capacity market upon the development of EES would be. This leads to the following research question: “How does a capacity market influence the development of EES capacity, if the share of renewable energy sources will grow as envisioned in the Delft Plan?”. To research this, an extension is built for the existing Energy Modelling Laboratory (EMLab) - Generation model. The EMLab-Generation model is an agent-based model which can simulate a typical European electricity market.
market. With this model the effects of different policy measures on the long-term development of the European electricity markets can be researched. A capacity market module was already incorporated in this EMLab-Generation model. The extension that was build consisted of an optimization model that stimulated the effects of EES capacity in an electricity market.

To answer the research question an experimental set-up was developed so that the EMLab-Generation model could simulate an electricity market with EES capacity, a capacity market and a combination of both. This electricity market was set-up along the lines of the Dutch electricity market. In this experimental set-up two hypotheses were developed. The first hypothesis states that because EES can provide peak capacity, a capacity market could have a positive influence on the development of EES. The second hypothesis states that a capacity market and EES can be seen as substitutes for each other and because of this the need for EES decreases with the introduction of a capacity market. These hypotheses were tested by looking at seven different indicators divided over three categories:

- The first category looks directly at revenues and profit of the EES operator to see if there is a difference between EES capacity with and without a combination of a capacity market. For this category the difference between the group of scenarios with 1) only EES capacity and the group of scenarios with 2) EES capacity and a capacity market is considered.
- The second category looks at the influence of the combination of a capacity market and EES on the electricity market itself. The indicators supply ratio, the ratio between RES and fossil fuel generation, average electricity price per year and price volatility fall under this category.
- The last category looks at the consumer variable costs to consumer.

The outcomes of the experiments show that the results of the scenarios with the combination of a capacity market and EES capacity, do not differ significantly from the results of the scenarios with only EES capacity. From these results is concluded that a capacity market does not have a positive influence nor a negative influence upon the development of EES capacity. So both hypotheses 1 and 2 are disproved by the results of the experiments.

However it can be concluded that when EES capacity is installed this reduces the need for a capacity market. The outcomes of the scenarios with EES capacity do differ substantially from the “baseline” scenario and the “only capacity market” scenario. The question whether a capacity market has an influence on the development of EES capacity can also be reversed. An increase in price volatility is one of the reasons that a capacity market is maybe needed and from the model results can be concluded that EES capacity decreases the price volatility in an equal way compared to a capacity market. This means that when there is EES capacity installed, this reduces the need for a capacity market when looking at price volatility. From the results of the experiments it can be seen that the effects of a capacity market on the supply ratio become smaller with the combination of EES and a capacity market. So here the same line of reasoning can be used as when there is EES capacity is installed; the need for a capacity market reduces because the EES capacity has the same or even a more positive effect on the supply ratio compared to a capacity market.

For policy makers these results mean that EES capacity can have the same influence upon the security of supply and price volatility as a capacity market. Therefore, the need to implement a capacity market in
the Netherlands would decrease if EES capacity is installed. However, a major drawback for EES capacity is the fact that it is not profitable. This means that without significant improvement in the fixed costs or subsidies from the government there could never be a profitable business case for EES capacity. Besides flexible capacity and EES capacity, the needed flexibility in the electricity market could also be provided by other measures like interconnection capacity, demand response and conversion of energy sources. More research is needed to see if these measures could have the same influence on the security of supply and price volatility as EES capacity and a capacity market.
## Abbreviations

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<tbody>
<tr>
<td>ABM</td>
<td>Agent-Based Modeling</td>
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<tr>
<td>APX</td>
<td>Amsterdam Power Exchange</td>
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<td>CAES</td>
<td>Compressed Energy Air</td>
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<td>CM</td>
<td>Capacity Market</td>
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<td>EES</td>
<td>Electrical Energy Storage</td>
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<td>EMLab</td>
<td>Energy Modelling Laboratory</td>
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<td>ETS</td>
<td>Emission Trading System</td>
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<td>EU</td>
<td>European Union</td>
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<td>EWEA</td>
<td>European Wind Energy Association</td>
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<td>FIT</td>
<td>Feed-in Tariffs</td>
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<tr>
<td>NYISO-ICAP</td>
<td>The New York Independent System Operator (NYISO) Installed Capacity market</td>
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<td>OM</td>
<td>Operation &amp; Maintenance</td>
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<tr>
<td>PCS</td>
<td>Power Conversion System</td>
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<td>RES</td>
<td>Renewable Energy Sources</td>
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<td>TPM</td>
<td>Technology, Policy and Management</td>
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<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
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<tr>
<td>TU Delft</td>
<td>Technical University of Delft TU Delft</td>
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<td>UML</td>
<td>Unified Modeling Language</td>
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Chapter 1

Problem Definition

This chapter aims at giving an insight in the motivation for the research that is reported in this thesis. This is done by first sketching the context of the problem whereupon the problem is defined in the problem definition. The problem definition forms the basis of the research objective of this thesis which leads to the main and sub research questions.

1.1 Context

Two important developments occurred in the past decades in the electricity sector. On the one hand there was the liberalization of electricity sector. Over the past decades wholesale electricity markets have emerged in several countries because of this liberalization trend, that started in the late 1980s in the UK (Haas, 2014; Simoglou, Biskas, Vagropoulos, & Bakirtzis, 2014). One of the major changes that was brought about was a change in price regimes. Beforehand the price of electricity was determined by a regulated tariff, which was calculated by dividing the total costs of supplied energy by the number of kWhs sold (Haas, 2014). After the liberalization prices were determined on competitive wholesale markets that result in market clearing prices that generally reflect the marginal costs of generation (Chao, 2011). In parallel to this development increasing environmental concerns have led to the promotion of Renewable Energy Sources (RES). The European Union (EU) has established the 20-20-20 targets, which are “mandatory targets consistent with a 20% share of energy from renewable sources by 2020” (European Commission, 2013). So far the share of RES in most European countries has been relatively low, but countries have put numerous support schemes in place to increase this share of RES. These measures resulted in a grow in RES. In 2009 60% of the newly installed capacity in Europe came from RES and in 2010 the renewable energy share in Europe was 12,7% (European Commission, 2013). These two phenomena in the energy markets developed in parallel, however they are not fully compatible with each other. RES have different characteristics than regular fossil fuel sources, - such as production variability, low predictability, zero-marginal-cost of generation, and strong site-specificity - and the current electricity markets are not optimally designed for efficient operation and adequate investments of large shares of RES (Henriot & Glachant, 2013). This has led to uncertainties about how the energy market should look like in the future.

1.1.1 The Delft Plan

The Technical University of Delft in cooperation with Roland Berger developed the so called Delft Plan in which they outline a framework stating how the Netherlands can play their role in the future energy system and energy industry. From this vision different policy strategies can be developed about technology development and the role of the Dutch government as unifying actor between the decentral energy system and the transnational energy systems. The Delft Plan states that the Netherlands can benefit from the long term implementation of a truly sustainable energy management system, because of its natural strengths. By building upon its natural strengths – like an advantageous geographical location in the middle of the different Northwestern European energy markets, a high-quality infrastructure and a strong sense of
mercantilism – the Netherlands can play a central role in the European energy system as the "Energy Gateway" for Northwest Europe. New energy and material flows, that come together in the Netherlands ask for new (energy) conversion- and storage-techniques and system flexibility (for the integration of renewable energy sources). Together this could form the basis for the Netherlands as the Energy Gateway of Europe. (TU Delft, 2014).

The Delft Plan does not prescribe the energy transition but indicates how the Dutch energy system and industry can adjust and prepare for this transition. The ambition which is pronounced in the Delft Plan is to achieve a fully sustainable energy system in the Netherlands by 2050. To realize this ambition a combination of 4 main elements is proposed:

1. **Storage of energy, in order to compensate for fluctuations in demand to supply in Northwest Europe**: The Netherlands will store energy in all kinds of forms, from small-scale to large-scale installations, central and decentral and for use on different timescales.

2. **Conversion, to increase flexibility**: The Netherlands will focus on small- and large-scale conversion of electricity into hydrogen, and thereafter methane, ammonia and other fuels, for storage and direct consumption purposes.

3. **Trade; to match complex supply and demand patterns**: The Netherlands will match supply and demand patterns and will operate as energy arbiter over time, type of energy and geographic dimensions based on conversion and trade. Besides this the Netherlands will provide the physical transport infrastructure to make trade possible.

4. **Valorization of biomass and geothermal resources**: The Netherlands will optimal utilize its natural resources such as biomass and geothermal resources.

The Delft Plan can be seen as a starting point for further development of the shared strategies of the Dutch government, market players and research institutions. This shared strategy could be a starting point to help harmonize the regulatory regimes across the EU or at least Northwest Europe and reduce regulatory risk. These are factors that are often discussed in literature which can improve the investment climate for investors in RES (Meulman & Méray, 2012). Improving this climate could trigger more investment in RES, which could help reach the mandatory targets of the European Union.

### 1.1.2 Renewable Energy Sources and Flexibility

An important question that can be asked is how to adjust and prepare the Dutch electricity market for a fully sustainable energy system in 2050. With the introduction of RES into the liberalized electricity market some problems have emerged. One of these challenges is the concern that the variability of RES has a negative effect on the reliability of the electricity grid. Because the wind does not always blow and the sun does not always shine, the risk is created that demand cannot always be met and this calls for more flexible capacity that can cover the fast fluctuating residual load when a generation mismatch occurs (Drury, Denholm, & Sioshansi, 2011). This flexible capacity could, among other things, be provided by Electricity Energy Storage (EES) or fossil fuel generators (Cutter, Haley, Hargreaves, & Williams, 2014).
The goal that is stated in the Delft Plan is to reach a fully sustainable energy system by 2050. Because fossil fuel generators are not sustainable, EES capacity is preferred from these two measure for providing flexible capacity. However, the development of EES capacities is lagging behind on the development of RES. At this moment the vast majority of electricity that is stored, is stored by pumped hydro storage plants (over 99%) and it can be expected that in the coming years this will be the only EES possibility that is available at reasonable capacities (Staveren, 2014). The projection is that the pumped EES capacities will nearly double in 2020, compared to 2005 in the EU. But if this is related to the total installed capacity of RES, it can be seen that it will shrink from 10.7% to only 7.2% in 2020. This shows that RES are growing much faster than the development of new pumped storage capacities can follow (Brauner et al., 2014). This development is shown in Figure 1 (Brauner et al., 2014).

![Figure 1 Development of pumped storage power in relation with development of RES](Brauner et al., 2014)

Because of the lag in development of EES capacity, another solution has to provide the required flexibility to the electricity system in the coming years. As mentioned before this can be done by thermal generators. However, in the current electricity market large shares of RES price these thermal generators out of the market. In the current electricity markets electricity plants are dispatched in such a way that the lowest possible costs of production (marginal costs) are attained at each moment. Because of this, power plants with the lowest marginal costs are put into production first. Features of RES are high capital costs but low operational and fuel costs, especially for intermittently renewables such as wind, solar or hydro, which have zero fuel costs (Klessmann, Nabe, & Burges, 2008). For that reason RES will come first in the merit order of the power plant dispatch and push nuclear and fossil fueled generation out of the market. Besides that, RES will also influence the costs of fossil fuel production. This is because of the fact that fossil fuel generators have much lower full load hours with RES in the merit order, yet the revenues that are earned in these hours must cover both the fixed and variable costs (Haas, 2014). Increasing uncertainty of potentially lower prices and lower load factors for conventional power plants, drive the so called “missing-money” problem (Henriot & Glachant, 2013). The missing-money problem can be seen as the concern that dispatchable power plants, being used for back-up capacity, might not recover their investment costs in the future and this can have a negative influence on the security of supply in the future (Haas, 2014).
A solution for this missing-money problem is a so-called capacity remuneration mechanism. Capacity mechanisms are policy tools that aim at providing incentives for investments into capacity reliability both over the long-term and short-term (Iychettira, 2013). One capacity mechanism that is envisaged in several European countries is a capacity market. Capacity markets can be defined as a quantity-based capacity mechanism where administratively an obligation exists for the demanding parties to buy supply capacity so a certain reserve margin of generation can be met (Bhagwat, Iychettira, & De Vries, 2014; Iychettira, 2013). These capacity markets give an incentive for investors to invest in thermal generators as flexible capacity.

1.2 Influence of Capacity Markets on EES Development

As described in the previous section the development of EES capacity and the introduction of a capacity market can both provide flexible capacity for the electricity market. Although a capacity market can be seen as an institutional measure and EES capacity can be seen as a technical measure. Because of this they can be seen as substitutes measures for each other. This creates the risk that the need for EES capacity decreases when a capacity market is introduced, leading to a decrease in investments in EES capacity. The European Wind Energy Association (EWEA, 2013) argues that “As national practice shows, capacity remuneration mechanisms turn out to be complex with free riders and other externalities resulting in further market distortions. Most notably, capacity remuneration mechanisms remove incentives for investments in cross-border grid infrastructure, demand-side response and energy storage.” On the other hand it can be argued that with the introduction of a capacity market, investments in EES increase. Capacity markets provide payments for capacity and this capacity can also be delivered by EES. Such payments can be particularly important for EES, which may rely to a greater extent than traditional generators on payments for societal benefits (Cutter et al., 2014).

Summarizing; to reach the goal of a fully sustainable energy market by 2050 that is mentioned in the Delft Plan, more flexible capacity is needed. This flexibility can, among other thing, be provided by EES or flexible capacity, which can be secured by a capacity market. However it is unsure how both measures influence each other. Will the development of EES provides enough flexible capacity to deal with large shares of RES, or do we need a capacity market to provide incentive for more thermal capacity? And if a capacity market is introduced what will be the influence on the development of EES and vice versa?

1.3 Problem Formulation

The ambition as formulated in The Delft Plan is to reach a fully renewable energy system in 2050 which is able to deal with the intermittency of RES by a combination of storage, conversion, and trade. But how does the current electricity market have to be adjusted to reach this ambition? An important problem with the introduction of RES is that the intermittency of RES requires more controllable resources to incorporate RES in the electricity grid. The Delft Plan does not describe the exact energy mix in the future, but states that whatever future energy system is in place, storage, conversion and trade are necessary. However at this moment the development of EES lags behind on the development of RES. A second way to provide more flexible capacity is the introduction of a capacity market. However a capacity market secures fossil fuel generators which are not sustainable and the risks exists that a capacity market has a negative influence on EES capacity.
At the faculty of Technology, Policy and Management (TPM) research is conducted with the central question “what is the combined effect of different policy instruments (in particular carbon policy and renewable energy policy) upon electricity markets, in isolation and in combination with neighboring electricity markets with different policies” (De Vries, Chappin, & Richtstein, 2013). To address this issue an agent-based simulation model is developed, which is called EMLab-Generation. The base model of the EMLab-Generation model enables to simulate two interconnected electricity markets in typical European countries. The model is designed to analyze the aggregate effects of investment decisions of electricity generation companies under different policy scenarios and market designs in order to assess the possible effects of different policy instruments on the long-term development of European electricity markets (De Vries, Chappin, et al., 2013). One of these policy instruments that is researched is different capacity mechanism in combination with the cross-border effects of these mechanism (Bhagwat et al., 2014).

Currently virtual agents in the model can own different power plants with different generating technologies, however it is not possible for the agents in the model to own or develop EES capacity. An interesting expansion of this model is the introduction of an EES module. This would allow to study the development of EES capacity in combination with the development of possible pathways of the Dutch electricity market. This could gain more insight whether a capacity market is a suitable policy measure for the Dutch electricity market on the route to a fully sustainable future. A more detailed description of this proposed expansion is given in chapter 3 where the methodology is discussed.

1.3.1 Research objective
Based upon the problem description and the identified knowledge gaps, the research problem can be recapitulated by formulating the research objectives and relevance.

This research aims at performing a first exploration into the influence of a capacity market on the development of Electrical Energy Storage in the context of the Dutch electricity market. This will be done by building a general EES extension to the EMLab-Generation model after which the parameter set-up for the experiments will be based upon the Dutch electricity market. Policy recommendations concerning the effect of capacity markets on EES will be based on the simulations of these experiments.

The social relevance of this research project is the insight that will be gained in the effect of a possible introduction of a capacity market in combination with growth in RES and EES capacity in the Netherlands. These insights can be used by policy makers to make more substantiated decisions about the energy transition in the Netherlands and the role the Netherlands can play within the energy system of Europe in the future. This is important for the social welfare because the energy transition affects the whole society. With the introduction of RES, the risks of more volatile energy prices and more extreme price spikes arises, which has a great influence on the costs of energy for households but also for the Dutch industry. A better understanding of the influence of policy instruments can help policy makers to better prepare for these risks.

The scientific relevance can be found in the new functionalities and possibilities of the EMLab-Generation model. With the EMLab-Generation model, a new type of model-based policy support is developed. Because the interactions and blend impacts of multiple policy instruments can be modelled, an agent-based model is able to stimulate the real-world interaction in more detail compared to an equilibrium model. This type of model has only been used to a limited degree to model European electricity markets (De Vries, Chappin, et al., 2013). So by extending this model to include at a capacity market in combination
with the growth of EES possibilities for the transition period, new scientific insights can be obtained that can be used in further research and discussions concerning the usefulness of capacity markets as a policy instrument in the current liberalized energy markets.

1.4 Research questions & Approach
The main research question for this graduation project is formulated as follows:

**How does a capacity market influence the development of electrical energy storage capacity, if the share of renewable energy sources will grow as envisioned in the Delft Plan?**

The research question is divided into three sub research questions:

1. How could the incorporation of EES capacity in the Dutch electricity system, and the relations between EES capacity and capacity markets be conceptualized?
2. How could the EMLab-generation model be extended by incorporating EES capacity?
3. How can the possible effects of capacity markets on the development of EES capacity be explored?

To answer these research questions this research is divided into 4 parts, as shown in Figure 2. In the first part a literature study is performed were the current power system is explored whereafter the growing role of RES in this current system is researched. The challenges that follow from this growing role of RES and at last the expected development and role of EES and capacity markets in this system are described. Besides this literature study a desk research are conducted into the current EMLab-Model. The literature study and desk research both provide insides that are used for the second part of the research. The second part of the research exists of the conceptualization, formulization and verification of the new additions of the EMLab-Generation model. The result of this part is an EES extension of the EMLab-Generation model and this model is used in part 3 of this research. In part 3 the experiments are set-up and the results from the simulations with the experimental set-up are analyzed. The literate study of part 1 also provides insights that are used for the experimental set-up. In the last part of this research the conclusions are drawn, recommendation for further research are given and a reflection is given upon the total research project.
Figure 2 research overview
PART I: LITERATURE & DESK RESEARCH

Part I
- Desk research EMLab - Generation
- Literature study

Knowledge EMLab

Part II
- Conceptualization
- Formulation
- Verification

Knowledge EMLab

Part III
- Results
- Validation

Parameter setup

Part IV
- Reflection
- Conclusions

Experimental setup
As explained in chapter 1 the power sectors has undergone two major changes over the past decades. On the one hand the liberalization of the electricity markets and on the other hand the introduction of more RES due to the growing environmental concerns. The growing shares of RES intensifies the variability, uncertainty and intermittency of the power supply, disrupting the optimal operation of conventional power systems and grid reliability (Zakeri & Syri, 2015). On the other hand more competition in the electricity markets, because of the liberalization, resulted in high capital cost requirement for meeting peak demands and volatile electricity prices. This new setting has imposed technical, economic, institutional, and environmental challenges for secure supply of electricity (Zakeri & Syri, 2015). The goal of this chapter is to determine the role of EES in this chancing power sector. This is done by first looking at the current situation of the electricity markets and its changes, zooming in at the growing share of RES. In the next section the challenges of these changes are discussed after which capacity markets and EES will be discussed as solutions for these challenges.

2.1 Electricity system and recent changes
The liberalization of the electricity markets resulted in a higher complexity of the entire power system due to the breakdown of the value chain of electricity, which used to be highly integrated. To analyze the electricity systems an distinction is made between the technical and institutional layer of this system. The technical layer is the physical supply chain of electricity which consists out of the electricity generators who generated the electricity, the transmission and distribution networks which transport the electricity and lastly the load, being the electricity customers who consume the electricity. The institutional layer consists out of the actors who control the physical layer and all the other actors that are involved in the electricity system (De Vries, Correljé, & Knops, 2013).

2.1.1 Current electricity systems
Figure 3 gives an overview of the technical and institutional layer of the Dutch electricity system. The single arrows indicate the direction of trade in electricity. Electricity is generated by electricity generators that are owned by generation companies. The market decides upon the quantity of electricity that each company may sell at each moment of time, based upon the prices that are offered by the generation companies. “The electricity market” itself consists of multiple related market of which the bilateral market is the greatest in volume. In this market electricity is directly sold by generating companies to their customers. Customers consist out of large electricity consumers, traders or supply companies who supply electricity to small and medium size customers. Contracts that are sold on this market have mostly contract times that are less than one year. Besides the bilateral market there is a power exchange. In this power exchange electricity is traded on an hourly basis, which means that the market is cleared for each hour of the day separately. Producers bid with a certain volume at a certain price and the market is cleared for the load that is determined by the consumers. This process results in one price for each hour. The need for such a short time market is created by sudden changes in demand and supply and the fact that energy cannot yet be stored in a economically
viable way. As a result, the value of electricity is much higher during peak hours and prices can be highly volatile. It can be assumed that in this market the market price is equal to the marginal costs of the most expensive generator in the merit order. The sold electricity is transported via the transmission and distribution network to the consumers. A technical characteristic is that these networks should always be balanced. This is the task of the Transmission System Operator (TSO) for the transmission network and distribution network manager for the distribution networks. To do so the TSO has operating reserves which are contracted on the balancing market. Besides the task of balancing the transmission network, the TSO also has to manage the transmission network and manage the import capacity of the interconnectors (De Vries, Correljé, et al., 2013). TenneT is the TSO for the Netherlands and large parts of Germany. TenneT has five main strategic priorities including “facilitate spread and store”. This means that to integrate RES TenneT states that distribution and sufficient storage is necessary to better balance the grid an create access to RES. This will result in less volatile supply, large storage capacity and different demand curves, thereby helping to realize Dutch renewable energy targets in a cost-efficient way (TenneT, 2014). However to execute the goals that are formulated in the strategic priorities TenneT has to focus on a number of enabling factors. One of them is regulation and legislation which states that TenneT’s capital and operating expenditures should be managed efficiently, while providing adequate returns to stimulate new investments in the electricity infrastructure. This means that TenneT has to have a transparent and predictable benchmarks based on costs and performance (TenneT, 2014)

The current electricity market can be seen as a so called energy-only market. In an energy-only market the electricity price only indicates the price of energy; the price for reliability of the system is not taken into account. This means that the electricity price in an energy only market merely reflects the marginal costs of the production of electricity and that there is no premium included for the availability of unused production capacity (De Vries, Correljé, et al., 2013). Consequentially, the capital costs of generation must be recovered exclusively via the electricity prices (Iychettira, 2013).

2.1.2 Increasing share of RES
In the past years some powerful drivers have led to the call for the change of our energy system. Drivers such as the dependence of imported oil and gas, the depletion of this oil and gas, and the rise of atmospheric...
concentrations of CO₂ have led to the promotion of Renewable Energy Sources (RES) (European Commission, 2006). The European Union has established the 20-20-20 targets, which are “mandatory targets consistent with a 20% share of energy from renewable sources by 2020”. So far the share of RES in most European countries has been relatively low, but countries have put numerous support schemes in place. This has resulted in a growth in RES. In 2009 60% of the newly installed capacity in Europe came from RES and in 2010 the renewable energy share in Europe was 12.7% (European Commission, 2013).

2.2 Challenges

The introduction of RES has a profound impact on the merit order of the current electricity market and the electricity prices that are cleared on this market. Firstly it has an impact on the dispatch of power plants in the electricity systems (Spiecker & Weber, 2014). In the current electricity markets electricity plants are dispatched in such a way that the lowest possible costs of production (marginal costs) are attained at each moment. Because of this, power plants with the lowest marginal costs are put into production first. Features of RES are high capital costs but low operational and fuel costs, especially for intermitted renewables such as wind, solar or hydro which have zero fuel costs (Klessmann et al., 2008). For that reason RES will come first in the merit order of power plant dispatch. This lowers the capacity factor of conventional generators and reduces the time that they can sell electricity to the market consequentially this will lead to a reduction in energy revenues (Brouwer, van den Broek, Seebregts, & Faaij, 2014). As a result nuclear and fossil fueled generation are pushed out of the market. Secondly, more RES requires more flexibility of the total energy system. Due to the more variable output of RES, conventional generators also have to operate with greater flexibility. This means more starts/stops per day and more often ramping up from minimum to maximum capacity output. This will probably lead to higher operation and maintenance costs and lower mean time between failures, (so lower availability). This means that conventional power plants will operate less often and with higher operating costs, reducing the profits of these plants (Griffes Peter H, 2014). Thirdly, the low marginal costs of RES lead to low electricity prices. On top of that support schemes isolate RES from market signals leading to the problem that prices can decrease to zero or even negative prices on some days (Klessmann et al., 2008). Summing up, conventional generators are needed to balance renewable intermittency, but will face lower output, higher O&M costs and lower energy prices.

There are many modeling studies that substantiated these conclusions, for example a study performed by Green and Vasilakos (2010) used historical wind data in the UK and existing & currently planned wind capacity to model the effect of wind energy on the wholesale spot prices in Great Britain. The conclusion was that one could see wide variations in the daily profitability of electricity generation due to highly volatile spot prices. Also in the model of Klinge et al. (2010) an increase of volatility of electricity prices is seen with an increase of wind energy.

