Security of supply during the energy transition

Evaluating the adequacy of the Dutch energy system during the transition to a zero-carbon energy system in a realistic scenario

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by

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Dissertation

for the purpose of obtaining the degree of Master of Science
Electrical Power Engineering
at the Delft University of Technology,
to be defended publicly on Friday September 23, 2022 at 15:00 PM.

Student number:	4484657	
Project duration:	September 1, 2021 – September 23, 2022	
Thesis committee:	Prof. dr. P. Palensky,	TU Delft
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Abstract

The climate change is evident and a big contributor to the negative effects of the climate change is the energy production sector. Therefore, the energy production must shift towards a more environment friendly mix. Changing our energy sources to mostly renewable energy sources comes with many challenges. Besides the technical challenges, such as the required rare earth materials for solar- and wind-energy, the transportation of the electricity and the concurrency of generation and consumption, economical problems will also arise.

The way the current Dutch electricity market is designed will lead to a drop in electricity prices on the wholesale market, when the market is penetrated with a high concentration of renewable energy sources. So the electricity market mechanism needs to be reformed to have a price determination system better suited for energy sources with low marginal costs. Furthermore, a capacity remuneration system needs to be implemented to create enough investment incentive in controllable energy capacity to maintain a high level of security of supply in the Dutch energy system during the energy transition.

The electricity markets get cleared according to the merit order curve, a mechanism to determine the clearing price and volumes. Since supply bids with the lowest marginal costs get dispatched first, according to the merit order curve, power plants with higher marginal costs get pushed out of the market. Therefore, a capacity remuneration mechanism needs to be added to the market to raise investment incentive in conventional power plants to keep them operational.

There exist many different forms of capacity remuneration mechanisms, but the strategic reserve and capacity markets are examined to check which one would work best in the Dutch energy system. In a strategic reserve a central authority sets the capacity volume, which will be contracted by an operator. This operator will dispatch the contracted capacity when needed. Besides the basic version of the strategic reserve, the German and the Swedish versions of the model are also examined. In a capacity market a central authority determines the amount of capacity each consumer should acquire through buying capacity credits on the market. Both the yearly and the forward capacity market designs are delved into.

To determine which capacity remuneration mechanism would deliver the highest level of security of supply, simulations of the Dutch energy system are run. The simulations were done using the models AMIRIS and EMLab, which are coupled to give a more accurate representation of reality. The coupling takes place in the Spine Toolbox, a tool providing a skeleton for bringing models and data together. The capacity remuneration mechanisms were created in Python and can be activated as modules in the Spine Toolbox.

The vertices are sketched of the possible future energy scenario of the Netherlands in 2050. These vertices are the so called scenarios, regional governance, national governance, European CO_2-governance and international governance. These scenarios were investigated to be used as reference. The simulations were run with a scenario in which the energy demand stays equal and with a scenario where the energy demand descends similar to the international governance scenario. The international governance scenario was chosen to base the simulations on, because the simulations make profit driven decisions, similar to the international governance scenario.

The results of the simulations show that, firstly, without any governmental interference, a (near) zero-carbon energy system will not be achieved in 2050. Secondly, when running the energy-only market in a realistic scenario, no shortage hours will occur and the system had sufficient generation capacity for supplying the demand, even in a ”dunkelflaute” scenario. Thirdly, the basic version of the strategic reserve offered the least costly solution for society for providing sufficient security of supply, so no significant shortage periods will occur in a realistic scenario. Finally, the best option for maintaining security of supply in the Netherlands during the transition to a zero-carbon energy system is the implementation of the yearly capacity market. Because the yearly capacity market offered sufficient generation capacity to prevent shortage hours in all scenarios.

Preface

Before you lies the dissertation ”Security of supply during the energy transition: Evaluating the adequacy of the Dutch energy system during the transition to a zero-carbon energy system in a realistic scenario.”, a study into the future of the Dutch energy system. This dissertation has been written for the purpose of obtaining the degree of Master of Science in Electrical Power Engineering and will mean the end of my time as a student at the Delft University of Technology. The process of the research and writing of the dissertation took me a full year, from September 2021 to September 2022.

As a student of Electrical Power Engineering, the topic of security of supply lies inside my comfort zone. Since I am also very interested in the energytransition and economics, this project was perfect for me. However, when my thesis supervisor Dr. Milos Cvetkovic proposed the project, I didn’t know it would involve so much coding in Python. I had never used Python before starting this project, so this was something I had to learn along the way. Afterwards I can say I’m thankful, because I learned a new skill that could be valuable the rest of my career. However, in the process it gave me a lot of headaches, since it was not easy to learn a programming language while contributing in a very large Python project.