The introduction of RES in the current electricity market leads to increased price volatility and the decrease of security of supply. This effect is even further strengthened by the support schemes for RES. To stimulate the development of RES, countries implemented renewable policies by means of different support schemes. These support schemes proved themselves to be very effective in stimulating the development of RES, but these support schemes kept RES isolated from the market signals (Hiroux & Saguan, 2010). In the initial development stage of RES this isolation of market signals has been accepted. However now RES are on the verge of a new large-scale development phase, RES integration costs due to variability and low predictability needed to be reduced via the right market signals.
In Europe three different types of support schemes can be distinguished. The first type is feed-in tariffs (FIT). Which guarantee a legally regulated price per kWh for which a RES producer can sell their electricity to the electricity demanders. The second, similar, type of support scheme are feed-in premiums in which RES producers sell their produced energy on the electricity markets and receive a fixed premium per kWh on top of the electricity price. The last support scheme are quota obligation or green certificates, these are based on a renewable generation obligation imposed upon suppliers. To fulfill this obligation, suppliers can either produce renewable electricity or buy the equivalent in green certificates in a special green certificate market (Hiroux & Saguan, 2010)(Klessmann et al., 2008). Figure 4 gives an overview of the different support schemes. Different support schemes give different exposures to market signals. RES generators are isolated from market prices and risks with feed-in tariffs because the supplementary payment varies with the market price and so the market itself carries the risk. The market risks are higher with feed-in premium because the price producers receive varies equally to the market price. With quota schemes there are two markets created, but the risks can be seen equal to feed-in premiums (Klessmann et al., 2008).

All these support schemes undermine the market signals given by the market, such as prices, to electricity producers. Some argue that RES producers have no means to react to market signals because in the short-run RES producers have high incentives to produce whenever the source (wind, solar, tides etc.) is available and without regard to the electricity price given its marginal costs that are equal to zero. Many studies are being conducted with the aim of finding the right balance between more market signals for RES producers and the risks that are generated by these signals, it is very important that these market signals do not undermine the effectiveness of the support schemes of the past years (Batlle, Pérez-Arriaga, & Zambrano-Barragán, 2012; Henriot & Glachant, 2013; Hiroux & Saguan, 2010; Klessmann et al., 2008; Riesz, Gilmore, & Hindsberger, 2013).

In the previous section the issue of price volatility caused by the low marginal costs of RES and the influence of different support schemes is discussed. Besides these issues, RES will also influence the costs of fossil fuel production. The reason of this is that fossil fuel generators have much lower full load hours when RES are integrated in the market, yet the revenues that are earned during these hours must cover both the fixed
and variable costs (Haas, 2014). This leads to a lacking contribution margin to fixed costs for fossil fuel generators. In the long-term these two issues drive the so called “missing-money” problem (Henriot & Glachant, 2013). The missing-money problem is the concern that dispatchable power plants, who are used as back-up capacity, might not recover their investment costs anymore and this can have a great influence on the security of supply in the future (Haas, 2014).

2.3 Solutions
To deal with the increasing variability and uncertainty it is argued that more flexibility in the power system is a necessity. In general four types of flexibility in the power system can be identified, namely flexible generation, electrical energy storage, interconnection capacity and demand response (Verzijlbergh, 2013). In this paragraph there will be looked at two of these four types; flexible capacity and EES.

2.3.1 Capacity markets
The structure of energy-only markets and the introduction of RES leads to the need for implementation of reliability in the market structure. To do so a type of policy instruments known as capacity mechanisms have been proposed, however previous research shows that there is no consensus on the effectiveness of these mechanisms, especially in combination with RES (Iychettira, 2013). There are several types of capacity mechanisms, price-based and quantity based mechanisms. One capacity mechanism that is envisaged in several European countries is a capacity market. Capacity markets are a capacity mechanism which works via adequation by volumes and it lets the price form for capacity by the market. In other words, in a capacity market, electricity producers are not only paid for selling electricity but also for the amount of capacity that they have available or plan to build. This gives additional assurance in the market for investors in power plants (Meulman & Méray, 2012). This market mechanism can be decentral with a mechanism which operates between energy traders and capacity providers, central via a national auction, and many mechanisms that lie in between (De Vries, 2007; Lyzwa & Mielczarski, 2014).

The capacity market mechanism that is modelled in the EMLab-Generation, and will be used in this research, is a centralized capacity market based upon the so called “New York Independent System Operator (NYISO) Installed Capacity market” (NYISO-ICAP). The NYISO-ICAP market design is a relatively simple design and it is also an example of a capacity market that is arguably well established and successful (Iychettira, 2013).

![Diagram of technical and institutional layer centralized capacity market](Figure 5 Technical and institutional layer centralized capacity market (Iychettira, 2013))
A centralized capacity market is a quantity based incentive where the quantity of the resource is administratively set by a central regulator. This means that the regulator of the capacity markets determines the total amount of capacity in the market. The price of this capacity is left to the market participants (Iychettira, 2013). The regulator determines the needed capacity by forecasting the peak demand and then adding an independent set reserve margin. Energy producers place volume-price bids in the capacity market. When a committed power plant is not available this results in a penalty for this energy producer. Capacity sales and purchases are conducted via transparent auctions. The reserve margin that is set by the regulator guarantees that investment signals appear before shortages occur (Iychettira, 2013). This principle of a centralized capacity market is shown in Figure 5.

Capacity market are already implemented in many countries around the world however, none of these capacity markets have been in place for a full investment cycle of electricity markets. So it is very difficult to currently derive any learning of the effects of these capacity markets on investments in flexible capacity and thus on the security of supply. Especially in combination with RES since in no country a capacity mechanism has been introduced to specifically cope with the problems of the short-term and long-term intermittency of RES (Meulman & Méray, 2012). In other words, it is currently difficult to learn from the effects of a capacity market - that is introduced to cope with fact that energy only markets do not cover for systems reliability and not because of the increased price volatility caused by RES - because these capacity markets are not yet in place long enough. It is even more difficult to say something about the effects of a capacity market in an energy market with an increased share of RES, because nowhere in the world a capacity market is already in place to cope with the problems of price volatility and the missing money problem caused by RES.

At the beginning of 2015 a capacity market was introduced in the UK to ensure power stations are always ready to generate enough electricity to meet the UK’s needs. Commission vice-president of the EU, in charge of competition policy, Joaquin Almunia said about this subject “The UK Capacity Market embraces the principles of technology neutrality and competitive bidding to ensure generation adequacy at the lowest possible cost for consumers, in line with EU state aid rules.”. However environment groups criticize the UK capacity market because old heavy pollutant coal plants are also eligible to apply for capacity payments and without these capacity payments these coal plants would probably closed. This will lead to the UK ending up with a more polluting energy mix throughout the 2020s than it otherwise could have (Hope, 2014). “The capacity market risks pushing up bills and holding up progress towards a decarbonized power sector by throwing money at the UK’s old, dirty coal plants,” (Chestney, 2014).

Some literature argues that capacity mechanisms are in a way subsidies to maintain a ready reserve of generation capacity, generally gas- or coal-fired plants because these can be switched on and off fairly quickly. In combination with the already in place support schemes for RES this contradicts the liberalization of the electricity markets (Buchan, 2013; Keay, 2013). This argument is substantiated by the research of Haas, Auer and Hartner (2014), who argue that capacity markets are a step back to a planned economy because of the quantity obligations who are imposed by the government, with – all in all – much higher costs for society. And in addition to pure power generation capacities other elements like smart grids, technical and economic demand-side management and short-term EES options will smooth a large part of the residual load profile (the difference between demand and supply from RES). Walter Boltz, Austria’s outspoken national regulator and member of the Council of European Energy Regulators argues, “We made the
problem ourselves with the growth in renewables, so let us think of how we can fix it without killing the market” (Buchan, 2013).

2.3.2 Electrical Energy Storage

In the previous sections it has become clear that the introduction of RES introduces new challenges for the electricity market and that flexible capacity is needed. This flexible capacity can be provided among others by both thermal generators and Electrical Energy EES. In this paragraph EES is discussed in further detail. EES can be employed in different ways to support the introduction of RES, for example relieving fluctuation suppression, low voltage ride through, and voltage control support; all resulting in smoother power outputs from RES (Zakeri & Syri, 2015). Because of the scope of this research this paragraph will however focus upon the application of EES: it can store electricity when there is an excess electricity production and discharge this electricity at any given time when for example demand is high and production is low. In this way energy production can be smoothed and eliminating the uncontrollability of RES, preventing power curtailment and oversized construction of power capacity (Zakeri & Syri, 2015).

Different EES technologies can provide a wide range of possibilities on different time scales. These possibilities can roughly be divided into three categories (Staveren, 2014). The first category is providing EES on a second to minute basis. As the grid needs to be in constant balance small variation in demand and supply will cause voltage and frequency variations on this small time scale. Using EES this way is called power quality support. A second time scale on which EES can be deployed is from minutes to one hour. EES can in this use case provide the same functionality as the reserve capacity that the TSO requires on the balancing market, this is called bridging power. Finally EES can be used for so called energy management, this means leveling out demand from hour to hour, day to day or even seasonal variations, this is also referred to as bulk energy EES (Staveren, 2014). Different types of EES technologies can provide these different services on different time scales. Which technology is best fitted for which services depends upon the characteristics of that technology such as the maximum capacity or the maximum discharge rate. In general different EES technologies can be defined by 5 characteristics, namely energy capacity, charging efficiency, discharging efficiency, charging rate and discharging rate (Korpaas, Holen, & Hildrum, 2003). These 5 general characteristics of EES technologies can be used to conceptualize different EES technologies in an agent-base model.

As mentioned earlier, EES can provide flexible capacity by storing electricity when energy prices are low (because of an excess in RES) and feeding this electricity back to the market when electricity prices are high. This is one of the reasons that the Delft Plan uses the argument that EES will be essential to maintain a high reliability of our energy system with high shares of RES (TU Delft, 2014). However the development of EES lags behind on the development of RES and electricity EES is not used on a large commercial scale at this moment. Currently over 140 GW of large-scale electricity EES is installed worldwide, making it a small share when compared with a total of 5550 GW of installed electricity production capacity. The vast majority, 99% of this 140 GW, is comprised of pumped hydro storage (Lott & Kim, 2014). One of the reasons that leads to EES not being used on a large scale is the fact that electricity is difficult to store. Most EES technologies first convert electricity in something else and later convert it back to electricity, leading to high energy losses (Staveren, 2014). As a result of the technical difficulties, most EES technologies are not yet matured. This can be seen in Figure 6 where some key technologies are displayed with respect to their associated initial capital investment requirements and technology risk versus their current phase of
development (Lott & Kim, 2014). A second reason that causes EES not being deployed on large scale, are the difficulties for economically analyzing the EES opportunities; benefits of EES are often uncertain and difficult to quantify. EES has the ability to provide multiple services such as load leveling, regulation and contingency reserves, and flexible capacity. For these services it is difficult to quantify the value streams without sophisticated modeling and simulations methods. Because of these difficulties utilities tend to rely on more traditional generation assets. This holds especially for regulated utilities whose risks are minimized and new technologies are adopted relatively slowly (Denholm, Ela, Kirby, & Milligan, 2010; Staveren, 2014).

2.3.3 Capacity market & Electrical energy storage
From this section it can be concluded that to deal with the increasing variability and uncertainty it is argued that more flexibility in the power system is a necessity. A capacity market can be seen as an institutional measure that can provide this flexibility to electricity markets and EES can be seen as a technical measure that can provide flexibility to electricity markets. A lot of research has been conducted towards these types of flexibility separately, however not a lot of research has conducted with the aim of studying the influence of these two types on each other. Especially the influence of capacity markets which can secure investment in flexible capacity upon more sustainable solutions as EES has not been given a lot of attention. As a result, the scope of this thesis will be limited to the influence of a capacity market upon the development of EES.

2.4 Conclusions
The goal of this chapter was to determine the role of capacity mechanisms and EES within the power system. It has become clear that both can provide, directly or indirectly, flexible capacity to the power system in different manners. To answer the research question an expansion to the EMLab-Generation model will be built for EES as capacity mechanism are already incorporated in the model in the form of a centralized capacity market. The focus in this chapter, regarding the conceptualization of the EES expansion, is the role of EES within the electricity system to store electricity when there is an excess and to discharge this electricity when there is a shortage. This can be done on different timescales, from seconds to seasonal EES, depending on the type of EES that is in place. Independent of the type of EES, EES technologies have 5 characteristics in common; energy capacity, charging efficiency, discharging efficiency, charging rate and...
discharging rate. These 5 characteristics will be taken into account in the conceptualization of the EES mode expansion together with the mechanism of storing electricity when there is an excess in electricity and discharging when there is a shortage.
For this research an extension to the EMLab-Generation model, which is developed on the faculty TPM of the TU Delft, will be built. The EMLab-Generation model is an Agent-Based model of two electricity markets which are interconnected by means of interconnectors. The main goal of the model is to analyze the aggregated effects of investment decisions of electricity generators under different policy scenarios and market designs in order to assess the possible effects of different policy instruments on the long-term development of the European electricity markets (De Vries, Chappin, et al., 2013). In the current model only electricity generation technologies are available and there is no possibility to simulate EES technologies. To research the effects of capacity markets on the development of EES an extra EES technology module will be added in which EES technologies will be incorporated into the EMLab-Generation model. In this chapter the basis of Agent Based Modeling will be discussed and a short description of the current EMLab-Generation model will be given.

3.1 Agent Based Modeling

The EMLab-Generation model is an Agent-Based model of two connected electricity markets. The electricity system can be described in terms of a complex adaptive socio-technical system. The physical layer of the electricity system consists of many technological artifacts such as power generating technologies, transmission lines, transformer stations, distribution lines etc. In this system fuel and renewable energy sources are transformed into electricity and this electricity is transported to consumers. In terms of a social system, the electricity system consists of many actors such as power generators, network operators, consumers, regulatory authorities etc. The operational decisions and investment strategies of these actors are influenced by institutions from local level to European and even worldwide level and by decisions that are made by other actors. Besides the operational and strategy decisions within the system, the total system also constantly changes. The electricity system evolved over many decades, constantly being re-shaped by the decisions of many actors in response to changes in economic conditions, user demands, societal priorities and institutional frameworks (van Dam, Nikolic, & Lukszo, 2013).

Agent-Based modeling is one of the most suitable ways of modeling these complex adaptive socio-technical systems such as the electricity system. In agent-based models, an agent is the software representation of some entity that completes an action or takes a decision, by which it effectively interacts with its environment (van Dam et al., 2013). This agent paradigm aligns with the concept of systems composed of multiple interacting social entities and technical subsystem and this concepts can be used to model these systems as long as the following conditions are satisfied (van Dam et al., 2013):
The problem has a distributed character; each actor is to some extent autonomous.

The subsystems (agents) operate in a highly dynamic environment.

Subsystems interaction is characterized by flexibility: it can result from a reactive or pro-active attitude, from a propensity to co-operate or to compete, or it can be the result of social interaction.

The electricity system satisfies all these conditions. Each actor in the electricity system is to some extent autonomous, electricity generators decide themselves how much electricity they bid into the market and consumers decide how much electricity they use etc. The electricity system is a highly dynamic environment which constantly changes and the subsystems interactions are characterized by flexibility, decisions of actors are influenced by the competition of the market and by institutions from local to worldwide level.

Now that we determined that Agent-Based modeling is a suitable way for modeling the electricity system we can look a little bit further what Agent-Based modeling means. Agent-Based models are models constructed from a bottom up perspective to discover emergent behavior, they examine the interaction of things instead of one particular thing or a collection of things to be replicated. Generally, agent-based modeling has no desired state or task to be achieved, instead they merely describing the entities and observing how they interact in order to explore the system’s possible states. Particularly this means that a set of agents are defined and a set of rules to which these agents should act. These agents can interact with each other, but they can also be influenced by the environment they interact in. The emergent behavior and possible states of the system can be analyzed and patterns, tendencies and frequent behaviors can recognized (van Dam et al., 2013).

For the EMLab-Generation model, Agent-Based modelling gives the possibility to capture the relations between actors in the electricity sector, that affect the long-term development of the electricity sector, instead of capturing behavior of these actors in formulas. This means that the outcomes emerge from the combined actions of the actors in the model instead of a result of equation-based calculations (De Vries, Chappin, et al., 2013).

3.2 EMLab-Generation model

As is become clear from the introduction, the aim of the EMLab-Generation model is to analyze the aggregated effects of investment decisions of electricity generators under different policy scenarios and market designs in order to assess the possible effects of different policy instruments on the long-term development of the European electricity markets. The base model enables to simulate two interconnected electricity markets and it can be used to analyze the effects of policy instruments upon CO₂ emissions, the volume of electricity generation, the price of electricity and the generation mix, and the effect upon investments in renewables. In the base model, the main agents are electricity generation companies and a single consumer agent who represents the aggregate demand of all consumers for electricity. The agents interact in two main markets, the electricity market and the CO₂ market. The model contains two separated electricity markets which are interconnected with interconnector capacity and one overall CO₂ market. The electricity generator agents make two types of strategic decisions:

1. The agent has to decide whether or not to invest in new power generation facilities.
2. If an agent decides to invest in new power generation facilities, it needs to choose a type of electricity generation technology.

Besides these two strategic decisions, power generators make three types of operational decisions:
1. Generators offer their electricity to the market at marginal costs plus a price markup. The marginal cost of generation is derived from fuel and CO₂ prices.
2. Generators determine and acquire the right amount of fuel based on their actual electricity production.
3. Generators determine the volume of CO₂ emission rights which they have to purchase. This is determined by an iterative process in which the arbitrage between the electricity and CO₂ markets is optimized.

The simulations of the model span over a couple of decades. Because of this the time step in the model is one year and every year the market is cleared and agents decide to whether to invest in new technologies.

The EMLab-Generation model is a general representation of an energy market model which enables to simulate two interconnected electricity markets in typical European countries. This means that the model itself is a generic model and that the parameter set-up of the model defines which specific electricity market/markets are simulated.

The above description forms the basis of the EMLab-generation model. To research the combined effect of different policy instruments, different modules that represent various energy and climate policies, can be switched on and off in the model. The two main modules so far constructed in the model are a module with different capacity mechanisms and a module that represent the EU emission trading system (ETS) for the reduction of CO₂ emittance or a CO₂ tax. An overview of the EMLab-Generation model and different modules is given in Figure 7.

In the base model there are two main algorithms, the market clearing algorithm and the investment algorithm. In the next paragraph the market algorithm is explained in more detail because this algorithm is important for the implementation of EES in the EMLab-Generation model.

![Figure 7: General overview EMLab-Generation model](image)
3.3 Electricity market algorithm

Electricity demand is in the EMLab-Generation model represented by a step-wise load duration function which is different per modeled zone (electricity market). The supply function is constructed by placing the generator bids in merit order. Generators place their bids based upon their marginal costs which are a function of the fuel prices and CO₂ price. The CO₂ price is constrained by the annual emission cap. An iterative process is used to determine the CO₂ price and the electricity price. The process is started with the CO₂ price of last year and with that price the markets are cleared. When the CO₂ emissions are higher than the cap, the CO₂ price is increased and when they are lower than the cap, the CO₂ is decreased. After this the markets are cleared again with the new CO₂ price, which leads to new emissions. This process is repeated until the CO₂ emissions are equal to the emission cap. This process is described in Figure 8 which gives an overview of the market clearing algorithm.

The market clearing algorithm is first run for both zones (electricity markets) together, and this results in a single electricity prices for both zones. If the resulting flows from one zone to the other zone exceed the interconnector capacity, the congestion is managed by means of market splitting. This process of market clearing and congestion management is completed for each step of the load-duration function.

![Figure 8 Market algorithm EMLab-Generation model (De Vries, Chappin, et al., 2013)]
3.4 Capacity Market algorithm

Before the market algorithm runs, the optional module of the capacity market algorithm can be switched on or off. This capacity market algorithm is based upon a centralized capacity market model, in more detail it is based upon NYISO-ICAP market. The NYISO-ICAP market design is a relatively simple design and it is also an example of a capacity market that is arguably well established and successful (Iychettira, 2013). In this algorithm the energy producer, regulator and energy consumer are the main agents. The basis processes in this algorithm are that the regulator forecasts the demand curve of the capacity market, whereupon the power producers bid into this capacity market with price-volume bids. After this the capacity market is cleared in a uniform price-clearing auction and all the payments to the energy producers are made (Bhagwat et al., 2014).

In more detail the algorithm works as follows. The capacity market regulator forecasts the demand and peak demand for the current year, using geometric trend regression based on demand values of the past. By adding the reserve margin to the forecasted peak demand, the minimum installed capacity is determined. After this the energy producers submit price-quantity bids for all their available power plants, in the zone of the capacity market. The difference between the fixed operation & maintenance costs and the net revenue from the spot market gives the bid price. If the O&M costs are higher than the net revenue the bid price is set to zero. The available capacity of the power plant in the peak segment determines the quantity of the bid. After the bids are placed by the energy producers, the bids are sorted in ascending order by price whereupon the market is cleared for the pre-determined demand curve based upon uniform price clearing. After market clearing all power producers are paid for all their accepted capacity (Bhagwat et al., 2014) (Bhagwat, Iychettira, & De Vries, 2013).

3.5 Influence of RES

Renewable energy sources that are intermittent such as wind and solar energy present a challenge to a long term model such as the EMLab-Generation model. The available capacity of intermittent energy sources can change over the hour due to variable weather conditions. These are short term effects, but the EMLab-Generation model abstracts from the details of short-term power system operation and price formation because of the reduction of complexity and run-time. In practice this means that the model uses a segmented load duration curve which is composed of 20 load segments. This means that details on hourly level are lost and that the sequence of hours is not taken into account. However to represent the influence of RES on electricity prices and the need for capacity the short term effects need to be represented in the model. As a solution to this challenge, an algorithm is developed in which the contribution of the RES to the load-duration curve are calculated on the basis of hourly time series. The calculations of this algorithm take place before the market clearing algorithm, as can be seen in Figure 9.
In this algorithm, the available capacity of the intermittent energy sources is determined by multiplying the time series of wind speed and solar hours with the installed RES capacity. This intermittent production is subtracted from the combined original load duration resulting in the residual total load-duration curve. After which the load factors are reduced by the obvious spill, that is RES production greater than demand plus interconnector capacity. A pre-market clearing of the RES is performed by checking for each time step if there is negative residual load in each zone. If there is negative residual load, power is transported from one zone to the other zone constraint by the interconnector capacity and if the residual load in the other county allows for that. If there is oversupply, the intermittent production is reduced by this oversupply resulting in residual load-duration curve for each zone. These load-duration curves are ordered with peak load first and base load last and divided into segments of approximately equal capacity needs. This process is described in Figure 10 which gives an overview of the market clearing algorithm. RES algorithm EMLab-Generation
3.6 EES & EMLab-Generation

Currently it is possible for the agents in the model that represent power companies to invest in different generation technologies, including thermal generators and renewable sources, however it is not possible to invest in EES capacity. In times of an excess in energy due to an excess in available renewable energy, this energy can be stored and released when there is less capacity available. The contribution of EES is thus highly linked with RES, so EES imposes the same challenge on the long-term EMLab-Generation model as intermittent energy sources. In more detail this means that to determine a possible dispatch for EES capacities the sequence of the load hours must be known so consecutive periods of electricity excess and electricity shortage, in which EES can be charged and discharged, can be determined. Because of this the
design to incorporate EES capacity in the EMLab-Generation model will be implemented in the same part where the residual load is determined for RES.

3.7 Conclusions
In this chapter a substantiation for the use of an ABM model to research the long term developments of the electricity market is given together with an overview of the current EMLab-Generation model. The most important conclusions for the coming chapters are that the current EMLab-Generation model is a model designed to model long-term effects. This lead to challenges when behavior such as RES and EES, which can change on the term, is tried to be incorporated in this model. To overcome this problem an extra module is added in which time series on an hourly basis are modelled to calculate the load factors for RES. Because of this, this module is the most suitable place in the model to build the EES expansion. In the next chapter the adjustment to the RES algorithm for EES will be conceptualized.
PART II: MODEL

Part I
- Desk research EMLab-Generation
- Literature study

Part II
- Conceptualization
- Formulazation
- Verification

Part III
- Results
- Validation

Part IV
- Reflection
- Conclusions

Knowledge EMLab
Knowledge EES
Experimental set-up
Parameter set-up
In the previous chapters the possible roles of EES within the electricity system are discussed, after which the current structure of the EMLab-Generation model are discussed. Important insights of these chapters were that the general characteristics of EES technologies are its energy capacity, charge- and discharge-efficiency and charge- and discharge rates and the fact that the most suitable place to expand the EMLab-Generation model is the “DetermineResidualLoadCurveForTwoCountries” algorithm. In this chapter these insights are translated into a conceptual design for the EES expansion of the EMLab-Generation model. The EES expansion for the EMLab-Generation model will be a generic representation of an EES system. This means that the model with the EES expansion can simulate every desired European electricity market depending on the input parameters and that the EES expansion itself can simulate every desired type of EES technique depending upon the input for the general characteristics. This will be accomplished by first capture the behavior of EES technologies in a mathematical model where after the changes to the “DetermineResidualLoadCurveForTwoCountries” algorithm that follow from this model will be discussed. The last part of this chapter will describe the assumptions that are made with the conceptualization of EES.

4.1 EES dispatch

A characteristic of the electricity network is that demand and supply should always be in balance and this is an important task of the network operator. At this moment the electricity system is designed in such a way that electricity is transported one-way from power plants to consumers, this means electricity must be produced precisely when electricity is used (Chen et al., 2009). The inherent intermittency and non-controllability of most RES introduces new challenges in the optimal operation of the electricity network. EES can provide an approach for dealing with the intermittency of RES and the unpredictability of their output. This is done by storing the surplus of energy when intermittent production is exceeds the demand and discharging this energy when the load is greater than the generation (Chen et al., 2009). In other words,
EES can flatten out the load profile and it can be shown that under most circumstances this will fulfill the objectives of the network operator to minimize losses and reduce peak loads (Verzijlbergh, 2013). Figure 11 shows this load leveling on a daily basis (Sabihuddin, Kiprakis, & Mueller, 2014). When EES is incorporated in the EMLab-Generation model, it must be able to determine the dispatch of possible EES units. The dispatch of EES is optimal when it ensures an as flat as possible load profile, so the expansion to the model must be able to determine an optimal dispatch of the EES units in the model. This can be done by incorporating an energy optimization model in the EMLab-Generation model. In an energy optimization model an objective function is minimized or maximized by changing the energy system’s variables. The changes in the variables are bound to a set of constraints, in this case for example the maximum capacity of the EES units, our the given load profile (Staveren, 2014). To formalize this energy optimization model into the EMLab-Generation model, first the model needs to be described mathematically. The mathematical description of this model is given in the following section.

4.1.1 Objective function
The objective of an as flat as possible load profile can be translated into an objective function for an energy EES optimization model. The objective is to flatten out the load profile i.e. to reduce the variance of the load profile as can be seen in Equation 1.

\[
\text{Minimize } \sum_t \sum_j (P_{tj} + S_{tj}^+ - S_{tj}^-)^2
\]

In Equation 1 \(P_{tj}\) is the load on time \(t\) in zone \(j\), \(S_{tj}^+\) is the EES inflow at time \(t\) in zone \(j\) and \(S_{tj}^-\) is the EES outflow on time \(t\) in zone \(j\).

4.1.2 Constraints
The objective is to flatten out the load profile by means of the EES in- and outflow. To do so it is needed to model the behavior of EES in the constraints. A EES device can be defined by its energy capacity, charging efficiency, discharging efficiency, charging power capacity and discharging power capacity (Zakeri & Syri, 2015)(Korpaas et al., 2003). The relationship between these factors can be describes as in Equation 2 (Korpaas et al., 2003).

\[
E_t = \begin{cases} 
E_{t-1} + S_{t-1}^+ \eta_{\text{charge}} \Delta t & (S_t \geq 0) \\
E_{t-1} - S_{t-1}^- \cdot \frac{1}{\eta_{\text{discharge}}} \Delta t & (S_t < 0)
\end{cases}
\]

Where \(E_t\) is the energy EES content of the EES at time \(t\) and \(\eta_{\text{charge}}\) and \(\eta_{\text{discharge}}\) are the charge and discharge efficiencies of the EES. The roundtrip efficiency of the EES is equal to \(\eta_{\text{charge}} \cdot \eta_{\text{discharge}}\). The above equation applies to one single EES, for multiple EESs in multiple zones the relationship can be described as Equation 3, in which \(E_{tj}\) is the energy EES content of EES in zone \(j\) at time \(t\).

\[
E_{tj} = \begin{cases} 
E_{t-1j} + S_{t-1j}^+ \eta_{\text{charge}} \Delta t & (S_t \geq 0) \\
E_{t-1j} - S_{t-1j}^- \cdot \frac{1}{\eta_{\text{discharge}}} \Delta t & (S_t < 0)
\end{cases}
\]
Hereby $E_t$ cannot be larger than the maximum capacity of the EES or smaller than the healthy depth of discharge, $S_t^-$ should lie between the minimum and maximum value of the charge capacity and $S_t^+$ should lie between the minimum and maximum value of the discharge capacity (Zheng, Meinrenken, & Lackner, 2014).

\[
E_{t_{\text{min}}} \leq E_{t_j} \leq E_{t_{\text{max}}} \quad (4)
\]
\[
S_{t_{\text{min}}}^+ \leq S_{t_j}^+ \leq S_{t_{\text{max}}}^+ \quad (5)
\]
\[
S_{t_{\text{min}}}^- \leq S_{t_j}^- \leq S_{t_{\text{max}}}^- \quad (6)
\]

Power can be exchanged between the market and the EES, but also between markets (zones) via the interconnector. The power exchange can be calculated via the power balance Equations 7 and 8, this is graphically represented in Figure 12. In which $M_{tA}$ is the power outflow of market A and $M_{tA}^+$ is the power inflow in market A respectively this is also true for $M_{tB}$ and $M_{tB}^+$ for market B. $I_t$ is defined as the power flow from market A to market B, so if there is a power flow from market A to B via the interconnector, $I_t$ will be positive and if there is a power flow from market B to A, $I_t$ will be negative.

\[
\text{Change in market A } = \begin{cases} 
M_{tA}^+ = S_{tA}^+ + I \\
M_{tA}^- = S_{tA}^- - I
\end{cases} \quad (7)
\]
\[
\text{Change in market B } = \begin{cases} 
M_{tB}^+ = S_{tB}^+ - I \\
M_{tB}^- = S_{tB}^- + I
\end{cases} \quad (8)
\]

The flow through the interconnector cannot exceed the maximum and minimum capacity of the interconnector, see Equation 9.

\[
I_{t_{\text{min}}} \leq I_t \leq I_{t_{\text{max}}} \quad (9)
\]
The total mathematical model is formulated as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{IA}$</td>
<td>Load in zone A at time i</td>
</tr>
<tr>
<td>$P_{IB}$</td>
<td>Load in zone B at time i</td>
</tr>
<tr>
<td>$E_{IA}$</td>
<td>Energy content in Storage in Zone A at time i</td>
</tr>
<tr>
<td>$E_{IB}$</td>
<td>Energy content in Storage in Zone B at time i</td>
</tr>
<tr>
<td>$M_{IA}^+$</td>
<td>Power outflow of market A at time i</td>
</tr>
<tr>
<td>$M_{IB}^+$</td>
<td>Power outflow of market B at time i</td>
</tr>
<tr>
<td>$M_{IA}^-$</td>
<td>Power inflow of market A at time i</td>
</tr>
<tr>
<td>$M_{IB}^-$</td>
<td>Power inflow of market B at time i</td>
</tr>
<tr>
<td>$S_{IA}^+$</td>
<td>Storage outflow out storage A at time i</td>
</tr>
<tr>
<td>$S_{IA}^-$</td>
<td>Storage inflow in storage A at time i</td>
</tr>
<tr>
<td>$S_{IB}^+$</td>
<td>Storage outflow out storage B at time i</td>
</tr>
<tr>
<td>$S_{IB}^-$</td>
<td>Storage inflow in storage B at time i</td>
</tr>
<tr>
<td>$\eta_{charge}$</td>
<td>Charging efficiency of energy storage</td>
</tr>
<tr>
<td>$I$</td>
<td>Power flow from zone A to B</td>
</tr>
</tbody>
</table>

subject to

\[
\begin{align*}
E_{IA} &= \begin{cases} 
E_{i-1A} + S_{i-1A}^+ \eta_{charge} \Delta t \\
E_{i-1A} - S_{i-1A}^- \cdot \frac{1}{\eta_{charge}} \Delta t 
\end{cases} \\
E_{IB} &= \begin{cases} 
E_{i-1B} + S_{i-1B}^+ \eta_{charge} \Delta t \\
E_{i-1B} - S_{i-1B}^- \cdot \frac{1}{\eta_{charge}} \Delta t 
\end{cases}
\]

\[
M_{IA}^- = S_{IA}^+ + I \\
M_{IA}^+ = S_{IA}^- - I \\
M_{IB}^- = S_{IB}^+ - I \\
M_{IB}^+ = S_{IB}^- + I
\]

\[
E_{A \min} \leq E_{IA} \leq E_{A \max} \\
E_{B \min} \leq E_{IB} \leq E_{B \max} \\
S_{A \min} \leq S_{IA}^+ \leq S_{A \max} \\
S_{A \min} \leq S_{IA}^- \leq S_{A \max} \\
S_{B \min} \leq S_{IB}^+ \leq S_{B \max} \\
S_{B \min} \leq S_{IB}^- \leq S_{B \max} \\
M_{A \min} \leq M_{IA}^+ \leq M_{A \max} \\
M_{A \min} \leq M_{IA}^- \leq M_{A \max} \\
M_{B \min} \leq M_{IB}^+ \leq M_{B \max} \\
M_{B \min} \leq M_{IB}^- \leq M_{B \max} \\
I_{\min} \leq I_i \leq I_{\max}
\]

4.2 EES dispatch in EMLab-Generation

The mathematical model formulated in the previous section needs to be included in the EMLab-Generation model. The objective function minimizes the variance of the load profile, for this purpose the input of the mathematical model needs to be the load profile over time as accurate as possible. In the current EMLab-Generation model the market clearing is performed with a segmented load duration curve in which the precise sequence of load hours is not known. The only part in the model were the sequence of hours is known, is the part where the residual load curve with RES is determined. Because of this, it is chosen to incorporate the energy optimization model in the algorithm for determining the residual load curve.

To calculate the optimal dispatch of EES, the optimization must take place after the residual load is determined by subtracting the load by the intermittent production but before the residual loads are reduced by its obvious spill (the RES production greater than demand plus interconnector capacity). This is because the intermittent production has off course to be taken into account, however it is possible that it is the most optimal to store the exceeding RES production (the obvious spill) and discharge it when RES production is low. This means that the energy optimization model is incorporated at the beginning of the algorithm for
determining the residual load, the changes to the algorithm are indicated in blue in Figure 13. In the new algorithm still first the available capacity of the intermittent energy sources is determined by multiplying the time series of wind speed and solar hours with the installed RES capacity and this production is subtracted from the original load duration curve. After this the energy optimization model flattens out the residual load curve by calculating the optimal charge and discharge dispatch for the available EES units and so determines a new residual load curve resulting in a new total load-duration curve. After this, the load factors are reduced by the obvious spill and the algorithm will work as described in paragraph Fout! Verwijzingsbron niet gevonden. The written model algorithm can be found in Appendix A.

![Flowchart showing the algorithm](image-url)

Figure 13 Changes in RES algorithm EMLab-Generation

Start

Create matrix with following columns and starting information:
- Hour of year
- SegmentID
- Load for both segments
- Intermittent production for both segments
- Residual load for both segments
- Residual load for both segments after storage
- Netto charge of storage capacity
- Storage capacity
- Interc. Capacity
- Residual load total
- Residual load total after storage
- Technology load factor

End

Grid load curve

Installed storage capacity

Installed RES capacity

Time series wind

Time series solar

Build national load curve & fill residual load columns with initial load.

Multiply time series with installed RES capacity and determine residual load per hour.

Optimize storage capacity for both segments and determine again residual load per hour.

Reduce the load factors by spill.

Check if there is a negative residual load.

Yes

Check if there is enough interconnector capacity available.

Yes

Export from one country to another country.

No

Reduce intermittent production.

No

Yes

Divide residual load curve in equal capacity needs and create an ordered segmented load curve.

Order the hours in the global residual load curve.

Calculate the total residual load curve over all countries.

Store the segment duration and the average load in that segment per country.

Create DynamicBins as representation for segments.
4.3 Investments
To answer the research question how a capacity market influence the development of EES there should not only be looked at the dispatch of EES but also at the investments in EES on the long run. In the investment algorithm in the EMLab-Generation model the energy producers looks at the long term expected revenues and costs of investment possibilities by predicting this yearly. To do this for EES is extra challenging because the expected costs and revenues depend upon the hourly difference in electricity prices and this is hard to predict in a long term oriented model such as the EMLab-Generation model. Because of this an adjustment to the investment algorithm of the EMLab-Generation model falls outside the scope of this thesis. However to still be given an answer to the research question an ex-ante analysis will be made for the investments in EES. This will be done by determining the amount of EES capacity in the zones as an exogenous factor and then calculating the cash flows of this EES capacity based upon the dispatch that is determined by the energy optimization algorithm. Depending on the cash flows it is subsequently determined if the initial investment in EES will outcome in a positive result. In this way it can be determined if a capacity market has an influence of this result.

The energy optimization model that is described in this chapter the algorithm optimizes the load curve over a whole year. In other words, the assumption has been made that the energy producers has perfect information for the load predications over a whole year. In reality this is not the case, accurate predictions for load can only be made for a couple of hours/days ahead and the residual load where intermittent sources are involved is even harder to predict. However to computation time of the model will increase significantly when the energy optimization model will optimize repeatedly only for a couple of days ahead, so because of this the chose is made for the assumption of perfect information. When conclusions are made it should be taken into account that the assumption of perfect information will lead to the most optimal results possible and that in reality this probably will not occur.

To calculate the most optimal dispatch of EES from the perspective of the energy producer, normally the objective function is to maximize the revenues by optimizing the EES dispatch over the price time series instead of optimizing the load time series. However in the EMLab-Generation model the sequence of hours is lost with the market clearing so because of this it was chosen to optimize the load duration curve by flatting it out. By optimizing in such a way that the load curve becomes as flat as possible it can be shown that under most circumstances this will minimize losses and reduce peak loads which will fulfill the objectives of the network operator instead of the energy producer (Verzijlbergh, 2013). However several studies show that electricity load and prices are strongly linked (Lisi & Nan, 2014; Lo & Wu, 2004), so the assumption is been made that the optimization over the load curve will closely resemble the results of an optimization over the price time series.

4.4 Conclusions
In this chapter the conceptualization of the EES expansion for the EMLab-Generation model is presented. The most important insights from this conceptualization are the model choices and assumptions that were made. The first choice is that the expansion is limited to the market algorithm part of the model and not the investment algorithm due to time constraints; this has important implications for the experimental setup. A second assumption is that perfect load information for a whole year is assumed in the model, this has
consequences for the interpretation of the results from the model. Lastly, it is explained that the load time series are optimized in the model and not the price time series.
In this chapter the model choices and assumption from the previous chapter are formulized. To do so first the AgentSpring framework in which the EMLab-Generation model is build is explained in terms of classes and the CPLEX package which is used to build the optimization model. This is done in order to get an understanding of the framework in which the concepts of the conceptualization phase need to be translated. After this the concepts from the previous section are translated into classes and objects of the AgentSpring framework, and are fitted in the whole EMLab-Generation model. At the end of the chapter the pseudo-code per class will be discussed.

5.1 AgentSpring & CPLEX Optimization Studio

The current EMLab-Generation model is implemented in the AgentSpring framework. The AgentSpring framework is developed and build by the developers of the EMLab-Generation itself and is developed as an open-source tool that is based upon Java technologies. Java is a computer programming langue that is concurrent, class-based and object-oriented (Gosling & Buckley, 2011). Object-oriented programming is based on the concept of “objects” which are data structures that contain data and procedures and “classes” that are definitions for the data format and available procedures for a given type or class of object (Gosling & Buckley, 2011). Besides the fact that AgentSpring is based upon Java technologies, another important character is that is makes use of a special way to contain the state of the modelled system. The state of the systems is captures in a graph database, that means that the information is stored using a graph structure of nodes, edges and properties. The EMLab-Generation is composed of the following four types of Java classes and other files.

- **Domain classes** are the definitions of thing and their properties. For instance it contains the classes Agent and PowerPlant.
- **Role classes** capture pieces of behavior, such as DetermineResidualLoadCurveForTwoCountriesRole, that can be executed by specific types (or classes) of Agents.
- **Repository classes** contain functions that deal with the interaction of typical model code and the database and also assist in updating current information or storing new information.
- **Scenario xml files** contain all data to define and initiate a simulation run.

For more information about the AgentSpring framework and the current EMLab-Generation model see the EMLab-Generation report (De Vries, Chappin, et al., 2013) or the website [http://emlab.tudelft.nl/generation](http://emlab.tudelft.nl/generation).

To solve the mathematical model that is presented in chapter 4 the IBM ILOG CPLEX Optimization Studio (CPLEX) is used. CPLEX is an optimization software package which has a modeling layer called Concert that provides an interface to Java, which is needed to in cooperate it with the Java based AgentSpring framework. CPLEX can solve integer programming problems, very large linear programming problems using either primal or dual variants of the simplex method or the barrier interior point method, convex quadratically
constrained problems and convex and non-convex quadratic programming problems of which this energy optimization problem is an example (IBM, 2015). With the formulation of the optimization model is build up from the following classes and interfaces from CPLEX.

- **IloCplex** is the class used to create and solve a large variety of Mathematical Programming models.
- **IloNumVar** is the interface that defines the API for numerical variables of any type. Objects implementing this interface are used to represent modeling variables in CPLEX. A modeling variable is characterized by its lower and upper bounds as well as by its type.
- **IloNumExpr** is the basic interface for all numerical expressions. Numerical expressions are represented by objects implementing this interface. They are constructed using the expression operator functions defined in the IloCplex class. Specifically the **IloLinearNumExpr** and **IloLQNumExpr** sub interfaces were used. The IloLinearNumExpr was used for scalar expressions that represent linear expressions, the IloLQNumExpr was used for expressions featuring both linear and quadratic terms.

For more information about CPLEX and its classes and interfaces see the website (IBM, 2015).

### 5.2 Concept Formalization

In this section the concepts from the conceptualization phase are translated into the objects and classes that are described in the previous paragraph. This is done by giving an overview of all relevant domain an role classes of the EMLab-Generation and adding the relevant concepts to these domain and role classes. This will lead to a concept formalization that can be translated into the pseudo code of the model.

#### 5.2.1 Domain & Role classes

In Figure 14 the UML diagram is showed with all relevant domain and role classes of the EMLab-Generation for the expansion of EES to the model. This figure only shows the changes made to model, in Appendix B the total UML can be found. From this UML diagram can be seen that an EnergyProducer is an Agent, that this EnergyProducer can own a certain amount of PowerPlants and that this PowerPlant has one PowerGeneratingTechnology. The PowerGeneratingTechnology has an aggregation relation with the IntermittentResourceProfile, this means that an IntermittentResourceProfile has a PowerGeneratingTechnology, more specifically an intermittentTechnology. The same can be said for a PowerGridNode and the intermittentResourceProfile, the intermittentResourceProfile has a PowergridNode, more specifically an intermittentProductionNode. The intermittentResourceProfile extents to the HourlyCSVTimeSeries and the HourlyCSVTimeSeries to the HourlyTimeSeries. The IntermittentResourceProfile provides information over the intermittent resource profile in different nodes for different technologies for the DetermineResidualLoadCurveForTwoCountriesWithEESRole which results in an IntermittentTechnologyNodeLoadFactor. With the IntermittentTechnologyLoadFactor a new segment load duration curve is determined and this results in Segments and SegmentLoad. The DetermineResidualLoadCurveForTwoCountriesWithEESRole calculates via an algorithm two residual load curves for both zones in the model, to do so it needs information about the interconnector with it gets from the Interconnector class. At last the DetermineResidualLoadCurveWithEESRole is executed by the DecarbonzationModel.

The most important change is that the class **DetermineResidualLoadCrueForTwoCountriesWithEESRole** is added to the model. This class works the same as the DetermineResidualLoadCurveForTwoCountriesRole except that the EES dispatch optimization model is
added to the algorithm, as was conceptualized in chapter 4. To calculate the EES dispatch the DetermineResidualLoadCurveForTwoCountriesWithEESRole needs extra information about the location of the EES and the five important characteristics of EES that were conceptualized in chapter 4. These characteristics are added to the PowerGeneratingTechnology class.

![UML diagram relevant domain & role classes EMLab-Generation](image)

5.2.2 Repository & Role classes

In Figure 15 the UML diagram is showed for all relevant repository and role classes of the EMLab-Generation model. This figure only shows the changes made to model, in Appendix B the total UML can be found. From this UML diagram it can been seen that the DecarbonizationModel has an aggregation relation with the Repos. This means that the DecarbonizationModel has a Repos, from which it extracts and stores data which is needed to run the model. In this UML diagram the Repository classes are shown which are used to execute the DetermineResidualLoadCurveForTwoCountriesWithEESRole.

To two Repository classes changes are made for the expansion for EES. First the PowerGeneratingTechnologyRepository has the function findAllEESGeneratingTechnologies which returns all EES technologies in the model, the second added function is the findAllEESAndIntermittentPowerGeneratingTechnologies which returns all EES and intermittent technologies. The function findOperationalEESPowerPlantsByPowerGridNode is added to the PowerPlantRepository, which finds all operational EES plants by node.
5.3 Model Formulization

In the previous paragraph the concepts from chapter 4 are translated to an UML diagram, in this paragraph the changes that were indicated in the UML diagrams are discussed in more detail. This is done by formulating the pseudo-code per changed class. The pseudo-code is a description of the algorithm in a human-readable form, providing an insight into the structure of the algorithm while omitting computer specific details (van Dam et al., 2013). In this paragraph the process of developing the pseudo code is per class is described, the pseudo code itself can be found in Appendix C.

**PowerGeneratingTechnology Class**: To store the characteristics of a EES technology such as the charge efficiency, charging rate, discharging rate and min- and max-EES capacity, these variables are added as double variables to the PowerGeneratingTechnology class of the EMLab-Generation model, in which all characteristics of the power generating technologies in the model are stored. To make a distinction between EES and all other technologies a Boolean variable is added if a technologies is a EES technology or not.

**PowerPlantTechnology Class**: To start the optimization algorithm the amount of energy stored in the energy EES technology has to be known. In hour 0 in year 0 this is equal to 0, however in each subsequent year this is equal to the amount in hour 8760 of the previous year. To store this value the characteristic initial EES value is added to the power plant technology class.

**PowerGeneratingTechnologyRepository Class**: In order to determine the residual load curve after the production of electricity by intermittent resources and the residual load curve after the EES dispatch optimization, first all existing technologies in the model are needed as input for the algorithm. To get this information from the repository three queries are created in the PowerGeneratingTechnologyRepository class.

**PowerPlantRepository Class**: In order to optimize the EES dispatch all EES plants in both zones are to be known by the algorithm. To do so a query is made that finds all (operational) EES plants in a node by searching for all generating technologies that are labeled as EES.
The DetermineResidualLoadCurveForTwoCountriesWithEES Role is a new class that is added to the model. It is a copy of the DetermineResidualLoadCurveForTwoCountriesRole which executes the algorithm that is described in chapter 3 paragraph fout! Verwijzingsbron niet gevonden.. In this section the changes to the algorithm that are described in the conceptualization chapter are described.

First 2 extra lists are created and one list is changed to store all existing intermittent and EES technologies in the model using the queries from the PowerPlantRepository Class. After this 7 extra columns are added to the RES matrix. This is done to store the net charge/discharge of the EES plants, the EES capacity and the residual load after EES dispatch for both zones separately and combined. The new EES optimization model is added after the residual load is determined by subtracting the load by the intermittent production but before the residual loads are reduced by its obvious spill. In this optimization model first all necessary values for this model are initiated. To start the optimization model a new IloCplex model is defined.

The first step of building an optimization model of IBM ILOG CPLEX Optimization Studio after the model is defined is to define the optimization variables of the model. The model variables of this model are P (load) at time t and zone z, E (energy EES content) at time t in zone z, mIn (market inflow) at time t in zone z, mOut (market outflow) at time t in zone z, sIn (EES inflow) at time t in zone z, sOut (EES outflow) at time t in zone z and I (interconnector flow) at time t. In Appendix C, which gives the total overview of the pseudo code, a generalized form of defining model variables is shown, the pseudo code for each specific variable can be found in Appendix D. After the model variables are specified, the expressions of the model need to be defined. The expressions of this model are the EESContent, marketOutflow, marketInflow and objective. For the pseudo code the same applies as for the variables, the pseudo code is generalized for all expressions in Appendix C and for the pseudo code per expression see Appendix D.

Once the variables and expressions are defined, the objective function and constraints can be added to the model and when all functions, constraints and variables are known, the model can be solved. If the cplex algorithm is able to solve the model, all outcomes of the model have to be saved in the matching columns in the matrix. First the netto charge of the EES technology at each hour is saved in the NETTOCHARGE column. Netto charge is defined as all electricity flowing in the EES minus all electricity flowing out at each hour, so nettoCharge = sIn - sOut. After the netto charge the used EES capacity and interconnector capacity are saved in the EESCAP and INTERCONNECTOR columns, the used EES capacity at each hour is equal to E and interconnector capacity to I. Hereafter the technology load factor of the EES technology can be calculated and saved in the column TECHNOLOGYLOADFACTOR. The technology load factor is defined as technology load factor = nettoCharge / maxStorageCapacity. This technology load factor is used to calculate the contribution of the EES technology to the total load at a given time in the market algorithm. After these variables are saved the model can be closed.

After the model is closed and the contribution of the EES to the residual load is known, the final column for the total residual load after EES can be filled. This is defined as the total residual load with RES minus the netto charge.

In the above paragraph the cplex model that is added to the DetermineResidualLoadCurveForTwoCountriesWithEESRole is described. Besides this, changes have been made to this class in order to save the technology load factors in the right way so they can be used in other algorithms of the model and changes so the this algorithm could also be used when there is only 1
zone in the model. These changes are not included in this paragraph due to the fact that this would decrease the readability and clarity of this paragraph.

5.4 Conclusions
In this chapter the expansion to the EMLab-Generation mode is formalized in terms of objects and classes and the implementation in the EMLab-Generation model is discussed on the basis of the pseudo-code. In the next chapter this translation from conceptualization to formalization will be verified.
Chapter 6

Verification

Now that the model is conceptualized and formalized and there is a working computer model, the question should be asked if the translation from conceptualization to formalization is done in the right way. In other words the model needs to be verified by checking if all relevant entities and relationships from the conceptualization phase are translated into computational model correctly (van Dam et al., 2013). The main question that is asked in verification is if the modeler build the *model right*. The question if the modeler build the *right model* is answered in the validation part in Chapter 9.

Verifying an agent-based model can be very challenging because of the complexity of these model that arise from the high number of agents, their states, and the number of possible interactions in the model. A specific difficulty of verifying in the EMLab-Generation environment is the fact that it is a very large model that is built by different developers and that the larger part of the model is outside the scope of this research. Because of this it is difficult to verify interactions between the extension build in this research and the rest of the EMLab-Generation model.

In general four main parts for verifying an agent-based model can be distinguished (van Dam et al., 2013):
- Recording and Tracking Agent Behavior
- Single-agent testing
- Interaction testing limited to minimal model
- Multi-agent testing

While verifying the EES extension of the model all four methods were used to a greater or lesser extent. In the following section these methods will be discussed.

### 6.1 Recording and tracking Agent Behavior

With recording and tracking agent behavior relevant output variables are selected and monitored to check if the outcomes are the same as the expected outcomes. These variables can be the same as the output variables of the final experiments but can also be other variables to have a closer look at the internal processes of the model. There are several ways available for recording and tracking agent behavior, however in the verification of the EES extension mainly loggers where used to log the input, states or output of the internal processes. In Table 1 some examples are given of loggers that were used to check the internal processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Logger</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding all EES technologies from repository by a query.</td>
<td>Log a list with all EES technologies found by the query.</td>
<td>Test if the list logged by the logger matches EES technology set-up.</td>
</tr>
</tbody>
</table>
Calculating and assigning residual load after EES optimization to the matrix
Log the first and last 10 values of the matrix after each added step of the optimization model
Calculate by hand the expected outcomes of the residual load and then check if this matches the outcomes of the logged matrix.

Using the end value of used EES capacity of each precious hour as starting value of the next hour in the optimization model.
Log at each hour the start and end value of used EES capacity.
Check if the end value of the previous hour is equal to the start value of the next hour.

### 6.2 Single-Agent Testing & Interaction testing with a minimal model

Agent-based models have often a very complex nature because of the large number of agents or interactions in the model. Because of this it wise to test the behavior of the model with a single agent or classes. After testing the model with a single agent or class the same test can be performed in a model with a minimal amount of agents so it can be tested if the basic interactions happen as laid out in the conceptualization phase. In the EMLab-Generation model a lot of interactions between different modules, roles and classes exists and to perform single agent tests and interaction tests, different combinations of single agent/class models and minimal models were performed.

Firstly, to test if the optimization model worked as intended, an optimization model was built in java independently of the EMLab-Generation model using the CPLEX packages. This single optimization model was tested with a simple load duration curve of 10 hours with one energy producer in one zone, so it could be tested if the optimization model worked as intended in a single agent test. After it was established that the optimization model worked correctly the single model was extended by a second zone with a second energy producer as a minimal agent model. This model was still independent of the EMLab-Generation model so it could be tested without the interaction with all different modules and classes of the EMLab-Generation Model. The java code of both the single agent and minimal agent model can be found in Appendix E.

After testing the optimization model apart from the EMLab-Generation model, the optimization model was implemented in the DetermineResidualLoadCurveForTwoCountriesRole class. To test if the optimization model interacted correctly with the rest of the DetermineResidualLoadCurveForTwoCountries role, unit tests with a minimal amount of agents were used. With a unit test a test is implemented in the software platform which exercise small parts of code by providing input and examining the code’s behavior by comparing the output with the listed expected output. After which these test can be run automatically so even if the code changes it can be know if the changed code passes the test (Louridas, 2005; van Dam et al., 2013). In this case multiple J-Unit tests were used to check the implemented optimization model. A J-Unit test is a unit test where instead of writing a series of if statements, assertions are used. An assertion is a way comparing a desired outcome on the basis of specific input with the actual outcome. If the two outcomes are equal the assertion succeeds, otherwise it fails (Louridas, 2005).

With the J-Unit test it could be tested of the DetermineResidualLoadCurveForTwoCountriesWithEES worked correctly. This was done by specifying input for this role in the form of a single energy producer and checking the outcomes of the role against predefined outcomes. This test is performed each time the model runs and it can run independently of the whole model, because of this each change in the code could easily be tested.
6.3 Multi-Agent Testing
After the single and minimal model verification, the model could be tested as a whole with all classes, roles and agents. Hereby the whole EMLab-Generation model runs with the new class DetermineResidualLoadCurveForTwoCountriesWithEES. This was done by running the model multiple times with different input scenarios to check if all interaction with the rest of the model are working correctly. To check of the model was working as a whole was a very time consuming process because running the model in total took 10 - 30 minutes for each run, depending on the input scenarios. This means that every time a small parameter or variables was changes the model had to run a long time to verify this change. An extra difficulty with this was the fact that the outcomes of single run could not be trusted because of the random character of an agent-based model.

6.4 Conclusions
In this chapter the results of the verification are presented. The verification of the EES extension was challenging because EMLab-Generation is a very large model that is built by different developers and that the larger part of the model is outside the scope of this research. The verification was carried out by performing four types of test. After performing these test it can be concluded that the extension of the EMLab-Generation model is verified, this means that the model is translated from the conceptualization phase to the formalization phase in the right way. In other words, the model is built in the right way.
Part III: Results
Chapter 7
Experimental Setup

In this chapter the experimental setup will be discussed. This will be done by first discussing all aspects of the experiment design whereafter the experiment setup and executing will be discussed. To do this the research question should be taken into account once again. The research question formulated in chapter 1 is “How does a capacity market influence the development of EES capacity, if the share of RES will grow as envisioned in the Delft Plan?”. In this research question is stated that this research looks at the influence of a capacity market on the development of EES technology. For the experimental setup this means that the electricity market in which EES is integrated should be studied with and without an capacity market.

Important considerations that should be taken into account with the experiments are the assumptions that were made in the conceptualization phase. Due to limitations in time, an EES module is only added to the market dispatch algorithm and not to the investment algorithm. This means for the experimental setup that the development of EES cannot directly be measured in the amount of investments made in EES capacity or the installed EES capacity. To still be able to answer the research question the experimental setup will be designed such that the amount of EES capacity in the model is an exogenous factor that is based on literature. When the model runs, it can calculate the size of the cash flows and subsequently allow for an ex-ante analysis to determine if the investments in the predetermined amount of EES would have been a wise choice to make.

The base model of the EMLab-Generation model is able to simulate two interconnected electricity markets in typical European countries. Because the Delft Plan focusses upon the Netherlands, the experimental set-up will be based upon the Netherlands. This means that the parameters of the model are set-up in such a way that the model simulates the Dutch electricity market.

The structure of this chapter is based upon paragraph 3.8 of the book Agent-Based Modelling of Socio-Technical Systems (van Dam et al., 2013).

7.1 Experimental Design

In this section the aspects of the experimental design will be discussed. First the hypotheses will be discussed, after which the time aspect of the experiments will be explained and at last the scenario’s will be specified.

7.1.1 Hypotheses

This research looks at the long term development of the electricity market and more specific, at the influence of a possible capacity market on the development of EES in the Dutch electricity market. From literature presented in chapter 1 and chapter 2 it can be concluded that a capacity mechanism could both have a
positive or a negative effect on the development of EES. This results in the following 2 hypotheses about the long term development of the Dutch electricity market in the context of the influence of a capacity market on the development of EES.

**Hypothesis 1:** Because EES can provide peak capacity, a capacity market could have a positive influence on the development of EES. The implementation of capacity market will provide payments for peak capacity in the market. This capacity could also be provided by EES when it discharges during peak hours. Because of that reason, EES can also bid into the capacity market with its capacity. The possible revenues from this capacity market positively influence the total positive cash flow of the EES operator.

**Hypothesis 2:** A capacity market and EES can be seen as substitutes for each other and because of this, the need for EES decreases with the introduction of a capacity market. The development of EES capacity and the introduction of a capacity market, both have stabilizing effects on the electricity market with an increasing share of RES. So they can be seen as substitutes for each other. This creates the risk that the need for EES capacity decreases when a capacity market is introduced, leading to a decrease in investments in EES capacity.

The mechanism described in hypotheses have the opposite effects upon the development of EES capacity. However this does not mean that they are mutually exclusive because the mechanism that are described by both hypotheses can occur simultaneously.

### 7.1.2 Time
For the experimental design it is important to determine an adequate time period for the simulation. This time period should be long enough to allow the emergent behavior of interest to become visible. In the EMLab-Generation model each tick represents one year. From preliminary runs with the EMLab-Generation model with capacity markets it is shown that the model reaches stability or equilibrium, and is independent of instabilities caused by initial conditions after the first 15-20 ticks (lychettira, 2013). The research question that is being answered is a research question within the context of the Delft Plant, which makes prediction till the year 2050. Because of this in combination with the conclusions form the preliminary runs it is decided to run each experiment for 40 ticks, resulting in the model simulating the time period between 2010 and 2050.

### 7.1.3 Sensitivity Analysis
The marginal costs for an EES operator consist largely of the price at which he buys the electricity to be stored times the amount he buys and his marginal revenues consists of the price this electricity is sold for times the amount of electricity he sells. The profit he makes is the difference between the prices. So to calculate the cashflows of the EES operator, these price differences are very important. In the model the market is cleared for all the segments of the load duration curve, in the standard set-up there are 20 segments so the model is cleared for 20 segments. This means that there are 20 prices that are determined and in each of these segments the load factor of the EES can be either negative or positive and price differences are only noticeable between these segments, the prices differences within the segments are smoothed out. So preferably the market would be cleared for every hour in the year so none of the price differences are smoothed out, however this increases the computational time enormously. The number of segments is thus an important variables because on the one hand it can have a significant influence upon the cashflow of the EES operator and so the validity of the model but on the other hand it has a great
influence on the computational time. Because of this a sensitivity analysis if preformed on the number of segments, first the model runs with the standard setting of 20 segments where after this number is doubled and tripled. The scenario design for this sensitivity analysis is presented in Table 2. The outcomes of the sensitivity analysis are discussed in Chapter 8.

<table>
<thead>
<tr>
<th>Scenario set-up sensitivity analysis</th>
<th>Energy Only Market</th>
<th>Capacity Market</th>
<th>EES</th>
<th>RES</th>
<th>CO2 - tax</th>
<th>Segments in load duration curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 – 20 Segments</td>
<td>x</td>
<td>-</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
<td>20</td>
</tr>
<tr>
<td>Scenario 2 – 40 Segments</td>
<td>x</td>
<td>-</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
<td>40</td>
</tr>
<tr>
<td>Scenario 3 – 60 Segments</td>
<td>x</td>
<td>-</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
<td>60</td>
</tr>
</tbody>
</table>

### 7.1.4 Scenarios

In order to test the hypotheses, which are presented in the section above, scenarios must be created. To research the combined effect of different policy instruments, different modules that represent various energy and climate policies, can be switched on and off in the EMLab-Generation model. Besides different modules that represent different energy and climate policies, different technologies can be used in the model. This has led to the scenario design that is presented in Table 3.

<table>
<thead>
<tr>
<th>Scenario set-up experiments</th>
<th>Energy Only Market</th>
<th>Capacity Market</th>
<th>EES</th>
<th>RES</th>
<th>CO2 - tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - Baseline</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 2a - StorageLow</td>
<td>x</td>
<td>-</td>
<td>Low</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 2b - StorageMedium</td>
<td>x</td>
<td>-</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 2c - StorageHigh</td>
<td>x</td>
<td>-</td>
<td>High</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 2d - StorageStep</td>
<td>x</td>
<td>-</td>
<td>Increase</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 3 - CapacityMarket</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 4a - StorageLow&amp;CapacityMarket</td>
<td>x</td>
<td>x</td>
<td>Low</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 4b - StorageMedium&amp;CapacityMarket</td>
<td>x</td>
<td>x</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 4c - StorageHigh&amp;CapacityMarket</td>
<td>x</td>
<td>x</td>
<td>High</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scenario 4d - StorageStep&amp;CapacityMarket</td>
<td>x</td>
<td>x</td>
<td>Increase</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

In this case it is chosen to run the model based upon an energy-only market, because this is the current market design of the electricity market in the Netherlands. Besides this it is chosen to run each scenario with RES, because the increasing share of RES had led to the need for flexible provided by capacity markets or EES. Another module that can be switched on and off is the CO2 module. The EU ETS is implemented by the EU to decrease the total amount of CO2 concentration and will likely have an effect on the development of RES. However the CO2 market in the model significantly increases the need for computational working capacity and so slows down the model. Because of this the CO2 market module will be switched off and the CO2 tax will be switched on, which will simulate the effects of the CO2 market instead. Besides the energy-only market, RES and CO2-tax, which are “switched on” in each scenarios, a capacity market in both countries and the use of EES technologies are alternately switched on and off to test the hypotheses.
Because only an extension for the market algorithm of the EMLab-Generation and not the investment algorithm, the model itself is not able to determine the most optimal amount of installed EES capacity. To see if the amount of installed EES capacity has an influence upon the results of the experiment, the amount of installed capacity is varied for all scenarios with EES. To make a comparison possible between the scenarios with only EES capacity and the combination of EES and a capacity market, the level of EES is varied in the same way for both groups of scenarios.

In Table 3, a general description is given of the different scenarios that will be executed is given. To further specify these scenarios this section will describe the assumption concerning the exogenous factors of the model. These factors are the demand growth, fuel prices, the energy mix, the amount of EES capacity, the capital costs of EES.

Demand growth & Fuel prices

In the EMLab-Generation model it is assumed that electricity producers are price takers upon the fossil fuel markets and because of that cannot influence these prices, nor can they influence policy decisions or demand growth. So these factors are exogenous determined variables in the model and in order to simulate the unpredictability of the demand growth and fuel prices they are created randomly using a triangular probability distribution.

The triangular probability distributions are created with a top, min, and max value. The values used in the scenarios are presented in Table 4. The values for the demand growth are based upon the electricity demand growth in the Netherlands from 1990 to 2010 retrieved from The Union of the Electricity Industry-Eurelectric (EURELECTRIC, 2012). The values of the biomass prices are based upon the research of Faaij (2006) and the values of the other fossil fuel prices are based upon data from the IEA (2011).

<table>
<thead>
<tr>
<th>Table 4: values triangular probability distributions exogenous variables</th>
<th>Top</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Growth NL</td>
<td>1,0194</td>
<td>0,9516</td>
<td>1,0435</td>
</tr>
<tr>
<td>Coal Price</td>
<td>1,0107</td>
<td>0,9707</td>
<td>1,0507</td>
</tr>
<tr>
<td>Gas Price</td>
<td>1,0146</td>
<td>0,9446</td>
<td>1,0846</td>
</tr>
<tr>
<td>Biomass Price</td>
<td>1,0100</td>
<td>0,9700</td>
<td>1,0500</td>
</tr>
<tr>
<td>Uranium Price</td>
<td>1,0100</td>
<td>1,0000</td>
<td>1,0200</td>
</tr>
</tbody>
</table>

To determine the output of the installed RES capacity, the hourly sun profile and the hourly on- and offshore wind profile in the Netherlands are needed. This data is based upon the data in the appendix of the article of (Hirth, 2013). After the output of the RES is calculated, hourly load data is needed to calculate the residual load taking in consideration the EES dispatch and the RES output. This hourly load data is also retrieved from the appendix of the article of (Hirth, 2013).

Energy mix

As mentioned above the experiments are based upon the Netherlands, this means that the initial set-up of energy producers and their power plant portfolios is also based upon the situation in the Netherlands in 2010. The initial set-up of power plants and their owners is loaded in the model via a CSV file and is based upon data from the thesis of Jeroen Alsem (Alsem, 2013). In the model there are 10 energy producers modelled, representing all energy producers that own over 1 MW installed electricity producing capacity that is located in the Netherlands in 2010 including RES. Their generation portfolios in the model are based upon their real generation portfolios in the Netherlands, an overview of the installed electricity production capacity
and their owners can be found in Appendix F, in Appendix G the overview of the CVS file that is used in the initials set-up of the model. In the scenarios where there is installed EES capacity, an extra energy producer is added to the model which owns all EES capacity in the model. This is done so the cashflows of the EES can be seen most easily in the outcomes of the model.

EES & RES

RES targets
The amount of installed RES capacity in the model is determined by the so called RES target. The RES target is an exogenously factor that determines the amount of installed RES capacity. This means that when there is X MW of installed RES capacity in year x owned by the standard energy producers and established by the normal investment algorithm and the target is set at Y MW of installed capacity, the difference between those two numbers is installed by a special energy producer. This energy producer does not look at the NPVs of the proposed RES investments and invest in them irrespectively of the costs. The targets used in the scenarios are based upon on RES predictions in the Netherlands per year estimated by the ECN that are based upon scenarios of the SCENARIOS (Michiel Hekkenberg, 2014). The targets can be found in Appendix H.

EES capacity
Due to the assumptions that were made in the conceptualization phase, the amount of installed EES capacity is an exogenously determined variable in the model. This means that the modeler controls the amount of installed EES capacity in the model and true the analysis of the outcomes determines if this EES capacity was viable. The amount of EES capacity in the model is based upon predictions of the TU Delft of the needed amount of EES with a determined amount of RES. This means that in this research the TU Delft calculated the required amount of EES that is needed to cope with fluctuations on different timescales for different amounts of RES penetration. Figure 16 gives this relation between the requirement amount of EES on different timescales and RES scenarios(TU Delft, Berenschot, & DNV GL, 2015). In this graph the same scenario is used as the scenario on which the ESN calculations for the RES targets are based. The timescale that is used as basis for the amount of EES in this model is 40 hours. This timescale is chosen because from the same research it is concluded that the potential for EES is the largest to cope with fluctuations on the intra-day market within a timeframe of 36 hours(TU Delft et al., 2015). So from this graph it can be concluded that with a timescale of approximately 40 hours, there is a need for 2*10e4 MWh = 20 GWh in 2030. The maximum charge and discharge capacity of a underground CAES system, at this moment, is around 300 MW and the average charging and discharging time is in the magnitude of hours (Chen, Zhang, Liu, & Tan, 2013; Lysen, Egmond van, & Hagedoorn, 2006). So a total capacity of 20000 MWh divided by 300 MW gives a charge and discharge time of 66,66 hours, this is unlikely for a CAES system. Because of this the assumption has been made that the total EES capacity will be provided by 10 CAES systems of each 2000MWh and 300 MW charge and discharge, leading in total to an overall capacity of 20000MWh with a charge and discharge capacity of 3000MW per hour and a charge and discharge time of 6,66 hour.

The calculated 3000 MW per hour capacity is used as the medium capacity level in the scenarios with EES capacity. For the scenarios with low EES capacity this amount is decreased with 20% and for the scenarios with a high EES capacity this amount is increased with 20%. The scenarios with a step wise increase of EES
capacity starts with a capacity of 0 MW at the beginning of the simulation and this increases linear to 3000 MW per hour in 2030.

Figure 16 Required amount of RES for different timescales

EES Costs
To calculate the total costs for the generation techniques, the capital costs per MW have to be known and the fixed operation & maintenance (O&M) costs per MW. The total capital costs (TCC) for EES consists of 2 parts. The first part are the capital costs related to the Power Conversion System (PCS), these are costs like power interconnections, cabling and piping, etc.. The PCS costs are proportional to the power rating of the EES system. The second part of the total capital costs, are the costs related to the storage unit itself, these are costs like all the costs undertaken to build energy storage banks or reservoirs, expressed per unit of stored or delivered energy €/kWh. The total investment costs can be calculated by Equation 10 (Schoenung & Hassenzahl, 2011).

$$C_{TCC}[\text{€}] = C_{PCS}[\text{€}] + C_{Storage}[\text{€}]$$ (10)

The total capital costs for the power conversion system can be calculated by Equation 11 and the total capital costs for the storage unit can be calculated by Equation 12 (Schoenung & Hassenzahl, 2011).

$$C_{PCS}[\text{€}] = \text{UnitCosts}_{PCS} [\text{€/kW}] \ast P [\text{kW}]$$ (11)

$$C_{Storage}[\text{€}] = \text{UnitCosts}_{Storage} [\text{€/kWh}] \ast E [\text{kWh}]$$ (12)

When the unit costs of the subsystems are known and the storage capacity in kWh is known, it is possible to rewrite the capital costs in terms of the power rating, as is necessary for the total costs calculating in the EMLab-Generation model. The total capital costs in terms of power rating is given in Equation X (Schoenung & Hassenzahl, 2011).

$$C_{system} [\text{€/kW}] = \frac{C_{total}[\text{€}]}{P [\text{kW}]}$$ (13)
Table 5 gives the investment and operations & maintenance (OM) costs related to CAES from the article of Zakeri (Zakeri & Syri, 2015). From this the total capital costs of the system can be calculated and divided by the rated power of 3000MW (see section above), this lead to capital costs of the system of €1109666 per MW. The fixed O&M costs are already given in costs in terms of power rating. All costs variables used in the model are summarized in Table 6.

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Type of CAES</th>
<th>Average</th>
<th>Middle fifty range, IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS (€/kW)</td>
<td>Aboveground</td>
<td>846</td>
<td>825–866</td>
</tr>
<tr>
<td></td>
<td>Underground</td>
<td>843</td>
<td>696–928</td>
</tr>
<tr>
<td>Storage section (€/kWh)</td>
<td>Aboveground</td>
<td>109</td>
<td>97–120</td>
</tr>
<tr>
<td></td>
<td>Underground</td>
<td>40</td>
<td>30–47</td>
</tr>
<tr>
<td>Fixed O&amp;M (€/kW-yr)</td>
<td>Aboveground</td>
<td>2.2</td>
<td>2.2–3.0</td>
</tr>
<tr>
<td></td>
<td>Underground</td>
<td>3.9</td>
<td>2.6–4.0</td>
</tr>
<tr>
<td>Variable O&amp;M (€/MWh)</td>
<td>Aboveground</td>
<td>2.2</td>
<td>2.1–2.6</td>
</tr>
<tr>
<td></td>
<td>Underground</td>
<td>3.1</td>
<td>2.6–3.6</td>
</tr>
</tbody>
</table>

**EES model variables**

Due to assumptions that were made during the conceptualization phase only one kind of EES technology can be modelled per scenario. From the EES roadmap from the TU Delft it can be concluded that Compressed Air Energy EES (CAES) has the greatest potential in the Netherlands. Because of this it is chosen to model the characteristics of CAES. The average charge and discharge capacity of a CAES site is 300 MW per hour and the charge and discharge efficiency are on average 0.84 and 1 /0.84 (Staveren, 2014). All EES characteristics that are used in the model are summarized in Table 7.

<table>
<thead>
<tr>
<th>EES characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy capacity</td>
<td>20,000 MWh</td>
</tr>
<tr>
<td>Charging efficiency</td>
<td>0.84</td>
</tr>
<tr>
<td>Discharging efficiency</td>
<td>1 / 0.84</td>
</tr>
<tr>
<td>Charging rate</td>
<td>300 MW per hour</td>
</tr>
<tr>
<td>Discharging rate</td>
<td>300 MW per hour</td>
</tr>
</tbody>
</table>

**7.2 Experimental setup**

In the first paragraph the factors of the design of ideal experiments are discussed, this section will discuss the more practical sight of preforming the experiments. In this section the practical limitations such as the number of unique experiments to run, how many times each ought to be run, and how to deal with randomness.

**7.2.1 Randomness**

To simulate different possible futures, the model is run under a set of the exogenous variables are modelled with random generators. The randomness arises from the following factors:
- The first agent each tick that begins the investment cycle is chosen randomly
- The triangular probability distributions of the demand growth
- The triangular probability distributions of the fuel prices

7.2.2 Repetition
Given the fact that agent-based models are chaotic and the fact that there are random variables in the model, the results of a single run cannot be trusted. It has been found that the EMLab-Generation model shows statistically stable results when the model is runs for 120 times. Because of this every scenario runs 120 times. On a normal computer one run takes about 15 to 30 minutes (depending on the scenario) and there are 6 scenarios, this means that on a normal computer this would take \(0.25 \times 120 \times 6 = 180\) hours. Because of this the model is runs on the high performance cluster of TPM.

7.3 Indicators
To analyze the results of the experiments a set of indicators is needed so the research questions can be answered. The main question of this research is what the influence of a capacity market is on the development of EES. To research this experiments are conducted with and without a capacity market so the effect on the development of EES can be seen. To see these possible effects the indicators must show how EES will behave in the model, with and without a capacity market. The first category looks directly at revenues and profit of the EES operator to see if there is a difference between EES capacity with and without a capacity market. For this category the differences between the group of scenarios with 1) only EES capacity and 2) with EES capacity and a capacity market are examined. The second category looks at the influence of the combination of a capacity market and EES on the electricity market itself. The indicators supply ratio, the ratio between RES and fossil fuel generation, average electricity price per year and price volatility fall under this category. The last category looks at the consumer variable costs to consumer.

7.3.1 EES operator indicators

Revenue
As already mentioned, one of the most important indicators of this research is the revenues received by the EES operator. Because the amount of EES capacity in this model is an exogenous variable, an indicator for the development of EES in the model is this positive cash flow. The higher the earnings of EES capacity are for its operators, the more likely it is that there will be more investments in EES capacity. So the expectation is that when the revenues of the EES capacity will be higher in the scenario with the combination of a capacity market and EES capacity, in comparison with the scenario where there is only EES capacity and no capacity market, it is more probably that hypothesis 1 is true. Vice versa it can be said that when the revenues of EES capacity are lower in the scenario with the combination of a capacity market and EES capacity, in comparison with the scenario where there is only EES capacity and no capacity market, this supports hypothesis 2 more.

Profit
Following both hypotheses, capacity markets could have a direct effect on the revenues of EES capacity, both positive or negative. However, even when a capacity market has a positive influence on the revenues of EES, the profit of EES can still be negative. If this is the case, the probability that the development of EES will increase is nihil. Because of this the profits of EES are also an important indicator for the development of EES.

7.3.2 Electricity market indicators

Supply Ratio
A capacity market is an institutional instrument which is introduced as a solution to ensure better security of supply because an energy only market may be unable to ensure sufficient operational capacity. This problem increases with the introduction of more RES capacity when the wind does not blow and there is not enough sun and not enough fossil fuel generators any more in order to cope with this supply problem. It can be said that EES is a technical solution to deal with this problem of security of supply. Because both solutions have a possible positive influence on the security of supply, there is a possibility that both solutions enforce each other in increasing the security of supply even further. So if EES has a more positive influence on the security of supply when a capacity market is in place, this would result in a positive influence on the development of EES. An important indicator of the security of supply is the supply ratio. The supply ratio is the ratio between operational capacity and the peak demand. A value of the supply ratio below 1 would indicate a shortage.

**Generation portfolio**
The goal of the Dutch government is a fully sustainable electricity market in 2050. To reach this goal the production of RES has to increase. However, sometimes RES production has to be curtailed because there is more renewable energy available than there is demand at that moment. EES is a possible solution for this, because the surplus of energy can be stored when RES supply exceeds demand, and can later be discharged when demand exceeds RES supply. As a result EES could potentially increase the production of RES relative to the production of fossil fuels. This can be seen as a positive development in the light of the goal of the Dutch government.

**Average electricity price**
The average electricity price is an important indicator for the consumers of the electricity market. The average electricity price is likely to rise with the introduction of more RES because the variability of RES increases peak prices which will lead to higher average electricity prices. A capacity market and EES could both possible lower this price again.

**Price volatility**
Due to the growing share of RES the price volatility is likely to increase. Possible solutions as a capacity market or EES can reduce this price volatility. Because of this, this is an important indicator to see what the effects are of a capacity market, EES capacity and more specifically the combination of both upon the price volatility in the electricity markets. It would be interesting to see to what extent a capacity market and EES capacity are separately stabilize prices in the electricity market and if the combination of both would have the same effect or an even more stabilizing effect on the prices.

7.3.3 Consumer Indicators

**Costs to consumer**
The total costs to consumer should be as low as possible for the total electricity market. The costs to consumer consists out of the costs of the energy only market and the (possible) capacity market. With the introduction of RES into the electricity market, there is a risk that the costs to consumer becomes higher due to the higher peak loads. A capacity market in combination with EES could possibly lower these costs. However, with no capacity market, the costs to consumer consist only out of the cost of the electricity market. With a capacity market the cost to consumer will increase with the costs of the capacity market.

7.4 Conclusions
The goal of this chapter was to describe the experimental set-up for the scenarios that are simulated with the EMLab-Generation model. This was done by first discussing all aspects of the experiment design where after the experiment setup and executing were discussed. In the experimental design two hypotheses were
drawn up. The first hypothesis states that because EES can provide peak capacity, a capacity market could have a positive influence on the development of EES. The second hypothesis states that because a capacity market and EES can be seen as substitutes for each other, the need for EES decreases with the introduction of a capacity market. These two hypotheses will be tested with experiments that are simulated with the EMLab-Generation model. This will be done on the basis of 10 scenarios that were presented in this chapter. The indicators on which the results from these experiments are going to be tested are: “EES revenue”, “EES profit”, “Supply Ratio”, “Generation portfolio”, “Average electricity price”, “Price volatility” and “Costs to consumer”. In the next chapter the analysis of the results will be described.
In this chapter the results of the experiments and the analysis of these results will be discussed. First the results of the sensitivity analysis will be discussed, after which the results of the experiments with the scenarios - that were drawn up in the previous chapter - will be discussed.

8.1 Sensitivity Analysis
The sensitivity of the model with respect to the number of segments in the load duration curve is tested. The number of segments is an important variable because on the one hand it can have a significant influence upon the cash flow of the EES operator and so the validity of the model. On the other hand it has a great influence on the computational time. In the standard set-up of the model, the model runs with 20 load segments. For this analysis the model runs with 20, 40 and 60 load segments. Because of a segmented load duration curve, the price differences - on which the EES operator earns his revenues - are smoothed out within the segment. This means that the revenues are calculated based upon the difference between segments, but not within segments. So to check the sensitivity of the model with respect to the number of segments, first the revenue (positive cash flows) of the EES operator have been studied. After this the influence of the number of segments on the overall electricity price is researched. This is done because the load factor of EES is calculated per segment. This means that the amount of segments could also have an influence on the electricity price.

8.1.1 Revenues EES operator
Figure 17 shows the revenues of the storage operator in the scenarios with 20, 40 and 60 load segments. In this figure the black line is the median, the blue striped line is the average, the light gray area is the 50%
confidence interval and the dark grey area is the 95% confidence interval over the 120 runs per scenario. The figure shows that the trend for all 3 scenarios is the same, however the confidence intervals become smaller with more segments. Besides the smaller confidence intervals, it can be seen that the peaks in overall revenue are larger with less segments.

Table 8 shows the average relative difference in revenues between the 3 scenarios. The information in Table 8 presents the average difference between the overall revenue for the 3 scenarios. The average difference in revenue per tick can be found in Appendix I. From this table it can be concluded that the relative difference between the scenarios increases with the number of segments, as was expected because the revenues depend on the difference in segments.

<table>
<thead>
<tr>
<th>Scenario 1 - 20 Segments</th>
<th>Scenario 2 - 40 Segments</th>
<th>Scenario 3 - 60 Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - 20 Segments</td>
<td>0.00%</td>
<td>6.69%</td>
</tr>
<tr>
<td>Scenario 2 - 40 Segments</td>
<td>6.69%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Scenario 3 - 60 Segments</td>
<td>10.82%</td>
<td>9.66%</td>
</tr>
</tbody>
</table>

In Figure 18 boxplots of the different scenarios for the mean overall revenues per single run are shown. The mean overall revenue per single run is calculated and the boxplots show the dispersion of these different values. Two observations can be made from this figure, the first observation is that for the scenario with less segments, a higher median for the “mean overall revenue” can be found. The second observation is that the boxes of the scenarios with a higher number of segments, are smaller compared to the boxes that are generated for the scenarios with a lower number of segments. This means that the dispersion of the values for the ‘mean overall revenue’ is lower with a higher number of segments. So when comparing different runs of the same scenario, the spread of the values of the “mean overall revenues” is lower with a higher number of segments.

To look at the spread of the revenues, the standard deviation of the revenues per single run is calculated. From these 120 values of standard deviation per scenario, boxplots are created as shown in Figure 19. It can be concluded from this figure that the average standard deviation over the 120 runs is higher in the scenarios with less segments. This means that the spread of the data per single run is on average higher with less segments compared to a higher number of segments. A second observation is that the box is wider for the scenarios with less segments compared to a scenario with a higher number of segments, meaning that the values of the standard deviation over the different runs per scenario are more spread. It can be concluded that there is more spread in outcomes with less segments.
compared to more segments. The same two observations can be made between the 20 and 40 segments and 40 and 60 segment scenarios. However, these two differences between scenarios seem smaller between the 40 and 60 segments scenarios than between the 20 and 40 segments scenarios.

8.1.2 Electricity Price

In Figure 20 the electricity prices for the scenario’s with 20, 40 and 60 segments are shown. From this figure the same observations as with the overall revenues analysis can be made. At first, the trend of the overall revenue analysis is evident.
revenue looks the same for all three scenarios. However, the spread of the data (the confidence intervals) becomes smaller with a higher number of segments. Besides this, the peaks become smaller with a higher number of segments. To dive further into these observations, also the mean electricity price and it's standard deviation are calculated per run for all three scenarios. The dispersions of these two indicators over all runs is shown in Figure 21. From these boxplots, the same observations can be made as with the revenue analysis. The mean electricity price per single run is higher and the spread of the mean electricity price per run is lower in a scenario with less segments.

![Figure 21 Boxplots mean and SD electricity prices sensitivity analysis](image)

8.1.3 Conclusions sensitivity analysis

In this sensitivity analysis the sensitivity of the model with respect to the number of segments in the load duration curve was tested. This was done with respect to the overall revenues of the EES operator and the average electricity price per year. With respect to both indicators it can be concluded that the spread of the data within the different runs per scenario was higher when using a scenario with a lower number of segments. Furthermore, it could be concluded that there were greater differences between the different runs within one scenario. This means that when using a lower number of segments, the output of the model over the different runs per scenario is more uncertain. For both conclusions applies that a higher number of segments gives more reliable outcomes of the model. This is because the spread of the data between the different runs decreases with a higher number of segments and the spread between different runs within one scenario - and so the uncertainty - decreases. These conclusions are both in line with the expectations that the model is sensitive to the amount of segments. However, it could be seen that the effect was more visible between the 20 and 40 segments scenarios compared to the 40 and 60 segments scenarios. Because of this and the fact that the computational time increases with the number of segments the experiments are chosen to run with 40 segments of the load duration curve per run.
8.2 Results

In this paragraph the results of the experiments are presented. This will be done by first discussing the results for each indicator separately and after this the overall conclusions will be drawn.

8.2.1 EES operator indicators

Revenues

The first indicator that will be discussed is the revenues from the EES operator. The revenues of the EES operator arise from the difference between the price of the electricity they buy for charging the EES unit and the price they receive when selling this electricity with discharging the EES unit. So in the revenues presented, the price of buying electricity is already included. The amount of storage in the model is determined in advanced. So to compare different scenarios with each other the total amount of revenues that can be earned by the EES operator over the total runtime of the model is researched. In other words, the cumulative revenues of the EES operator are studied. In Table 10 the average cumulative revenue over 40 years and 120 runs for all the different scenarios with EES is shown. It can be seen that the highest overall revenue is earned for the scenario with only EES and no capacity market with a step wise increased of EES in the model. On average the EES operator earns 23% more than in the scenario with the lowest revenues for the only EES scenarios (Scenario2a-StorageLow). If the scenarios with only EES are compared with the scenarios with a combination of EES and a capacity market, the scenarios with only EES provide on average more revenues over 40 years. Table 10 shows the percentages higher revenues earned when scenarios with the same amount of EES are compared for only EES and EES with a capacity market. It can be seen that the EES operators in all scenarios with only EES capacity, earn on average higher revenues compared to the revenues in the scenarios with the combination of EES and a capacity market. On average, EES operators in the scenarios with only EES capacity earn 14% more revenues compared to EES operators in scenarios with a combination of EES and a capacity market. From this it can be concluded that a capacity market does not have a positive influence on the revenues of an EES operator. It even seems that it has a small negative influence. With a high amount of EES in the model the difference is only 2%. Besides the conclusions when the two types of scenarios are compared, conclusions can be drawn about which level of EES capacity is the most optimal looking at the revenues for the EES operator. In both type of scenarios, the EES operator of the scenarios with the step wise increased amount of EES capacity, earns the highest revenues.

This can be explained by the fact that the EES operator earns his revenues by the price differences in the electricity prices. RES cause more extreme price differences in the electricity markets, so when the installed RES capacity increases, the price differences become more extreme. In the set-up of all scenarios the

<table>
<thead>
<tr>
<th>Compared scenarios</th>
<th>Difference in revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2a &amp; 4a</td>
<td>25%</td>
</tr>
<tr>
<td>Scenario 2b &amp; 4b</td>
<td>15%</td>
</tr>
<tr>
<td>Scenario 2c &amp; 4c</td>
<td>2%</td>
</tr>
<tr>
<td>Scenario 2d &amp; 4d</td>
<td>12%</td>
</tr>
</tbody>
</table>

Table 10 Cumulative revenues 40 years

<table>
<thead>
<tr>
<th>Scenario 2a - StorageLow</th>
<th>Cumulative Revenue 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>€</td>
<td>1,076,891,452</td>
</tr>
<tr>
<td>Scenario 2b - StorageMedium</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>1,137,529,022</td>
</tr>
<tr>
<td>Scenario 2c - StorageHigh</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>1,205,573,062</td>
</tr>
<tr>
<td>Scenario 2d - StorageStep</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>1,327,632,111</td>
</tr>
<tr>
<td>Scenario 4a - StorageLowCM</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>863,477,173</td>
</tr>
<tr>
<td>Scenario 4b - StorageMediumCM</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>988,789,774</td>
</tr>
<tr>
<td>Scenario 4c - StorageHighCM</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>1,177,715,933</td>
</tr>
<tr>
<td>Scenario 4d - StorageStepCM</td>
<td>€</td>
</tr>
<tr>
<td></td>
<td>1,183,327,911</td>
</tr>
</tbody>
</table>
installed RES capacity increases over time, this means that in the beginning the price differences are smaller. Because of the smaller price differences, less flexibility is needed to cope with these differences. This means less EES capacity is needed in the beginning of the simulation, however the needed amount increases over time when there is more installed RES capacity. So a more optimal scenario for EES capacity would be a scenario were the amount of EES capacity increases over time. This is the case for the scenarios with a step wise increase in EES capacity. In Appendix J graphs can be found of the revenues earned per year and the cumulative revenues over 40 years.

**Profit**

The second indicator that will be discussed is the profits earned by the EES operator. These profits are highly related to the revenues earned by the EES operator. In the EMLab-Generation model, the profits are calculated by subtracting the variable and fixed costs from the overall revenues. The variable costs of EES consist of the costs of electricity that is bought to charge the EES, these costs are already included in the revenue calculating in the model, so the variable costs in this calculating are equal to zero. The fixed costs consist of the fixed O&M costs and the fixed capital costs. The capital costs in the model are calculated by taking the loan for the investment and the economic lifetime of the type of generator into account. Because the amount of EES capacity is determined outside the model in advanced for the whole duration of the model and these costs are not dependent on the economic- of technical-lifetime of the EES, the fixed costs calculation gives biased results. Because of this, the profit for this analysis are calculated by subtracting the annualized life cycle costs of the EES technique CAES (Zakeri & Syri, 2015). These costs can be found in Appendix K.
An interesting way to compare the profits of the different scenarios would be to look for example at the payback time of the investment, the return on investment or the net present value. However because the total amount of EES is determined in advance as an external variable, these calculation will not give reliable insights. Because of this the profit will be analyzed in the same way as at the revenues. This means that the cumulative profit after 40 year of the EES operators is analyzed. However to get better insights in when the profits are earned, the behavior of the profits over time will be analyzed. In Figure 22 the cumulative revenues over time are shown. It can be seen that the EES operator makes a loss from the beginning of the simulation independent of the used scenario. The behavior of the cumulative loss over time has the same trend for all scenarios. This trend appears to be linear for all scenarios, meaning that during each year approximately the same amount of loss is made. However, the slope of the curves for the different scenarios are different. The slope is the steepest for the scenarios with a high amount of EES capacity. This can be explained by the fact that the fixed costs of storage are dependent on the amount of installed capacity, which in the beginning of a simulation is the largest for the scenarios with a high amount of EES capacity installed. The loss in the step wise scenarios is smaller because in the beginning of a simulation, the amount of installed capacity is smaller. When the losses of the two different types of scenarios - with and without a capacity market - are compared, the differences between the scenarios with EES capacity and the scenarios with a capacity market and EES capacity are even smaller compared to the revenue analysis. In Table 11 the differences in loss is given between the scenarios of group 2 and the scenarios of group 4. In these groups the scenarios with the same amount of EES capacity are compared with each other. It can be seen that the scenarios with a capacity market have a lower profit, however the differences between the scenarios are smaller compared to the revenue analysis and almost negligible. From this it can be concluded that a capacity market does not have a significant influence on the profit of an EES operator and as a result it can be expected that there will be no increase or decrease in investments in EES when a capacity market would be introduced.

<table>
<thead>
<tr>
<th>Compared scenarios</th>
<th>Difference in revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2a &amp; 4a</td>
<td>2%</td>
</tr>
<tr>
<td>Scenario 2b &amp; 4b</td>
<td>1%</td>
</tr>
<tr>
<td>Scenario 2c &amp; 4c</td>
<td>0%</td>
</tr>
<tr>
<td>Scenario 2d &amp; 4d</td>
<td>1%</td>
</tr>
</tbody>
</table>

### 8.2.2 Electricity market indicators
#### Supply Ratio
The first electricity market indicator that is analyzed is the supply ratio. The supply ratio is the ratio between the operational capacity and the peak demand. This means that the supply ratio should be higher than 1 to avoid shortages. Figure 23 shows the supply ratios for all 10 scenarios. The black line is the median, the blue stripes line the mean, the dark grey area is the 50% confidence interval and the light grey area is the 90% confidence interval.

From this figure it can be seen that the supply ratio is on average higher with EES capacity in the model. This can be explained by the fact that the EES capacity is added to the model "on top" of the already existing generation capacity, because of this the supply ratio is automatic higher. Table 12 shows the average supply ratio and the relative difference to the baseline scenario. This is calculated by calculating the average supply
ratio over all runs per scenario per tick whereupon the relative difference per tick between each scenario and the baseline scenario is calculated and this is averaged over all 40 ticks. The relative difference per tick can be found in Appendix L.

![Figure 23 Peak capacity supply ratios](image)

**Table 12. Average supply ratio**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Supply Ratio</th>
<th>Relative difference compared to baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - Baseline</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Scenario 2a - StorageLow</td>
<td>1.21</td>
<td>16%</td>
</tr>
<tr>
<td>Scenario 2b - StorageMedium</td>
<td>1.25</td>
<td>20%</td>
</tr>
<tr>
<td>Scenario 2c - StorageHigh</td>
<td>1.26</td>
<td>21%</td>
</tr>
<tr>
<td>Scenario 2d - StorageStep</td>
<td>1.25</td>
<td>20%</td>
</tr>
<tr>
<td>Scenario 3 - CapacityMarket</td>
<td>1.09</td>
<td>5%</td>
</tr>
<tr>
<td>Scenario 4a - StorageLowCM</td>
<td>1.22</td>
<td>17%</td>
</tr>
<tr>
<td>Scenario 4b - StorageMediumCM</td>
<td>1.25</td>
<td>20%</td>
</tr>
<tr>
<td>Scenario 4c - StorageHighCM</td>
<td>1.27</td>
<td>22%</td>
</tr>
<tr>
<td>Scenario 4d - StorageStepCM</td>
<td>1.25</td>
<td>20%</td>
</tr>
</tbody>
</table>
It can be seen that the scenario with only a capacity market has on average a 5% higher supply ratio compared to the baseline scenario. When looking at the difference per tick in Figure 23, it can be seen that this difference is on average higher after the first few ticks. The reason for this is that the effects of the capacity market only become visible after the first few ticks, because investments take a couple of years. However what stands out is the fact that both EES and a capacity market separately ensure a higher supply ratio, a combination of the two does not. This means that the effects of a capacity market on the supply ratio probably becomes smaller with the combination of EES and a capacity market. This conclusion can be drawn because the amount of EES capacity is an exogenous variable in the model.

In all the scenarios the demand growth is modelled with the same triangular distribution with the same parameters. Because of this, the change in supply ratios between the different scenarios can to a large extend be explained by a change in operational capacity (not completely since the peak demand changes between scenarios because of the randomness in the distribution). This line of reasoning can be reversed by saying that with a certain level of EES capacity, the same level of supply ratio can be reached with less generation capacity. In this case it would seem that with a medium, high or step wise level of EES capacity, about 20% of generation capacity is no longer required. However this does not mean that there is a direct relation because the “extra” capacity that is supplied in the model by the EES first needs to be charged and for this charging generation technologies are needed. Nevertheless it can be concluded that EES capacity ensures a higher supply ratio and so less generation capacity is needed.

In Appendix L the dispersion of the count that the supply ratio became lower than 1 and 1,1 per single run can be found and the average supply ratio per tick for all scenarios.

**Generation portfolio**

The second electricity market indicator is the generation portfolio and more specifically, the ratio between RES generation and conventional generation. Figure 24 gives an overview of the electricity generation per technology. In this figure it can be seen that in all the scenarios with a capacity market, EES capacity or a combination of both, the generation in MWh for coal fired power plants increases over time. A possible explanation for this effect is that due to EES or a capacity market more flexibility is provided to the electricity market. As a result cheap baseline generators such as coal power plants can produce at a higher baseline level. This would mean that measures to increase flexibility in the electricity market indirect provide the increase of more polluting generation techniques.

In Chapter 7 the hypothesis was made that EES capacity could increase the generation by RES compared to fossil fuels because less RES generation needed to be curtailed as it could be stored. Table 13 gives the ratio between RES generation and fossil fuel generation for the years 2010, 2020, 2030, 2040 and 2050. This ratio is calculated by calculating the average generation per tick for both RES and fossil fuels after which the first is dived by the latter.
Table 13: Ratio between RES and fossil fuels

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - Baseline</td>
<td>0.02</td>
<td>0.49</td>
<td>1.20</td>
<td>2.03</td>
<td>2.92</td>
</tr>
<tr>
<td>Scenario 2c - StorageHigh</td>
<td>0.02</td>
<td>0.46</td>
<td>0.81</td>
<td>1.59</td>
<td>2.63</td>
</tr>
<tr>
<td>Scenario 2a - StorageLow</td>
<td>0.02</td>
<td>0.46</td>
<td>0.81</td>
<td>1.59</td>
<td>2.62</td>
</tr>
<tr>
<td>Scenario 2d - StorageMedium</td>
<td>0.02</td>
<td>0.45</td>
<td>0.80</td>
<td>1.59</td>
<td>2.66</td>
</tr>
<tr>
<td>Scenario 3 - CapacityMarket</td>
<td>0.02</td>
<td>0.44</td>
<td>0.77</td>
<td>1.45</td>
<td>2.30</td>
</tr>
<tr>
<td>Scenario 4c - StorageHigh&amp;CapacityMarket</td>
<td>0.02</td>
<td>0.46</td>
<td>0.80</td>
<td>1.54</td>
<td>2.59</td>
</tr>
<tr>
<td>Scenario 4a - StorageLow&amp;CapacityMarket</td>
<td>0.02</td>
<td>0.45</td>
<td>0.77</td>
<td>1.46</td>
<td>2.44</td>
</tr>
<tr>
<td>Scenario 4b - StorageMedium&amp;CapacityMarket</td>
<td>0.02</td>
<td>0.45</td>
<td>0.78</td>
<td>1.49</td>
<td>2.44</td>
</tr>
<tr>
<td>Scenario 4d - StorageStep&amp;CapacityMarket</td>
<td>0.02</td>
<td>0.45</td>
<td>0.79</td>
<td>1.53</td>
<td>2.53</td>
</tr>
</tbody>
</table>

From this table it can be seen that the hypothesis is refuted. The opposite effect is visible, the ratio between RES and fossil fuel generation is on average the highest for the baseline scenario compared to the other scenarios. The ratio is on average the lowest for the scenario with only a capacity market, after that the
scenarios with the combination of EES and a capacity market and next the scenarios with EES capacity have the lowest RES share. This means that EES has a more positive effect on the ratio between RES and fossil fuel generation compared to a capacity market. However not having any measures to increase flexibility in the electricity market seems to be the best option to achieve a high ratio between RES and fossil fuels. From Figure 24 it can be seen that the difference in RES generation between the baseline scenario and the other scenarios lies in the biomass generation. Biomass is a more flexible generation technology compared to coal fired power plants, so because in the baseline scenario no flexibility is added, a possible explanation for the increased generation of biomass is the fact that flexibility is still required and biomass is able to provide this flexibility. Which lead to a higher ratio between RES and fossil fuel generation.

However an important remark has to be made with the reasoning in this subsection. In the model there is an agent implemented called the “RES target investor”, which means that in the model there is a RES target for each tick, if this target is not met by investments by the normal investors, the target investor will invest a certain amount until the RES target is met, without considering the costs of these investments. For that reason statements regarding the electricity generation per technology are very uncertain because the capacity of RES is artificially increased in the model.

In Appendix M the ratio between RES and fossil fuels per tick can be found and graphs showing the RES and fossil fuel generation per year.

8.2.3 Consumer variables indicators

**Average electricity price**

Figure 25 shows the electricity price averaged over all segments in one year per tick.
The black line is the median over 120 runs, the blue stripped line the mean, the dark grey area is the 50% confidence interval and the light grey area the 90% confidence interval. It can be seen that the trend for all scenarios is the same, however what stands out is that in the baseline scenario the peaks in the average electricity price are much higher compared to all other scenarios. The price peaks are the lowest for the scenarios were a capacity market is combined with EES and especially for the scenario with the step wise increase of EES capacity. This phenomenon can also be observed in Figure 26. In Figure 26 the distribution of the standard deviation per run for all scenarios is shown. From this figure it can be concluded that runs from the scenario with a step wise increase of EES capacity combined with a capacity market have the lowest standard deviation. This means that the spread of the data per run for this scenario is the lowest for all scenarios, in other words the peak and valleys are closest to the mean for this scenario. So the average electricity price over the years is the most stable for this scenario. In the section about price volatility a more in-depth analysis will be performed on price stabilization.

In Figure 27 the distribution of the mean ‘average electricity price’ over all ticks per run is given per scenario. Here it can be seen that the baseline scenario has the highest mean per run for the average electricity price. So it can be concluded that the average electricity price in the baseline is higher compared to all other scenarios. For all other scenarios the distribution of the mean is much more equal compared to each other. This means that all measures to increase flexibility in the electricity market also have a reducing effect on the average electricity price per year, however no clear distinction between EES, a capacity market or a combination of both can be made regarding the average electricity price.
Electricity price volatility describes how quickly and/or widely prices can change. Price volatility in the model can be measured on two different timescales. This first timescale is the price volatility over the 40 years duration of the model. The second timescale is the volatility within one year of the simulation. First the volatility over 40 years will be discussed where after the volatility within one year will be discussed.

In general there are two ways of measuring the volatility of commodity markets. The first way is the so-called implied volatility which gives an estimation for the future volatility by analyzing forwards contracts. The other option is the statistical volatility which looks backwards as it captures the amplitude of the price movement for a given period of time (European Commission, 2011). In the EMLab-Generation model there is no real data about forward contracts so to calculate the price volatility of the results the second method will be used. A common way to calculate a volatility index is to take the logarithmic difference between two consecutive time steps and then compute the relative standard deviation for a given period of time from this logarithmic difference. To calculate the relative volatility for the given time period the value of the standard deviation is multiplied by the square root of the number of time steps of time period. These equations are shown in Equations 14, 15 and 16 (European Commission, 2011).

\[ X_i = \log_{10} P_t - \log_{10} P_{t-1} \quad (14) \]

\[ X_k = \frac{\sum_{i=1}^{k} X_i}{k} \quad (15) \]
\[ VOL_{(t-k+1,t)} = \sqrt{N} \times \sqrt[2]{\sum_{i=1}^{k} (X_i - \bar{X})^2 \over k} \]  

The difference with the standard deviation that was calculated in the previous section, is that the price volatility index also takes into account how quickly prices can change instead only how widely the prices change. The price volatility for every single run within every scenario is calculated and the distribution of these values per scenario is displayed in the boxplots of Figure 28. In this figure it can be seen that the boxes of all scenarios are approximately of equal in size. This means that the spread of volatility indices over all runs per scenario is equal for each scenario. However the volatility indices for the baseline scenario are on average higher, which means that the average electricity prices over the years changes more quickly and widely in this scenario. The volatility indices for the scenario with a capacity market and a step wise increase of storage are on average the lowest. This means that prices are the most stable in this scenario.

Besides measuring the price volatility over the years, price volatility can be measured within one year, in other words price changes over a short period of time. In the EM Lab-Generation model, there is no information available about the electricity prices per hour or per day because of the way the market clearing is formalized. However, the prices for the different segments are known. It can be said that if the price duration curve is steeper, the prices are more volatile as the price differences between the segments are larger. In Figure 29 the price duration curve for the year 2030 is presented, the price duration curve for the years 2010, 2020, 2040 and 2050 can be found in Appendix N. From Figure 29 it can be seen that the price duration curve of the baseline scenario (red line) is much steeper compared to the price duration curve of
the other scenarios. This means that the price volatility of the baseline scenario within a year is also higher compared to the price volatility of the other scenarios. The price duration curves of the other scenarios have approximately the same level of steepness. This means that as well a capacity market, EES capacity and a combination of both have the same positive effect on the price volatility of the electricity market.

From the price duration curve of the other years (see Appendix N), the same effect is visible. The price duration curve of the baseline scenario is in all years steeper compared to the other scenarios. However when the simulation time increases (2040 and 2050) it is visible that the prices of the first segments for all scenarios increase. This can be explained by the increasing share of RES in the model. The scenario with the flattest price duration curve in both years is the scenario with the combination of a step wise increase of EES capacity and a capacity market.

**Costs to consumer**

The last indicator that will be discussed is the costs to consumer. The costs to consumer are calculated by adding up the costs of the energy only market and the capacity market. In Figure 30 these costs to consumers are shown for all scenarios. The black line is the median, the blue stripped line are the average costs to consumer, the dark grey area is the 50% confidence interval and the dark grey are is the 90% confidence interval. from this figure it can be seen that the total cost to consumer are the highest and most volatile for the baseline scenario. In Table 14 the cumulative cost to consumer over 40 years are presented. Here it can be seen that the overall costs are indeed the highest for the baseline scenario and that the scenario with a step wise increase of EES is the cheapest scenario for consumers. This can be explained
by the fact that due to the high electricity prices in the baseline scenario which lead to high cost to consumer. However, the electricity prices in the other scenarios are almost equal to each other, so there the difference in the cost to consumer are explained by the cost of the capacity market. In the scenarios with no capacity market these cost are equal to zero and because of this the total costs to consumer are the lowest for all scenarios.

### Table 14 Cumulative cost to consumer

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cost to consumer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - Baseline</td>
<td>€ 517,969,678,087</td>
</tr>
<tr>
<td>Scenario 2c - StorageHigh</td>
<td>€ 408,967,794,916</td>
</tr>
<tr>
<td>Scenario 2a - StorageLow</td>
<td>€ 400,222,289,733</td>
</tr>
<tr>
<td>scenario 2b - StorageMedium</td>
<td>€ 424,255,821,501</td>
</tr>
<tr>
<td>Scenario 2d - StorageStep</td>
<td>€ 386,490,118,079</td>
</tr>
<tr>
<td>Scenario 3 - CapacityMarket</td>
<td>€ 396,352,078,792</td>
</tr>
<tr>
<td>Scenario 4c - StorageHigh&amp;CapacityMarket</td>
<td>€ 408,587,807,623</td>
</tr>
<tr>
<td>Scenario 4a - StorageLow&amp;CapacityMarket</td>
<td>€ 414,394,941,466</td>
</tr>
<tr>
<td>Scenario 4b - StorageMedium&amp;CapacityMarket</td>
<td>€ 426,915,573,031</td>
</tr>
<tr>
<td>Scenario 4d - StorageStep&amp;CapacityMarket</td>
<td>€ 397,755,585,257</td>
</tr>
</tbody>
</table>

### 8.2.4 Additional analyses

When looking at the results of all indicators combined a few extra remarks can be made. In the graphs for the average electricity prices and cost to consumer a peak around tick 7 is visible in all scenarios. This peak
can be explained by the choice of basing the dismantling algorithm upon the lifetime of the generation plants. The set-up of the generation portfolio in the model is based upon the generation portfolio of the Netherlands in 2010. In 2010 a lot of old gas turbines (30 - 35 years) were installed. In the model all these generation plants are dismantled when they reach the age of 40 and because of this an electricity shortage occurs around tick 7 which is visible in the electricity prices and the costs to consumer.

Besides this it can be seen that the electricity prices and the costs to consumer remain quite stable for the years between 2020 and 2040 and after 2040 start to increase, this effect is also visible in the price duration curves of the years 2040 and 2050. For this effect there are multiple explanations. The first explanation is that the average lifetime of generation technologies in the model lies between 15 (wind) and 40 (OCGT) years and after year 7 in the model the first investment cycle in the model starts and these generation technologies are starting to get dismantled after 2040. The second explanation regards the share of RES in the simulation. The share of RES is increasing during the simulation and in the beginning the price spikes that are caused by the variability of RES are absorbed by the flexible capacity of a capacity market, EES or a combination of both. However when the share of RES keeps increasing when the simulation progresses, the flexible capacity is no longer adequate to absorb all the price spikes, so the price spikes become more extreme at the end of the simulation. This can be seen in the price duration curves of 2040 and 2050 in which for all scenarios the first segments have very high prices, which results in higher average electricity prices.

8.3 Conclusions

In this chapter the results of the sensitivity analysis and the experiments are presented. In the sensitivity analysis the sensitivity of the model was tested towards the amount of load segments in the load duration curve. This was done by looking at the effects of the amount of these segments upon the revenues of the EES operator and the average electricity price. For both indicators the conclusion applies that a higher number of segments gives more reliable outcomes of the model. This is because the spread of the data between the different runs decreases with a higher number of segments and the spread between different runs within one scenario - and so the uncertainty - decreases. However, it could be seen that the effect was more visible between the 20 and 40 segments scenarios compared to the 40 and 60 segments scenarios. Because of this and the fact that the computational time increases with the number of segments the experiments are chosen to run with 40 segments of the load duration curve per run.

The main findings from the experiments are that the model cannot tell us if a capacity market has a positive or negative influence on the development of EES. When looking at the indicators revenue and profit of the EES operator it can be seen that there is no significant difference between the EES-only scenarios and the combined scenarios. For the electricity market and consumer market indicators the same conclusions can be drawn. For both groups of scenarios with EES capacity the supply ratios are higher compared to the baseline scenario and the capacity market scenario, but compared to each other they are almost equal. When looking at the generation portfolio after 40 years, this portfolio looks almost the same for both groups of scenarios with EES capacity. For the average electricity price no substantial difference can be noticed between the scenarios with only EES capacity and the combination between EES capacity and a capacity market. The electricity prices are almost equal to each other with these two groups of scenarios, however also with this indicator there is a difference between the baseline scenario and these two groups of scenarios. When looking at the price volatility it can be noticed that there is a large difference between the baseline scenario and all other scenarios. However the same applies as for all other indicators regarding the
difference between the EES-only scenarios and the combined scenarios, no significant difference can be observed. For the consumer indicator, cost to consumer, the results show the same pattern. Between the two groups of scenarios with EES capacity no significant difference can be noticed. However it can be seen that the cost to consumer are considerably lower for these groups of scenarios compared to the baseline scenario. However it can be seen that there is a significant difference between the baseline scenario and both groups of EES scenarios.

Concluding it can be said that both hypotheses are disproved by the findings of the experiments. This means that the model cannot tell us if a capacity market has a positive or negative influence on the development of EES. The insight from these results will be discussed in Chapter 10. However first the extension of the EMLab-Generation model will be validated.
Chapter 9

Validation

After it was checked in the verification phase if the model was built right, in the validation phase the question can be asked in the right model was built. In other words, is the model able to answer the research questions that were asked. In traditional model validation there is look whether the model is an accurate representation of the real-world system. This is done by comparing real-world data with the experimental results. However this method is often not compatible with (long-term) agent-based models because agent-based model often explore possible future states. In that case it is impossible to compare experimental results with real world data, because there is no real world data available (van Dam et al., 2013). Also in the case of this research it is near impossible to compare model results with real world data because this research explores the influence of a capacity market on the development of EES, a situation that has not yet occurred in the real world. So instead of using traditional validation, in the validation part there is looked whether the model is useful and suitable to answer the research question. In literature there are several studies that deal with the validation of long-term decision support models for which traditional validation is not applicable. In the study of Augusiak, Van den Brink and Grimm (2014) a literature study to this subject is preformed and a standard set of terms for validation is determined, which they call evaluation. In this research there six elements of evaluation are used for validating the model. The six elements are, data evaluation, conceptual model evaluation, implementation verification, model output verification, model analysis and model output corroborator.

9.1 Data Evaluation

With data evaluation, the data that is used to parameterize the model, undergoes a quality assessment. With the term data, not only numerical data is meant but also qualitative data such as expert knowledge or pattern that are used in the model (Augusiak et al., 2014). In the EES expansion of the EMLab-model both numerical data is used for the set-up of the model, as well patterns that are used for extrapolation of the exogenous variables of the model. The numerical data that is used for the set-up of the different scenarios of the model is described in Chapter 7. Data that is used for the set-up describes the current set-up of the Dutch electricity market, such as the number of power plants in the Netherland, there capacity, the current electricity demand in the Netherlands, the fuel prices of fossil fuels, the hourly wind and sun profiles in the Netherlands and the installed EES capacity and it’s parameters. The quality of this data can be assessed as high because this is data based upon measurements and analyzes of reliable institutes and sources such as TenneT, TU Delft and the ECN. A more detailed description of this data and its sources is given in Chapter 7.

A second type of data that is used for parameterizing the EES expansion of the EMLab-model are the pattern that are used to extrapolate the exogenous variables of the model. The growth of fuel prices and demand growth in the model are extrapolated with triangular probability distributions. This is a model choice that is made by the developers of the original EMLab-Generation model because these type of distributions make...
it possible to determine which trend is simulated, even when the year-to-year realization is probabilistic and because of their properties the trend lines show multi-year swings which resemble the cycles in the real market. A more detailed explanation of these distributions can be found in the EMLab-Generation report (De Vries, Chappin, et al., 2013). Because of substantiation of the choice for these patterns and the fact that these patterns are already used in the original EMLab-Generation model which is validated, the quality of these patterns is considered as high.

9.2 Conceptual model evaluation

With conceptual model evaluation is meant, the critical assessment of the simplifying assumptions that underlying a model’s design. Evaluating this means to explicitly list, discuss, and justify the most simplifying and important assumptions of the model (Augusiak et al., 2014). The conceptual model itself is described in detail is Chapter 4. In this conceptualization an effort is made to translate the short term effects of EES in a long term electricity market model. Translating short term effects into a long term model comes with some difficulties and because of that some important assumptions had to be made. The main difficulty with conceptualization of the short term effects is that the current EMLab time step is too big for short term effects and because of that somewhere in the sequence of the model algorithm this time step had to be reduced. Due to time constraints and the current architecture of the model choices - concerning the reduction of the time step - had to be made that have a significant influence on the model outcomes. The most important choice was to implement the optimization model in the RES algorithm, which takes place before the market clearing. This choice was made because in this algorithm already a reduced time step of 1 hour was implemented. This choice led to 3 important assumptions that had to be made. These 3 most important and simplifying assumptions that were made during the conceptualization phase are:

1. The first assumption is that the model expansion is limited to the market algorithm part of the model and not the investment algorithm due to time constraints, this has important implications for the experimental setup.
2. A second assumption is that perfect load information for a whole year is assumed in the model, this has consequences for the interpretation of the results from the model.
3. The third assumptions is that the load time series are optimized in the model and instead of the price time series.

These assumptions that are made have to be taken into account when conclusions are drawn from the experimental results. However the assumptions and simplifications are well-considered and aforethought, so when they are taken into account in drawing conclusions, the conclusions of the model can still give some interesting insights into the behavior of the combination of a capacity market with EES in the context of the Dutch electricity market.

9.3 Implementation verification

Implementation verification is defined as the critical assessment whether the model code that that is the result of the formulization phase is tested for programming errors and if the implemented model performs as was indicated in the conceptualization phase (Augusiak et al., 2014). This is the verification of the model, which is described in the previous paragraph. From this verification could be concluded that the translation from the conceptualization phase to the formulization phase was done in the right way and that the model is debugged.
9.4 Model output verification

Model output verification is defined by Augusiak (2014) as the critical assessment of how well the model output matches observations and to what degree calibrations and effects of environmental drivers were involved in obtaining good fits of model output and data. This is important because risk exists that a high degree of parameter calibration in order to enforce successful verification may actually result in a set of unrealistic parameter combinations.

Because this research is a first exploration into possible effects of a capacity market on the development of EES, parameters were not calibrated to get good model fits with observations.

9.5 Model Analysis

Model analysis is defined by Augusiak as the assessment of how sensitive the model output is to changes in the model input parameters and how well the emerged behavior from the model output is understood by the modeler. In 7.1.3 the sensitivity analysis of the model is described. In this paragraph the sensitivity of the model output is tested against two sets of input parameter. The first set is the amount of segments of the load duration curve because it was expected this could have a significant influence on the revenues for the EES operator. From the analysis it could be concluded that the model showed some sensitivity to changes in the amount of segments, however this was not that big.

9.6 Model output corroboration

With model output corroboration a comparison is made between the experimental results from the model and independent data and patterns that were not used in the conceptualization, formulization and verification phase (Augusiak et al., 2014). In this research an exploratory study is performed into the influence of a capacity market on the development of EES. From literature two different hypotheses could be established with opposite expectations. Because of this it is difficult to compare the experimental results of this influence with independent data, because this data contradicts itself. However the EMLab-Generation model is an exploratory model of a electricity market. So it can be seen if the outcomes of the model on general indicators of a electricity market lie within expected ranges. A main general indicator of the electricity market is the average electricity price. In Figure 12 the average electricity prices on the APX per month of the last year are shown (APX Group, 2015). From this figure it can be concluded that the average electricity price fluctuates between 35 and 45 €/MWh. The average electricity price in the baseline scenario of the model fluctuates around 70 €/MWh. This electricity price is higher than the average electricity price of the APX however this could be declared because in the baseline scenarios of the EMLab-generation model high amounts of RES are incorporated in the generation portfolio because of the target investor (the installed RES capacity is on average higher in the model compared to the current installed capacity of RES). These high amount provide high price spikes which leads to a higher electricity price. If there is looked at the scenarios with a capacity market, EES or a combination the electricity prices fluctuates around €50/MWh. In these scenarios the same amount of RES is incorporated however the measure ensure more flexible capacity which smooths out the price spikes.

So concluding if the electricity prices of the baseline scenario are compared with prices from the real Dutch electricity market, the prices from the model look to high. However in the baseline scenario a higher amount of RES capacity is installed and this ensures higher price spikes. When measures smooth out these price
spikes the prices of the model resemble more the prices of the Dutch electricity market. Because of this it can be concluded that the data from the model resembles an independent data pattern.

9.7 Conclusions

The goal of this chapter was to see if the extension that was built to the EMLab-Generation model was the right model. In other words, is the model able to answer the research questions that were asked. The validation was performed on the basis of the study of Augusiak et al. (2014). In this study a standard set of six terms for validation is determined, which is called evaluation. The six elements are, data evaluation, conceptual model evaluation, implementation verification, model output verification, model analysis and model output corroboration. After going through the six steps of the evaluation method it can be concluded that the model is valid.
Chapter 10

Conclusions & Discussions

The main research question of this research was: “How does a capacity market influence the development of electrical energy storage capacity, if the share of renewable energy sources will grow as envisioned in the Delft Plan?”

In this chapter an answer will be given to this research question on the basis of the results that were presented in Chapter 8. This will be done in the first section of this chapter. After this the results will be discussed in the context of the assumptions that were made in the conceptualization phase. Subsequently the insights of the results for society will be discussed and in the last section the recommendation for further research will be given.

10.1 Main findings

In the past few years some powerful drivers have led to the call for a change of the energy system. Trends such as the dependence on imported oil and gas, the depletion of oil and gas reservoirs, and the rise of atmospheric concentrations of CO$_2$ have driven the promotion of Renewable Energy Sources (RES). Because of these factors the European Union has established the 20-20-20 targets, which are “mandatory targets consistent with a 20% share of energy from renewable sources by 2020”. This growing share of RES in the electricity markets in combination with the liberalized energy markets in Europe however, raises concerns about the security of supply of the future electricity markets. Especially the variability and unpredictability of RES lead to these concerns.

To address these concerns Delft University of Technology, in combination with Roland Berger, developed the so-called Delft Plan. In this Delft Plan a vision is presented on how the Netherlands can anticipate on these complex system changes in the electricity markets. The aim of the Delft Plan is a fully sustainable Dutch energy system in 2050. Concepts as conversion, transport, system integration and electrical energy storage (EES) are of vital importance to reach this aim.

So far we have seen that the level of installed EES capacity, needed to provide flexibility in the market, grows much slower than the level of installed RES capacity. A possible alternative approach to provide this flexibility would be the use of thermal generators. To secure investments in thermal generators several European countries envision the institutionalization of a capacity market in electricity markets with a growing share of RES. The introduction of these capacity markets might also lead to higher investments in EESs. This because capacity markets provide payments for back-up capacity and besides thermal generators also EESs can provide this capacity. Such payments can be particularly important for EES, which may rely to a greater extent than thermal generators on payments for societal benefits. On the other hand both measures have the same stabilizing effect on the electricity market. The introduction of a capacity market could however also lead to a decline in EES investments. Because both measures can be seen as substitutes for each other, the possibility is created that the need for EES capacity decreases when a capacity market is
introduced, leading to a decrease in investments in EES capacity. Given these contradicting hypotheses it is thus unsure what the influence is of a capacity market on the development of EES would be. To research this an EES extension was built for the existing Energy Modelling Laboratory (EMLab) - Generation model following two sub-research questions:

1. How could the incorporation of EES capacity in an electricity system, and the relations between EES capacity and capacity markets be conceptualized?
2. How could the EMLab-generation model be extended by incorporating EES capacity?

A last and third sub research questions is as follows:

3. How can the possible effects of capacity markets on the development of EES capacity be explored?

To answer these questions an experimental set-up was developed to let the EMLab-Generation model simulate the Dutch electricity market with EES capacity, a capacity market and a combination of both. In this experimental set-up two hypotheses were introduced. The first hypothesis states that because EES can provide peak capacity, a capacity market could have a positive influence on the development of EES. The second hypothesis states that a capacity market and EES can be seen as substitutes for each other and because of this the need for EES decreases with the introduction of a capacity market.

These two hypotheses are tested by looking at seven different indicators, divided over three categories. The first category looks directly at revenues and profit of the EES operator to see if there is a difference between EES capacity with and without a capacity market.

- For this category the differences between the group of scenarios with 1) only EES capacity and 2) with EES capacity and a capacity market are examined.
- The second category looks at the influence of the combination of a capacity market and EES on the electricity market itself. The indicators supply ratio, the ratio between RES and fossil fuel generation, average electricity price per year and price volatility fall under this category.
- The last category looks at the consumer variable costs to consumer.

The most important conclusion of the research is that the model cannot tell us if a capacity market has a positive or negative influence on the development of EES, however it can be concluded that when EES capacity is installed the need for a capacity market is reduced. These conclusions will be further elaborated in the section below.

**Fout! Verwijzingsbron niet gevonden.** shows the indices of the cumulative revenues and profits of an EES operator over 40 years. As a base value the scenario with the lowest revenues/profit is taken. The red bars show the results of all scenarios with only EES capacity and the yellow bars show the results of the scenarios with EES capacity and a capacity market.

The results of the experiments show that a capacity market does not have a substantial influence on the revenues and profit of the EES operator. When examining the cumulative revenues over 40 years for the EES operator we see that there is a difference of only 14% between the cumulative revenues of the scenarios with only EES and the scenarios with a combination of both. If the profits of the EES operator are calculated by subtracting the costs from these revenues, the difference between both groups of scenarios shrinks even further to less than 1%. This means that the earning of EES capacity for its operator are not significantly
higher or lower when there is a capacity market implemented. So looking at the results of the revenue and profit indicator it can be concluded that a capacity market does not have a positive influence on the investments in EES capacity, however it also does not have a negative influence on the investment in EES capacity. This means that both hypothesis 1 and hypothesis 2 are disproved.

Figure 33 shows the indices of the electricity market indicators and the consumer indicator. Also for these indicators applies that the base value per indicator is the scenario with the lowest value. The blue bar shows the results of the baseline scenario, the red bars show the result of the scenarios with only EES capacity, the green bar shows the capacity market scenario and the yellow bars show the results of the scenarios with the combination of a capacity market and EES capacity. Looking at all indicators it can be concluded that the combination of a capacity market with EES capacity makes a no substantial difference compared to the scenarios with only EES capacity:

- For both groups of scenarios with EES capacity the supply ratios are higher compared to the baseline scenario and the capacity market scenario, but compared to each other they are almost equal.
- When looking at the generation portfolio after 40 years, this portfolio looks almost the same for both groups of scenarios with EES capacity. In Figure 33 the indices for the ratio between RES and fossil fuels generation in 2050 are shown. For this indicator it also can be said that there is no significant difference between the both groups with EES.
- In Figure 33 the indices for the average electricity price per year are shown. No substantial difference can be noticed between the scenarios with only EES capacity and the combination between EES capacity and a capacity market. The electricity prices are almost equal to each other with these two groups of scenarios, however also with this indicator there is a difference between the baseline scenario and these two groups of scenarios.
For the consumer indicator, cost to consumer, the results show the same pattern. Between the two groups of scenarios with EES capacity no significant difference can be noticed. However it can be seen that the cost to consumer are considerably lower for these groups of scenarios compared to the baseline scenario.

This means that the results on the indicators - that are not directly related to the revenues or profits of the EES operator - also disprove both hypothesis 1 as well as hypothesis 2. For none of the indicators a positive influence from the combination of EES and capacity market can be noticed, which would support the mechanism that because EES can also provide peak capacity, a capacity market could have a positive influence on the development on EES. Yet regarding hypothesis 2 also none of the indicators shows a significant decrease, which would have supported the idea that a capacity market and EES can be seen as substitutes for each other and because of this the need for EES decreases with the introduction of a capacity market.

Concluding we can say that for none of the indicators a significant difference can be noticed between the scenarios with only EES capacity and the scenarios with EES capacity and a capacity market. However the outcomes do differ substantially from the baseline and only capacity market scenario. In this research the question was asked if a capacity market has an influence on the development of EES capacity, but this question can also be reversed. An increase in price volatility is one of the reasons that a capacity market may be needed, however if EES capacity decreases this price volatility the need for a capacity market might in its turn be reduced. When looking at the price volatility in the experimental results it can be seen that the price volatility decreases for all the scenarios with EES capacity, a capacity market or a combination of both.
This is both true for the price volatility over the years and for the price volatility within one year. From the price duration curves of the years 2020, 2030, 2040 and 2050 it can be concluded that the price volatility is the greatest for the baseline scenario and that the price volatility for all other scenarios is approximately equal. This means that EES capacity has the same positive influence on price volatility as a capacity market with increasing shares of RES. So when there is EES capacity installed, this reduces the need for a capacity market regarding price volatility. When looking at the supply ratio it can be seen that both EES and a capacity market separately ensure a higher supply ratio, but that the combination of both does not ensure a higher supply ratio. This means that the effects of a capacity market on the supply ratio even become smaller with the combination with EES. So here the same line of reasoning can be used that when there is EES capacity is installed, this the need for a capacity market reduces because the EES capacity has the same or even a more positive effect on the supply ratio compared to a capacity market.

10.2 Discussions of results
In the previous section the conclusions of the analysis were presented. From these results some interesting conclusions can be drawn. The most important conclusion of the research was that the model cannot tell us if a capacity market has a positive or negative influence on the development of EES, however it can be concluded that when EES capacity is installed the need for a capacity market is reduced. However in the conceptualization phase many assumptions had to be made to model the short-term effects of EES in the long term EMLab-Generation model. These assumptions influence the way the results and conclusions of the previous chapter can be interpreted. In this section all the assumptions and their effect on the results will be discussed.

10.2.1 EES investments
This research was set-up to make a first exploration if a capacity market could have an influence on the development of EES. In other words, to look if a capacity market would influence the investments in EES. This because the current installed EES capacity cannot cope with the fluctuations in supply of the installed RES capacity and the investment in EES are growing slower compared to the investment in RES capacity. The method used to research this was expanding the EMLab-Generation model of the TU Delft in which both the market clearing of the electricity market and investments in new technologies are modelled. However due to time constraints it was impossible to expand the model with an EES module in both the market algorithm and the investment algorithm. Because of this it was chosen to only build a module for the market algorithm part of the EMLab-Generation model. This modeling choice has important consequences for answering the initial research question.

Because by not incorporating EES in the investment algorithm, the investment in EES over time could not be modelled in the model itself and so no direct conclusions about these investments can be drawn from the model. The alternative way of answering the research question is to determine a fixed amount of EES capacity as an exogenous variable in the model and look at the revenues and profit of this EES capacity. Based on this analysis it can be determined if this fixed amount of EES makes a profit in the model and if a capacity market influences its revenues and profit. However a development in investment cannot be seen and only indirect conclusions can be drawn about this by speculating if investors would invest in EES capacity based on the results of the revenues analysis from the model.
Besides the fact that only indirect conclusion can be drawn, the amount of EES is fixed in the model, so it cannot be seen if storage would be more or less profitable with changes over time in the amount of storage, because it is not possible to adjust the optimal amount of EES internally in the model. This is partly overcome by changing the amount of storage between different scenarios and examining if this would make a difference, however the fact remains that the model itself cannot determine the optimal amount of investment in EES capacity and so the optimal amount of EES capacity. The results of the experiments show that a capacity market seems not to have a significant influence on the revenues and profit of EES. However taken the above remarks into account it could be possible that if the model is able to determine the most optimal amount of EES capacity, the revenues of storage would increase and the influence of the capacity market could be bigger because the revenues of this capacity market could be taken into account with the investment decisions in the model, leading to a more optimal amount of EES in the model. However looking at the current results it is not expected that this could increase the profits of storage so much that it becomes interesting for investors to invest in storage.

A second consequence of the fact that EES is not incorporated in the investment algorithm is that this makes it more difficult to test hypothesis 2. Hypothesis 2 states that EES and a capacity market both have stabilizing effects on the fluctuations in the load duration curve. So because of this they can be seen as substitutes for each other and this creates the risk that the need for EES decreases because fossil fuels generators can recover their fixed costs more easily due to the capacity market. And because of this investments in the (more) expensive alternative of EES capacity would decrease. This hypothesis is difficult to test with the current model because in the current model the amount of EES capacity is determined exogenously. So the choice of an investor for either EES or fossil fuels (to increase flexibility) cannot be seen in the model. The only thing that can be observed is if in the market clearing algorithm the revenues of EES or fossil fuels are greater so which of the two would be more interesting to invest in from an investors point of view. Because of this more research is needed to draw conclusions if the mechanism that is described by hypothesis 2 works in that way.

10.2.2 Short term effects in a long term model
To implement an EES module in the market algorithm of the EMLab-Generation model some important assumptions had to be made. The working of EES is based upon (relatively) short term fluctuations of a few hour to a couple of days in the load and price curves of the electricity market. However the EMLab-Generation model is a long term model with time steps of a year, so it disregards these short term fluctuations. This problem already occurred with implementing RES generating techniques, because the effects on the load duration curve of RES are also based upon hourly wind and sun time series. So to implement RES generation techniques in the model a module was build were hourly times series were used to calculate the RES generation after which these were subtracted from the load duration curve. Hereby the assumptions is made that when there is enough wind or sun to produce form RES, this produced electricity will always be sold first because it’s marginal cots are equal to zero. Because this assumption the RES module could take place before the market algorithm runs. Since this is the only place in the model were the time step that is used for calculations is equal to one hour instead of one year, it was chosen to implement the EES module in this part of the model. However this had two important consequences, the first is that EES has also priority before all other generators (except for RES), this means that EES will always be dispatched if this smooths out fluctuations in the load duration curve, even when it was a cheaper option to do this with fossil fuel generators. This effect of this on the model results is that the revenues and the dispatch
of EES is to positive, this means that in reality EES would not have been dispatched as much as in done in the model right now. The second consequence is that the optimization model optimizes EES use over the load duration curve and not the price duration curve. To calculate the most optimal dispatch of EES from the perspective of the energy producer, normally the objective function is to maximize the revenues by optimizing the EES dispatch over the price time series instead of optimizing the load time series. By optimizing in such a way that the load curve becomes as flat as possible this will minimize losses and reduce peak loads which will fulfill the objectives of the network operator instead of the energy producer. While in the model the revenues are calculated for an energy producer and not the network operator. So it could be that if the dispatch of EES was calculated by optimizing a price time series, a more optimal dispatch of EES for the energy producer would been found and thus the revenues could be higher. For the results of the current model this means that with optimization over the load duration curve, less optimal results in terms of revenues were calculated. However research shows that the price duration curves follows the load duration curve closely, so it would be unlikely that this has a really great influence on the revenues.

10.2.3 Simplified version of EES

To model an EES module a lot of assumptions were made which lead to a simplified working of the EES module. One of the assumption that was made is, that with the optimization model perfect load information for one year is assumed. This means that the most optimal dispatch for EES is calculated for a full year. However in the real world, the load information from hour to hour is even exactly known for a few days ahead, let alone for a full year. For the results this means that the revenues and the influence of EES on the electricity market is too optimistic. The current results show that the combination of a capacity market with EES could have positive effects on the electricity market and that the revenues of EES increase over the years, however the cumulative profits of EES are still negative. Taken the assumptions of perfect information into account, this means that it could be expected that the profits in the real world would be lower.

To calculate the amount of EES capacity in the model a research of the TU Delft was used in which the optimal amount of EES capacity was calculated for fluctuations on different timescales. Because research showed that EES has the most potential for fluctuations on a time scales around 40 hours, the amount of storage was chosen for fluctuations on a time scale of 40 hours. This means that the most optimal amount of storage was chosen on the most optimal time scale. Because these parameters represent the most optimal values, the model result based upon these parameters would show optimal results. However in the real world these optimal conditions do not apply, because of that in the real world the results of the scenarios with storage would be less positive than the results from the model.

Another model choice is that it is only possible to have one EES installation in each zone of the model. This means that only one type of storage per zone can be simulated. In the set-up of the experiments the Compressed Air Energy Storage was chosen as the storage type, because research showed that this has the greatest potential in the Netherlands. However CAES is not the most optimal type of storage for different fluctuations on different time scales. So probably it would be more optimal to have more types of EES in the model with each having a different set of parameters for the EES characteristics. This would also be more realistic when compared to the real world. It would be very unrealistic to only have one type of storage in each country. Regarding the results this would mean that the results will turn out a bit more positive from an EES owner’s perspective, because the storage dispatch would be closer to optimal.
10.3 Insights for society

The Delft Plan can be seen as a starting point for further development of the shared strategies of the Dutch government, market players and research institutions. This shared strategy could be a starting point to help harmonize the regulatory regimes across the EU or at least Northwest Europe and reduce regulatory risk. These are factors that are often discussed in literature which can improve the investment climate for investors in RES. Improving this climate could trigger more investment in RES, which could help reach the mandatory targets of the European Union.

The main insight from this research is that it cannot be concluded from the results that a capacity market has a positive nor negative influence on the development of EES, however it can be concluded that when EES capacity is installed, it reduces the need for a capacity market. In this section this conclusion is translated into insight for society. In other words what does this conclusion mean for all the actors involved.

The Dutch government has to reach the mandatory RES targets that have been imposed by the European Union. However these growing shares of RES have a negative influence upon the price volatility and the security of supply of the Dutch electricity network. For that reason some other European countries have introduced capacity markets to secure investments in flexible generation capacity. From this study it can be concluded that a capacity market would have a positive influence on the price volatility and the supply ratio in the Dutch electricity market. However a capacity market secures investments in thermal generator that are mainly fueled with fossil fuels which are not sustainable. For that reason EES capacity could be a better alternative. From this study it can be concluded that EES capacity has the same or even slightly better influence on the supply ratio and the same positive influence on the price volatility as a capacity market. However a major drawback for EES capacity is the fact that it is not profitable. This means that without significant improvement in the fixed costs or subsidies from the government there could never be a profitable business case for EES capacity. The hypothesis that a capacity market could have a positive influence on this business case is with the results of this study disproved. Besides flexible capacity and EES capacity, the needed flexibility in the electricity market could also be provided by other measures like interconnection capacity, demand response and conversion of energy sources. More research is need to see if these measures could have the same influence on the security of supply and price volatility as EES capacity and a capacity market.

Another interesting conclusion can be drawn from this research concerning policy measure to increase flexibility in the Dutch electricity market. The results show that when flexibility is increased in the electricity market, the share of electricity that is produced by coal generators increases. The reason for this is that when flexibility increases, cheap baseline generators such as coal fired power plants can produce at higher baseline levels, because the flexibility smooths out the load duration curve. This means that the CO₂ emissions increase as a result of an increase in flexibility. A measure to counteract this effect is to penalize the emissions of CO₂. At this moment an example of such a penalty is the European Union Emission Trading Scheme. This mechanism is also in cooperated in the EMLab-Generation model, so an interesting research topic would be to see if this ETS counteracts the effects of the increased flexibility regarding the CO₂ emissions.

As mentioned in chapter 2, TenneT is responsible for balancing the electricity network and in that way safeguarding the security of supply of the electricity network. The strategic priorities of TenneT mentions
that they want to facilitate “spread and store”. What this means is that to integrate RES TenneT states that distribution and sufficient storage is necessary to better balance the TenneT grid and create access to RES. Resulting in less volatile supply, large storage capacity and different demand curves, thereby helping to realize Dutch renewable energy targets in a cost-efficient way. This means that TenneT wants to facilitate more EES capacity in the Dutch electricity market. However from this research it can be concluded that EES capacity is not cost efficient, because the fixed costs are too high compared to the revenues that can be earned be the differences in electricity prices. Because of this reason other measure to help integrate RES such as interconnection capacity, demand response or facilitating energy conversion techniques seem more realistic options for TenneT in both the short term as the long term, as EES capacity is not expected to become more cost effective.

If the Dutch government decides to introduce a capacity market in the Dutch electricity market this also has an influence on TenneT. As can be seen from this research a capacity market has a positive influence on the supply ratio and the price volatility. These effects are in line with the goals of TenneT to maintain the grid stability. So the introduction of a capacity market contributes in a positive way to the goals of TenneT.

From an investors point of view this thesis showed that a capacity market does not positively influence the revenues of EES capacity. Researched so far showed that EES capacity at this moment does not have a positive business case and so for investors it is not interesting to invest in EES capacity and its development. This is one of the important reasons the development of EES capacity is lagging behind on the development of RES. This research shows that when a capacity market would be introduced, this does not have a significant positive influence on the revenues of EES capacity, making EES capacity not more interesting form an investors point of view. Interesting further research would be which policy measures would make the business case of EES capacity more interesting for investors. This research showed that EES capacity does have a positive influence on the security of supply and price volatility so it contributes to a better integration of RES into the electricity system.

From a consumer perspective this research shows that the total costs to consumer probably are going to increase in the upcoming years. The increased share of RES increases the price volatility which leads to on average higher electricity prices. Both a capacity market, EES capacity as well the combination of both measures reduce price volatility. A consequence is that also the average electricity prices decrease because peak prices are lower. So from a consumer point of view both measures have positive effects on the average electricity price. When looking at the total costs to consumer of the scenarios with only EES capacity, it can be seen that the total costs to consumer are slightly higher for the scenarios with a capacity market only. This can be explained because in these scenarios the costs of a capacity market are included in the total costs to consumer. However this difference is not considerably large.

10.4 Recommendations for further research

This research showed the tip of the iceberg of the possibilities to research EES in EMLab-Generation in combination with different policy instruments. This research itself showed - as many other studies (Brauner et al., 2014; Denholm et al., 2010; Lott & Kim, 2014; Staveren, 2014; Verzijlbergh, 2013) - that there is a problem with the development of storage because the fluctuations in electricity prices do not ensure sufficient revenues, even in the combination with a capacity market. However with EMLab-Generation the combination between EES and many different policy instruments can be researched to see what their effects are on the
development of storage. To do so first the EES implementation needs to be improved. Important improvements are:

- Incorporating EES in the investment algorithm of EMLab-Generation. The main difficulty hereby would be calculating the expected revenues of storage and so the NPV on which the investment decision would be based. This is difficult because the revenues of storage arise from fluctuations in electricity prices and it would be very hard to extrapolate these to calculate expected revenues.
- Place the EES algorithm after the market clearing algorithm. This would mean that it is possible to optimize the storage dispatch over time series and EES would not get priority over fossil fuel generators, which would give a more realistic outcomes of the model. To do this the load duration curve needs to be translated back into times series and more specially price times series instead of the load time series.
- Make it possible to have more EES techniques in one zone. This can be done by rewriting the market constraints in the optimization model.

If these improvements are made to the EMLab-Generation EES module interesting topic for research could be:

- Cross border effects of EES. This is already possible because the EES optimization algorithm already works with two zones, however because of time constraints this was not researched in this study.
- Look further into the influence of a capacity market on EES. Because of the limitations of the EES module in this research, a lot of assumptions had to be made. With the proposed improvements some conclusions could be sharpened and new insights could be gained.
- In this research only one specific type of capacity remuneration is researched. It could be interesting to see the influence of multiple capacity mechanism on the development of EES.
- Different types of EES with different characteristics on different time scales.
- The influence of other measure to increase flexibility on the development of EES
Chapter 11

Reflection

After having drawn the conclusions and now that an answer is given to the research question, this research will end with a reflection on the total graduation project. First the research will be positioned existing literature, by giving reflection on the contribution to present theory. After this a more personal reflection upon the used methods in this research and the graduation process itself will be given.

11.1 Position of research in existing literature

Due to the growing environmental concerns and the continuously increasing global warming, the past few years a lot of research has been conducted on the topic of how the development of renewable energy sources (RES) can be accelerated and the share of RES in electricity markets can be increased. Combined with changing legislation and subsidy regimes this has led to a growing share of RES in the past few years. This change in the electricity markets has in its turn led to a broad range of studies that have been conducted on the topic of the influence of RES on the development of future electricity markets (Haas, 2014; Klessmann et al., 2008; Milstein & Tishler, 2011). Two of the main challenges that are identified in these studies are that the variability of RES has a negative influence on the reliability of the electricity grid and that it increases the price volatility of electricity prices. Possible solutions are: flexible capacity, energy storage, interconnection capacity, and demand response amongst others. Flexible capacity could be secured by a capacity market and from this point of view, research has been done looking into the effect of capacity markets upon the security of supply with growing shares of RES (Iychettia, 2013). The needed flexibility could also be provided by energy storage, however, research shows that the costs of energy storage are difficult to quantify and even when they are quantified the costs of storage are relatively high. This is why with current technologies storage has a negative business case.

A lot of research has been done into the measures that can provide (extra) flexibility for the electricity market. Research up until now has mainly focused on these measures separately. However, limited research has been done into the effects of these measures upon each other. The research that is described in this thesis can be positioned between research into capacity markets and its influence on the security of supply of electricity and the effect of electrical energy storage (EES) upon the security of supply. This study researches the influence of a capacity market upon the development of EES capacity. This means that the influence of a capacity market on the security of supply and the influence of EES on the security of supply is researched. However, this research mainly focuses on the differences between both measures and if it would lead to different results if both measures are combined.

From this research it is concluded that a capacity market does not directly influence the development of EES capacity because it does not have a significant effect upon the profits of EES capacity. Besides this, the combination of a capacity market and EES capacity shows no different results upon the indicators ‘supply ratio’, ‘average electricity price’, ‘price volatility’, ‘ratio between RES and fossil fuel production’ and ‘costs to
consumer’ compared to scenarios of an electricity market with only EES capacity installed. However, the outcomes do show that there is a significant positive difference between all the scenarios with EES capacity (with and without a capacity market) compared to the baseline scenario and that these results are comparable or even slightly more positive compared to the scenario with only a capacity market. This means that when EES capacity is installed in an electricity market, the need for a capacity market decreases. These results could give a positive boost for research into EES capacity. Interesting further research could be to look at the influence of other measure that can increase flexibility in the electricity market upon EES capacity and to see if a combination with these measures could have a positive influence on the development of EES capacity.

11.2 Reflection on used method

Going through the process of graduating, I learned a lot and looking back, I made a lot of choices that with the hindsight knowledge that I have now, I maybe would not make again. In this section the choices regarding the methodology of this research will be discussed.

At the start of this graduation project I came up with the research question what the influence of a capacity market would be on the development of storage capacity in the Dutch electricity market. An important part of this research question is the development of storage. With this development of storage I wanted to focus on how the amount of installed storage capacity would change over time. Building an extension to the EMLab-Generation model seemed like the perfect method to research this because the EMLab-Generation model had both a market clearing algorithm as well as an investment algorithm. However, after a few weeks, it became clear that modeling an EES extension to only the market algorithm part of the model would be a big enough challenge for my master thesis. If I now evaluate this decision afterwards, I would argue that I made a good decision timewise. Modeling an EES expansion for the market clearing algorithm took a lot of time, especially verifying and validating this extension and the coupling with the rest of the EMLab-Generation model. Nevertheless, when I now look at the ability of the model and its scenarios in answering my research question, the choice to model only an extension to the market algorithm limited this ability significantly. With only an extension to the market algorithm I was only able to look at revenues of predetermined amounts of installed EES capacity, compared to letting the model itself determine the most optimal amount of installed capacity. I tried to tackle this problem by changing the amount of installed storage capacity for the different scenarios, however, there are an infinite amount of possible levels of installed storage capacity and also an infinite amount of ways this installed capacity can change over time. So determining the optimal amount of installed storage capacity can be a master thesis by itself. The changing levels of storage in this model already showed some substantially different results upon the indicators, so having the most optimal amount of EES capacity in the model could potentially result in a more accurate answer to the research question.

Besides the fact that the model cannot determine the optimal amount of storage itself and the influence of this on the results, the choice to only model an extension for the market algorithm had an influence upon the ability of the model to research the mechanisms of one of the two hypotheses. Hypothesis 2 states that EES and a capacity market both have stabilizing effects on the fluctuations in the load duration curve. So because of this, they could be seen as substitutes for each other. This would create the risk that the need for EES decreases when a capacity market is in place because fossil fuels generators can recover their fixed costs more easily. This hypotheses is difficult to test because in the current model the amount of EES capacity is
predetermined. So the choice of an investor for either EES or fossil fuels (to increase flexibility) cannot be observed in the simulation results. The only thing that can be observed is if in the market clearing algorithm the revenues of EES or fossil fuels are greater so which of the two would be more interesting to invest in from an investors point of view.

Thus choosing to only model an extension for the market algorithm of the EMLab-Generation model was timewise a wise decision, however it had a relatively large impact on the results of this study and the ability to answer the research question.

The current EMLab-Generation model is a model that is able to simulated two interconnected zones or countries. Because of this set-up, I developed a mathematical storage optimization model in the conceptualization for two interconnected zones or countries and with the formalization I translated this optimization model into the pseudo code. This was an iterative process were I first conceptualized and modelled an optimization model for one zone or country only. Conceptualizing a model for 2 zones took some extra time and especially incorporating the two zone extension into the EMLab-Generation model took quite some extra time. My scenarios are set-up with only 1 electricity market in 1 country. This means that for my scenario set-up it was not necessary to build an extension for two zones. Which means I could have spared time by not building an extension for two zones. On the other hand building this extension for two zones provided me with more insights in how storage capacity influences electricity markets and how the EMLab-Generation model itself was build. These insights were very helpful during the rest of the project with the verification and validation of the model and interpreting the results of the experiments.

The main methodology that was used in this study was agent-based modeling. One of the characteristics of an agent-based model is the fact that it is a strong simplification of the real world. This means that the results from the model have to be considered in the context of a far more complex real world. So it would be interesting to look at the developments of the electricity market that are not taken into account in the experiments and/or the EMLab-Generation model itself. An example of this is that in the experimental set-up I chose to model the compresses energy air storage (CAES) technique. Hereby I made the assumption that the total needed amount of EES capacity to deal with fluctuations in 2030 could be provided only by CAES. For the use of CAES, empty closed spaces are needed to compress the air, such as empty gas fields. However, at this moment the total technical potential of CAES is not yet known for the Netherlands as it is not yet known how many Dutch empty gas fields are suitable for the technology (Lott & Kim, 2014). Apart from the total technical potential that is not yet known, it can be expected that this technology will get a lot of resistance from the Dutch society, as was the case with Carbon Capture Storage (Holt, 2009). Both of these factors are not taken into account because assumption had to be made to simplify the real world so it can be translated into an agent-based model. However, these factors have an influence on the development of EES capacity in the Netherlands and especially on the development of CAES capacity in the Netherlands. Because of this it could be very interesting to see what the influence is of the characteristics of different EES techniques upon the results of this study. This could provide insides in if the choice for a specific EES technique in the Netherlands would have other implication for the Dutch electricity market.

Validation of agent-based models is a challenging part of an agent-based study. One of the ways of validating your model is by comparing real-world data with the experimental results. Though this method is often not compatible with (long-term) agent-based models because agent-based model often explore possible future states. In that case it is impossible to compare experimental results with real world data, because there is...
no real world data available. Also in the case of this research it was nearly impossible to compare model results with real world data because this research explored the influence of a capacity market on the development of EES, a situation that has not yet occurred in the real world. Because of this it was very time consuming and difficult to validate the model. This has led to the fact that even when the deadline of this thesis was almost met, a big error in the model occurred by validating the results of the baseline scenario with earlier model results of the EMLab-Generation model. Because of this my advice is to always allocate sufficient time to the validation process of agent-based models and never forget this.

11.3 Personal reflection

At the start of my graduating process I was looking for a challenging project on the subject of the long term strategy of the Dutch/European electricity markets regarding sustainability. Via the Delft Energy Initiative and Paulien Herder I got the idea to use the Delft Plan as a starting point of my graduating project. When I got in touch with the EMLab-Generation model, I was directly interested in using this agent-based model as the primary method to research the long term strategies of the Dutch electricity market. Looking back, using the EMLab-Generation model as the primary method of my research can be described as challenging. The EMLab-Generation model is an agent-based model that is build using JavaScript in an AgentSpring environment. Except for both the introductory and advanced courses in agent-base modeling at this faculty, before I started this project I had limited to no programming experience. Using EMLab-Generation meant that I had to make myself familiar with programming in JavaScript, writing queries in Gremlin, using GitHub, Springsource, Linux and had to learn to use R-statistics. This was a process with a steep learning curve with moments in which I thought I did not understand anything of what my computer was doing. In this process I was very grateful for all the help I got from the PhD researchers working on EMLab-Generation and the graduating students that also were working on this topic.

Learning to code itself was a new skill I acquired during my graduating process. However, applying it to model electricity markets gave me new insights in the mechanism of these electricity markets and how these markets can develop over time. These new insights confirmed to me again that my interests in the long term lie with answering questions regarding the world’s energy system. Questions as in what way are we going to meet the energy demand in the future; how are we going to increase the share of RES in the energy markets and in what way can we comply these energy markets with the growing shares of RES. I am very glad that with my graduating project I was able to contribute to these questions, even though it was only for a very small part.
Bibliography


Appendices
Appendix A

Model Algorithm

1. Create big matrix which contains columns for the information later used. Fill the columns with starting information (hour of year, initial maximum interconnector capacity. Create Matrix with following columns:
   - Hour of year
   - SegmentId
   - 2x Load
   - 2x intermittent Prod.
   - 2x Res. Load
   - Res. Load Total
   - Interc. Cap.
   - SegmentsAccordingToA
   - SegmentsAccordingtoB

2. Build national load curves, by adding up grid node load curves in each zone. Also fill the residual load columns with the initial load curves. For now simply multiplied with the market wide growth factor.

3. For each power grid node multiply the time series of each intermittent technology type with the installed capacity of that technology type. Subtract intermittent production from the residual load column (one column per zone). Calculate the total residual load (assuming no interconnector constraints). Reduce the load factors by obvious spill, that is RES production greater than demand + interconnector capacity. Do a pre-market clearing of RES production: For each time step check if there's negative residual loads in each country.

4. Export from one country to another country if interconnector constraints and residual and residual load in the other country allow for that. Reduce intermittent production if oversupply. In the end calculate the total residual load curve over all countries. Order the hours in the global residual load curve. Peak load first, base load last.

5. Find values, so that each segments has approximately equal capacity needs.

6. Create DynamicBins as representation for segments and for later calculation of means, no etc. Per bin one sort of information (e.g. residual load, interconnector capacity) and the corresponding hour of the year can be stored. Thus connection to the matrix remains.

7. Store the segment duration and the average load in that segment per country.
Appendix B

UML

Figure 34 UML Domain and Role classes
Figure 35 UML Repository Classes
Appendix C

Pseudo Code optimization model

**PowerGeneratingTechnology Class:**
1. create new Boolean variable $EES$
2. create new double variable $chargeEfficiency$
3. create new double variable $disChargeEfficiency$
4. create new double variable $chargingRate$
5. create new double variable $discharingRate$
6. create new double variable $maxEESCapacity$
7. create new double variable $minEESCapacity$
8. create method to set $EES$ variable to true or false
9. create method to return the value of $EES$ variable
10. create method to set $chargeEfficiency$ to a specific input value
11. create method to return the value of $chargeEfficiency$ value
12. create method to set $disChargeEfficiency$ to a specific input value
13. create method to return the value of $disChargeEfficiency$ value
14. create method to set $chargingRate$ to a specific input value
15. create method to return the value of $chargingRate$ value
16. create method to set $discharingRate$ to a specific input value
17. create method to return the value of $discharingRate$ value
18. create method to set $maxEESCapacity$ to a specific input value
19. create method to return the value of $maxEESCapacity$ value
20. create method to set $minEESCapacity$ to a specific input value
21. create method to return the value of $minEESCapacity$ value
22. create new double variable $initialEES$
23. create new optimization model $cplex$ of the IloCplex class

**24. PowerPlantTechnology Class:**
24. create method to set $initialEES$ to a specific input value
25. create method to return the value of $initialEES$

**27. PowerGeneratingTechnologyRepository Class**
28. create a query $findAllIntermittentPowerGeneratingTechnologies$ which looks up a type value in the class $PowerGeneratingTechnology$ and filters these values by intermittent = true and $EES$ = false
29. create a query $findAllEESPowerGeneratingTechnologies$ which looks up a type value in the class $PowerGeneratingTechnology$ and filters these values by $EES$ = true
30. create a query `findAllEESAndIntermittentPowerGeneratingTechnologies` which looks up a type value in the class `PowerGeneratingTechnology` and filters these values by `intermittent = true`
31. create a query `findOperationalEESPowerPlantsByPowerGridNode` which starts his search at the input node in `LOCATION` and then searches for all types that are equal to `PowerPlant` and out of technology filters on `EES = true` and lasts checks if it is operational

32. **DetermineResidualLoadCurveForTwoCountriesWithEES**
33. create new List `intermittendTechnologyList` which stores `PowerGeneratingTechnologies` and store all EES technologies by executing `findAllIntermittentPowerGeneratingTechnologies`
34. create new List `EESTechnologyList` which stores `PowerGeneratingTechnologies` and store all EES technologies by executing `findAllEESPowerGeneratingTechnologies`
35. create new List `technologyList` which stores `PowerGeneratingTechnologies` and store all EES technologies by executing `findAllEESAndIntermittentPowerGeneratingTechnologies`

36. create a HashMap to store `NETTOCHARGE`
   a. For all `zones` in `zoneList` do
      i. Associates the `columnIterator` value with the key `zone` in the `NETTOCHARGE` map
      ii. Increment `columnIterator` with 1
   b. end for

37. create a HashMap to store `EESCAP`
   a. For all `zones` in `zoneList` do
      i. Associates the `columnIterator` value with the key `zone` in the `EESCAP` map
      ii. Increment `columnIterator` with 1
   b. end for

38. create a HashMap to store `RLOADINZONESRES`
   a. For all `zones` in `zoneList` do
      i. Associates the `columnIterator` value with the key `zone` in the `RLOADINZONESRES` map
      ii. Increment `columnIterator` with 1
   b. end for

39. create new IloCplex model `cplex`

40. create new optimization variable `X` of the IloNumVar class with two indexes → `zone` and `hour`
41. for all `zones` do
   a. for all `hours` do
      i. add variable `X` to the model with minimum value equal to `minimumValue` and maximum value equal to `maximumValue`
   b. end for
42. end for

43. create new expression `X` of the IloLinearNumExpr class with two indexes → `zone` and `hour`
44. for all zones do
   a. for all hours do
      i. add expression $X$ to the model
      ii. add first term $Y$ to expression $X$
      iii. add second term $Z$ to expression $X$
   b. end for
45. end for
46. add minimization object function $objective$ to the model

47. for all zones do
   a. add the following equality constraint to the model: $E_{zone,0} = initialStorage$
48. end for

49. for all zones do
   a. add the following less than or equal constraint to the model: $sOut_{zone,0} \leq E_{zone,0}$
50. end for
51. for all zones do
   a. for hour 1 till last hour do
      i. add the following equality constraint to the model: $storageContent_{zone,hour} = E_{zone,hour}$
   b. end for
52. end for
53. for all zones do
   a. for all hours do
      i. add or the following equality constraint to the model: $mOut_{zone,hour} = marketOutflow_{zone,hour}$ or add $mIn_{zone,hour} = marketInflow_{zone,hour}$ to the model
   b. end for
54. end for

55. if cplex model solves
   a. create new double array variable $nettoChargeZone$ for both zones
   b. create new double array variable $usedEESCap$ for both zones
   c. for all zones & hours do
      i. add to $nettoChargeZone$ array for each hour → nettoCharge = $sIn - sOut$
      ii. add to $usedEESCapZone$ array for each hour → usedEESCap = $E$
   d. end for
   e. for all zones & hours do
      i. add $nettoChargeZone$ array to NETTOCHARGE column in matrix m
      ii. add $usedEESCapZone$ array to EESCAP column in matrix m
   f. end for
   g. for all hours do
i. add Interconnectorcap \( I \) to \textit{INTERCONNECTOR} column in matrix \( m \)

h. end for

i. for all \textit{zones, hours, nodes \& technologies} do
   i. assign \textit{technologyloadfactor} to \textit{TECHNOLOGYLOADFACTORSFORZONEANDNODE} column in matrix \( m \), \textit{technologyloadfactor} = \textit{NETTOCHARGE} / \textit{maxEESCapacity}
   j. end for

56. create a integer variable \textit{RLOADTOTALWITHEES} and set its value equal to columnIterator
57. increment columnIterator with 1
58. create a new array \textit{loadZoneA} with length equal to \textit{amount of rows in matrix m}
59. create a new array \textit{loadZoneB} with length equal to \textit{amount of rows in matrix m}
60. for all rows in matrix \( m \) do
   a. Assign the value of row \( x \) of \textit{RLOADINZONE} in zone A to the \( x \)th value of the \textit{loadZoneA} array
   b. Assign the value of row \( x \) of \textit{RLOADINZONE} in zone B to the \( x \)th value of the \textit{loadZoneB} array
61. create new int \textit{HOURS} which is equal to the amount of hours in the simulation
62. create new double \textit{initialEES} which is equal to the initial energy level of the EES
63. create new list \textit{EESPowerPlantList} which stores objects of class PowerPlant
64. for all zones do
   a. for all nodes do
      i. add all operational EES plants, that are found in the Repository, to the \textit{EESPowerPlantList}
65. end \textit{cplex} model

66. for all \textit{zones \& nodes} do
   a. assign residual load after EES to \textit{RLOADTOTAL} column in matrix \( m \)
67. end for
Appendix D

Pseudo code variables & expressions

1. // Initialize optimization values
2. create a new array loadZoneA with length equal to amount of rows in matrix m
3. create a new array loadZoneB with length equal to amount of rows in matrix m
4. for all rows in matrix m do
   a. Assign the value of row x of RLOADINZONE in zone A to the x\textsuperscript{th} value of the loadZoneA array
   b. Assign the value of row x of RLOADINZONE in zone B to the x\textsuperscript{th} value of the loadZoneB array
5. create new int HOURS which is equal to the amount of hours in the simulation
6. create new double initialEES which is equal to the initial energy level of the EES
7. create new list EESPowerPlantList which stores objects of class PowerPlant
8. for all zones do
   a. for all nodes do
      i. add all operational EES plants, that are found in the Repository, to the EESPowerPlantList
9. // Define new optimization model
10. create new optimization model cplex of the IloCplex class
11. // Define optimization variables
12. create new optimization variable P (load) of the IloNumVar class with two indexes → zone and hour
13. for all zones do
   a. if zone is equal to zone A
      i. for all hours do
         1. add variable P to the model with minimum value equal to the load in zone A at time equal to hour
      ii. end for
   b. end if
   c. if zone is equal to zone B
      i. for all hours do
         1. add variable P to the model with minimum value equal to the load in zone B at time equal to hour
      ii. end for
   d. end if
14. end for
15. create new optimization variable $E$ (energy EES level) of the IloNumVar class with two indexes $\rightarrow$ zone and hour
16. for all zones do
   a. for all hours do
      i. add variable $E$ to the model with minimum value equal to the $\text{minEESCapacity}$ from the EES plant in zone equal to $\text{zone}$, and maximum value equal to the $\text{maxEESCapacity}$ from the EES plant in zone equal to $\text{zone}$
   b. end for
17. end for
18. create new optimization variable $mIn$ (market flow in) of the IloNumVar class with two indexes $\rightarrow$ zone and hour
19. for all zones do
   a. for all hours do
      i. add variable $mIn$ to the model with minimum value equal to zero and maximum value equal to infinity
   b. end for
20. end for
21. create new optimization variable $mOut$ (market flow out) of the IloNumVar class with two indexes $\rightarrow$ zone and hour
22. for all zones do
   a. for all hours do
      i. add variable $mOut$ to the model with minimum value equal to zero and maximum value equal to infinity
   b. end for
23. end for
24. create new optimization variable $sIn$ (EES inflow) of the IloNumVar class with two indexes $\rightarrow$ zone and hour
25. for all zones do
   a. for all hours do
      i. add variable $sIn$ to the model with minimum value equal to zero and maximum value equal to the maximum $\text{chargingRate}$ of the EES plant in zone equal to $\text{zone}$
   b. end for
26. end for
27. create new optimization variable $sOut$ (EES outflow) of the IloNumVar class with two indexes $\rightarrow$ zone and hour
28. for all zones do
   a. for all hours do
      i. add variable $sIn$ to the model with minimum value equal to zero and maximum value equal to the maximum $\text{disChargingRate}$ of the EES plant in zone equal to $\text{zone}$
   b. end for
29. end for
30. create new optimization variable \( I \) (interconnector flow defined from A to B) of the IloNumVar class with one index \( \rightarrow \) hour

31. for all \( hours \) do
   i. add variable \( I \) to the model with minimum value equal to minus the maximum interconnector capacity and maximum value equal to the maximum interconnector capacity
   end for

32. end for

33. // Define expressions

34. create new expression \( EESContent \) of the IloLinearNumExpr class with two indexes \( \rightarrow \) zone and hour

35. for all \( zones \) do
   a. for all \( hours \) do
      i. add expression \( EESContent \) to the model
      ii. add term \( E_{t-1} \) to the expression \( EESContent \)
      iii. add term \( S_t^{+} \eta_{charge} \Delta t \) to the expression \( EESContent \)
      iv. add term \(- S_{t-1} \frac{1}{\eta_{discharge}} \Delta t \) to the expression \( EESContent \)
   end for

36. end for

37. create new expression \( marketOutflow \) of the IloLinearNumExpr class with two indexes \( \rightarrow \) zone and hour

38. for all \( zones \) do
   a. if \( zone \) is equal to zone A
      i. for all \( hours \) do
         1. add expression \( marketOutflow \) to the model
         2. add term \( S_t^{+} T_A \) to the expression \( marketOutflow \)
         3. add term \( I \) to the expression \( marketOutflow \)
      end for
   b. end if
   c. if \( zone \) is equal to zone B
      i. for all \( hours \) do
         1. add expression \( marketOutflow \) to the model
         2. add term \( S_t^{+} T_B \) to the expression \( marketOutflow \)
         3. add term \(- I \) to the expression \( marketOutflow \)
      end for
   d. end if

39. end for

40. create new expression \( marketInflow \) of the IloLinearNumExpr class with two indexes \( \rightarrow \) zone and hour

41. for all \( zones \) do
   a. if \( zone \) is equal to zone A
      i. for all \( hours \) do
         1. add expression \( marketInflow \) to the model
         2. add term \( S_t^{+} T_A \) to the expression \( marketInflow \)
         3. add term \(- I \) to the expression \( marketInflow \)
      end for
2. add term $S_{TA}$ to the expression $\text{marketInflow}$
3. add term $-I$ to the expression $\text{marketInflow}$

b. if zone is equal to zone B
i. for all hours do
   1. add expression $\text{marketOutflow}$ to the model
   2. add term $S_{TB}$ to the expression $\text{marketInflow}$
   3. add term $I$ to the expression $\text{marketInflow}$
ii. end for

c. end if

42. end for

43. create new expression $\text{objective}$ of the IloLQNumExpr class with two indexes $\rightarrow$ zone and hour
44. for all zones do
   a. for all hours do
      i. add expression $\text{objective}$ to the model
      ii. add term $P_{\text{zone}, \text{hour}} \ast P_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
      iii. add term $\text{mIn}_{\text{zone}, \text{hour}} \ast \text{mIn}_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
      iv. add term $\text{mOut}_{\text{zone}, \text{hour}} \ast \text{mOut}_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
      v. add term $2 \ast P_{\text{zone}, \text{hour}} \ast \text{mIn}_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
      vi. add term $-2 \ast P_{\text{zone}, \text{hour}} \ast \text{mOut}_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
      vii. add term $-2 \ast \text{mIn}_{\text{zone}, \text{hour}} \ast \text{mOut}_{\text{zone}, \text{hour}}$ to the expression $\text{objective}$
   b. end for
45. end for
46. // Add objective function to the model
47. add minimization $\text{objective}$ to the model
48. // Add constraints to the model
49. for all zones do
   a. add the following equality constraint to the model: $E_{\text{zone}, 0} = \text{initialStorage}$
50. end for
51. for all zones do
   a. add the following less than or equal constraint to the model: $\text{sOut}_{\text{zone}, 0} \leq E_{\text{zone}, 0}$
52. end for
53. for all zones do
   a. for hour 1 till last hour do
      i. add the following equality constraint to the model: $\text{storageContent}_{\text{zone}, \text{hour}} = E_{\text{zone}, \text{hour}}$
   b. end for
54. end for
55. for all zones do
   a. for all hours do
i. add or the following equality constraint to the model: $mOut_{zone,hour} = marketOutflow_{zone,hour}$ or add $mIn_{zone,hour} = marketInflow_{zone,hour}$ to the model

b. end for

56. end for
Appendix E

Verification: Single agent model & Minimal agent model

Single agent model

```java
import ilog.concert.*;
import ilog.cplex.*;

public class OptimizationModelTest {
    public static void main(String[] args) {

        int HOUR = 10; // hours in a year in this test
        double[] load = {1, 10, 1, 10, 1, 10, 1, 10, 1, 10}; // load per Hour

        double maxEnergycontentStorage = 10;
        double minEnergycontentStorage = 0;
        double initialStorage = 0;
        double maxStorageFlowIn = 1.5;
        double minStorageFlowIn = 0;
        double maxStorageFlowOut = 2;
        double minStorageFlowOut = 0;
        double n = 0.90; // Storage efficiency
        double nInv = 1/n; // Inverse efficiency

        try {
            // define new model
            IloCplex cplex = new IloCplex();

            // define variables
            IloNumVar[] sIn = new IloNumVar[HOUR];
```
for (int i = 0; i < HOUR; i++) {
    sIn[i] = cplex.numVar(minStorageFlowIn, maxStorageFlowIn);
}

IloNumVar[] sOut = new IloNumVar[HOUR];
for (int i = 0; i < HOUR; i++) {
    sOut[i] = cplex.numVar(minStorageFlowOut, maxStorageFlowOut);
}

IloNumVar[] e = new IloNumVar[HOUR];
e[0] = cplex.numVar(initialStorage, initialStorage);
for (int i = 1; i < HOUR; i++) {
    e[i] = cplex.numVar(minEnergycontentStorage, maxEnergycontentStorage);
}

IloNumVar[] loadPerHour = new IloNumVar[HOUR];
for (int i = 0; i < HOUR; i++) {
    loadPerHour[i] = cplex.numVar(load[i], load[i]);
}

IloNumVar[] Hour = new IloNumVar[HOUR];
for (int i = 0; i < HOUR; i++) {
    Hour[i] = cplex.numVar(i, i);
}

// define expressions
IloLinearNumExpr[] exprStorageContent = new IloLinearNumExpr[HOUR];
for (int i = 1; i < HOUR; i++) {
    exprStorageContent[i] = cplex.linearNumExpr();
    exprStorageContent[i].addTerm(1.0, e[i - 1]);
    exprStorageContent[i].addTerm(n, sIn[i - 1]);
    exprStorageContent[i].addTerm(-nInv, sOut[i - 1]);
}

IloLQNumExpr objective = cplex.lqNumExpr();
for (int i = 0; i < HOUR; i++) {
    objective.addTerm(1, loadPerHour[i], loadPerHour[i]);
    objective.addTerm(1, sIn[1], sIn[i]);
    objective.addTerm(1, sOut[1], sOut[i]);
    objective.addTerm(2, loadPerHour[i], sIn[i]);
objective.addTerm(-2, loadPerHour[i], sOut[i]);
objective.addTerm(-2, sIn[i], sOut[i]);
}

// define objective function
cplex.addMinimize(objective);

// define constraints
for (int i = 1; i < HOUR; i++) {
cplex.addEq(exprStorageContent[i], e[i]);
}

// solve model
if (cplex.solve()) {
    System.out.println("objective function is:");
    System.out.println(cplex.getObjValue());
    for (int i = 0; i < HOUR; i++) {
        System.out.println("Hour " + i);
        System.out.println("Storage in " + cplex.getValue(sIn[i]));
        System.out.println("Storage out " + cplex.getValue(sOut[i]));
        System.out.println("Storage " + cplex.getValue(e[i]));
    }
}
else {
    System.out.println("model did not solve");
}

// close cplex

cplex.end();

catch (IloException exc) {
    exc.printStackTrace();
}
package optimizationModelTwoZones;

import java.io.BufferedReader;
import java.io.FileNotFoundException;
import java.io.FileReader;
import java.io.IOException;
import java.util.ArrayList;
import ilog.concert.*;
import ilog.cplex.*;

public class TestModel2 {
    public static void main(String[] args) {

        // Start reader

        String inputFileA = "/home/sophie/Downloads/TestCSVA.csv";
        String inputFileB = "/home/sophie/Downloads/TestCSVB.csv";
        BufferedReader brA = null;
        BufferedReader brB = null;
        String line = "";
        ArrayList<String> hourlyDataA = new ArrayList<String>();
        ArrayList<String> hourlyDataB = new ArrayList<String>();

        try{

            brA = new BufferedReader(new FileReader(inputFileA));
            while((line = brA.readLine()) != null){
                hourlyDataA.add(line);
            }
            brA.close();

            brB = new BufferedReader(new FileReader(inputFileB));
            while((line = brB.readLine()) != null){
                hourlyDataB.add(line);
            }
            brB.close();

        } finally {

            if(brA != null) brA.close();
            if(brB != null) brB.close();

        }

    }
}
brB  =  new BufferedReader(new FileReader(inputFileB));

while((line = brB.readLine()) != null){
    hourlyDataB.add(line);
}

}  

catch(FileNotFoundException e){
    e.printStackTrace();
}

catch(IOException e){
    e.printStackTrace();
}

finally{
    if (brA != null) {
        try {
            brA.close();
        } catch(IOException e){
            e.printStackTrace();
        }
    }

    if (brB != null) {
        try {
            brB.close();
        } catch(IOException e){
            e.printStackTrace();
        }
    }

    double[] hourlyDataDoubleA = new double[hourlyDataA.size()];
    for(int i = 0; i < hourlyDataDoubleA.length; i++){
        hourlyDataDoubleA[i] = Double.parseDouble(hourlyDataA.get(i));
    }

    double[] hourlyDataDoubleB = new double[hourlyDataB.size()];
    for(int i = 0; i < hourlyDataDoubleB.length; i++){
hourlyDataDoubleB[i] = Double.parseDouble(hourlyDataB.get(i));
}

// Start Optimization model

int HOURS = hourlyDataDoubleA.length; // amount of hours in simulation
int[] zone = {1, 2};
int ZONES = zone.length;
double[] loadA = hourlyDataDoubleA; // load per Hour zone A
double[] loadB = hourlyDataDoubleB; // load per Hour zone B
double maxEnergycontentStorage = 10;
double minEnergycontentStorage = 0;
double initialStorage = 0;
double maxStorageFlowIn = 5;
double minStorageFlowIn = 0;
double maxStorageFlowOut = 5;
double minStorageFlowOut = 0;
double maxMarketFlowIn = 10;
double minMarketFlowIn = 0;
double maxMarketFlowOut = 10;
double minMarketFlowOut = 0;
double minInterCap = -5;
double maxInterCap = 5;
double n = 0.90; // Storage efficiency
double nInv = 1/n; // Inverse efficiency

try {
    // define new model
    IloCplex cplex = new IloCplex();

    // define variables
    IloNumVar[][] P = new IloNumVar[ZONES][HOURS]; // load in zone j at time i
    for (int j = 0; j < ZONES; j++){
        P[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
        if (j == 0){
            for (int i = 0; i < HOURS; i++) {
                P[j][i] = cplex.numVar(loadA[i], loadA[i]);
            }
        }
    }

    cplex.numVar(114)
if (j == 1) {
    for (int i = 0; i < HOURS; i++) {
        P[j][i] = cplex.numVar(loadB[i], loadB[i]);
    }
}

IloNumVar[][] E = new IloNumVar[ZONES][HOURS]; // Energy storage content in Zone j at time i
for (int j = 0; j < ZONES; j++) {
    E[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
    for (int i = 0; i < HOURS; i++) {
        E[j][i] = cplex.numVar(minEnergycontentStorage, maxEnergycontentStorage);
    }
}

IloNumVar[][] mIn = new IloNumVar[ZONES][HOURS]; // Power outflow of market j at time i
for (int j = 0; j < ZONES; j++) {
    mIn[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
    for (int i = 0; i < HOURS; i++) {
        mIn[j][i] = cplex.numVar(minMarketFlowIn, maxMarketFlowIn);
    }
}

IloNumVar[][] mOut = new IloNumVar[ZONES][HOURS]; // Power inflow of market j at time i
for (int j = 0; j < ZONES; j++) {
    mOut[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
    for (int i = 0; i < HOURS; i++) {
        mOut[j][i] = cplex.numVar(minMarketFlowOut, maxMarketFlowOut);
    }
}
IloNumVar[][] sIn = new IloNumVar[ZONES][HOURS];
// Storage inflow in storage j at time i
for (int j = 0; j < ZONES; j++){
  sIn[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
  for (int i = 0; i < HOURS; i++)
    sIn[j][i] = cplex.numVar(minStorageFlowIn, maxStorageFlowIn);
}

IloNumVar[][] sOut = new IloNumVar[ZONES][HOURS]; // Storage outflow of storage j at time i
for (int j = 0; j < ZONES; j++){
  sOut[j] = cplex.numVarArray(HOURS, zone[j], zone[j]);
  for (int i = 0; i < HOURS; i++)
    sOut[j][i] = cplex.numVar(minStorageFlowOut, maxStorageFlowOut);
}

IloNumVar[] I = new IloNumVar[HOURS]; // Power flow from zone A to B
for (int i = 0; i < HOURS; i++)
  I[i] = cplex.numVar(minInterCap, maxInterCap);

// define expressions
IloLinearNumExpr[][] storageContent = new IloLinearNumExpr[ZONES][HOURS];
for (int j = 0; j < ZONES; j++){
  for (int i = 1; i < HOURS; i++)
    storageContent[j][i] = cplex.linearNumExpr();
  storageContent[j][i].addTerm(1.0, E[j][i - 1]);
  storageContent[j][i].addTerm(n, sIn[j][i - 1]);
  storageContent[j][i].addTerm(-nInv, sOut[j][i - 1]);
}
IloLinearNumExpr[] marketOutflow = new IloLinearNumExpr[ZONES][HOURS];

for (int j = 0; j < ZONES; j++) {
    for (int i = 0; i < HOURS; i++) {
        if (j == 0) {
            marketOutflow[j][i] = cplex.linearNumExpr();
            marketOutflow[j][i].addTerm(1, sIn[j][i]);
            marketOutflow[j][i].addTerm(1, I[i]);
        } else if (j == 1) {
            marketOutflow[j][i] = cplex.linearNumExpr();
            marketOutflow[j][i].addTerm(1, sIn[j][i]);
            marketOutflow[j][i].addTerm(1, I[i]);
        }
    }
}

IloLinearNumExpr[] marketInflow = new IloLinearNumExpr[ZONES][HOURS];

for (int j = 0; j < ZONES; j++) {
    for (int i = 0; i < HOURS; i++) {
        if (j == 0) {
            marketInflow[j][i] = cplex.linearNumExpr();
            marketInflow[j][i].addTerm(1, sOut[j][i]);
            marketInflow[j][i].addTerm(-1, I[i]);
        } else if (j == 1) {
            marketInflow[j][i] = cplex.linearNumExpr();
            marketInflow[j][i].addTerm(1, sOut[j][i]);
            marketInflow[j][i].addTerm(-1, I[i]);
        }
    }
}
IloLQNumExpr objective = cplex.lqNumExpr();
for (int j = 0; j < ZONES; j++) {
  for (int i = 0; i < HOURS; i++) {
    objective.addTerm(1, P[j][i],
    mIn[j][i]);
    objective.addTerm(1, mIn[j][i],
    mOut[j][i]);
    objective.addTerm(1, mOut[j][i],
    mOut[j][i]);
  }
}

// define objective function
cplex.addMinimize(objective);

// define constraints
for (int j = 0; j < ZONES; j++) {
  cplex.addEq(E[j][0], initialStorage);
}
for (int j = 0; j < ZONES; j++) {
  cplex.addLe(sOut[j][0], E[j][0]);
}
for (int j = 0; j < ZONES; j++) {
  for (int i = 1; i < HOURS; i++) {
    cplex.addEq(storageContent[j][i],
    E[j][i]);
  }
}
for (int j = 0; j < ZONES; j++) {
  for (int i = 1; i < HOURS; i++) {
    cplex.addEq(storageContent[j][i],
    E[j][i]);
  }
}
for (int j = 0; j < ZONES; j++) {
    for (int i = 0; i < HOURS; i++) {
        cplex.or(cplex.addEq(mOut[j][i],
            marketOutflow[j][i]), cplex.addEq(mIn[j][i], marketInflow[j][i]));
    }
}

// solve model
if (cplex.solve()) {
    System.out.println("Objective function is: " + cplex.getObjValue());
    for (int j = 0; j < ZONES; j++) {
        for (int i = 0; i < HOURS; i++) {
            System.out.println("Hour is: " + (i + 1));
            System.out.println("Storage in : " + j + cplex.getValue(sIn[j][i]));
            System.out.println("Storage out : " + j + cplex.getValue(sOut[j][i]));
            System.out.println("Storage : " + j + cplex.getValue(E[j][i]));
            System.out.println("I: " + cplex.getValue(I[i]));
            System.out.println("Market in : " + j + cplex.getValue(mIn[j][i]));
            System.out.println("Market out : " + j + cplex.getValue(mOut[j][i]));
        }
    }
} else {
    System.out.println("Model did not solve");
}

// close cplex
    cplex.end();
}

} catch(IloException exc) {
    exc.printStackTrace();
}
# Appendix F

## Overview Dutch Electricity Generators

### Table 15: Overview Dutch electricity generators (Alsem, 2013)

<table>
<thead>
<tr>
<th>Name</th>
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<th>Power plant type</th>
<th>Power plant type according to EIR (2009)</th>
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Appendix G

CSV-Input file generators

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## CSV-Input file RES targets

**Table 17: Input file RES targets**

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### Appendix I

## Sensitivity Analysis

Table 18: Revenue difference per tick

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| Average over 40 ticks | 6,69% | 10,82% | 9,66% |
Figure 36 Installed capacity per technique

Figure 37 Generation per producer
Figure 38 Generation per technique

Figure 39 Average electricity price with 50% confidence interval
Figure 40: Storage generation with 50% confidence interval

Figure 41: EES producer revenue with 50% confidence interval
Appendix J

EES Revenues

Figure 42 Cumulative revenues per year EES operator
Figure 43: Revenues per year EES operator with confidence intervals
Figure 44: Profits per year for EES operator with confidence intervals.
Appendix K

EES Costs

Figure 45 Total annualized lifecycle costs EES techniques (Zakeri & Syri, 2015)
# Appendix L

## Supply ratios

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Scenario2b: 23% 23% 22% 20% 19% 22% 23% 26% 26% 35% 33%
Scenario2c: 22% 23% 22% 20% 14% 17% 22% 29% 30% 38% 36%
Scenario2d: 18% 18% 19% 19% 17% 17% 21% 24% 26% 34% 33%
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Scenario4a: 19% 19% 20% 19% 17% 18% 21% 21% 30% 29%
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Figure 46: Count supply ratios below 1.

Figure 47: Count supply ratios below 1.1.
## Appendix M

### Generation Portfolio

#### Table 20 Ratio RES/Fossil fuel generation per tick

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Figure 48 Generation per producer

Figure 49 Generation RES/Fossil fuels
Appendix N

Price volatility

Price duration curve 2010

![Price Duration Curve 2010](image)

*Figure 50 Price duration curve 2010*

Price duration curve 2020

![Price Duration Curve 2020](image)

*Figure 51 Price duration curve 2010*
Price duration curve 2040

![Figure 52 Price duration curve 2040](image)

Price duration curve 2050

![Figure 53 Price duration curve 2050](image)