I would like to sincerely thank my supervisor Dr. Milos Cvetkovic. Not only did he give me guidance during the project, but he allowed me to chase a lifelong dream of mine. So I became a ski instructor in Austria for four months during the winter, in which period my thesis was on pause. Next up, I would like to thank Ingrid Sánchez Jiménez, since she helped me a lot on a daily basis. The coupling of AMIRIS and EMLab is her baby and, although it was sometimes hard for her, she didn’t lose her patience while she had to help me when I was learning to understand the basics of Python. Thirdly, I would like to thank Prof. dr. ir. Laurens de Vries for providing valuable insights on the capacity mechanisms, not only through our conversation, but also through the many research papers from him that I have read.

Last but not least, I would like to convey my gratitude towards my family, friends and especially my girlfriend. She had to live with me for the last few months of the project and never lost faith in me.

B.C. van Nobelen
Delft, September 2022

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List of Abbreviations

ABM	Agent-Based Modelling
AMIRIS	Agentenbasiertes Modell zur Integration Regenerativer In den Strommarkt
	Agent-based Market model for the Investigation of Renewable and Integrated energy Systems
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CRE	Controllable Renewable Energy
DAM	Day-Ahead Market
DLR	Deutsches Zentrum für Luft- und Raum-fahrt (German Aerospace Center)
EMLab	Energy Modelling Laboratory
ETM	Energy Transition Model
EUPHEMIA	Pan European Hybrid Electricity Market Integration Algorithm
GHG	Greenhouse Gas
IDM	Intraday Market
IPCC	Intergovernmental Panel on Climate Change
IRM	Installed Reserve Margin
LLD	Load Limiting Device
LOLE	Loss of Load Expectation

LSE	Load Serving Entity
NPV	Net Present Value
NYISO	New York Independent System Operator
OCGT	Open Cycle Gas Turbine
OTC	Over-The-Counter
RES	Renewable Energy Source
TSO	Transmission System Operator
UCAP	Unforced Capacity
VoLL	Value of Lost Load
VRE	Variable Renewable Energy

1

Introduction

The evidence for global warming is growing and so is the need to change our energy production to a more environment friendly mix. This has become painfully clear from the recently published Sixth Assessment report on the physical science basis of the climate change by the Intergovernmental Panel on Climate Change (IPCC) [1]. Due to human activities the greenhouse gas (GHG) concentrations have increased in the atmosphere, which has led to each of the last four decades being successfully warmer than the preceded decades, with a total estimated human-caused temperature increase of 1.07°Celsius. This increase of temperature has led to the global retreat of glaciers, which in turn has led to an increase of the global mean level of the sea by 0.20 m between 1901 and 2018.

To stop the process of global warming humanity needs to significantly lower its greenhouse gas emissions. A big contributor to the emission of CO_2-equivalent is the energy production sector [2], large coal- and gas-fired power plants emit a lot of gasses that are harmful to nature. There are multiple solutions to this problem, like carbon capture and storage (CCS), but the most obvious solution is to shift towards renewable energy sources, like wind and solar power. According to the UNFCCC Paris agreement [3], which is a legally binding international treaty on climate change signed by 196 countries in 2015, the global warming must be limited to well below 2°Celsius. Therefore, the CO_2-emissions have to be reduced by at least 55% in 2030 in comparison to 1990 levels.

Lowering the CO_2-equivalent emissions so radically is a must to prevent massive natural disasters and to keep planet Earth a liveable place. However, to reach these very low levels of emission, the electricity generation sector should undergo a level of decarbonisation between 96% and 99% before 2050 [4]. This challenge brings more problems with it than most people will think of at first. Besides the enormous amount of windmills, solar panels and other renewable energy sources that need to be installed, which will require massive amounts of rare earth metals, the transportation of the electricity and the concurrency of generation and consumption will be problematic. These challenges are mostly technological, however, the high penetration of renewable energy sources (RES) will also impose economical problems.

The economical problems will arise because of the current system of the Dutch electricity wholesale market, on which electricity suppliers and some large industrial consumers buy their electricity [5]. On this wholesale market there are multiple factors that play a role in the determination of the electricity price [6]. Besides the supply and demand of electricity, the price is largely determined by the price of the (fossil) fuels needed to produce the electricity, since the fuels make up the largest part of the marginal price. The marginal price of wind and solar is, however, low or close to zero and as their penetration in the system increases, prices will become very low. This will reduce the revenues for all generators, which will not only make it economically less viable for investors to invest in renewable energy sources, but also to keep investing in generators which might be needed to ensure sufficient capacity in case the wind is not blowing and the sun is not shining [4]. Investors therefore have increasing concerns about price volatility and the ability to recover capital and fixed operating costs.

1.1 European electricity market design

The current situation of the electricity system in Europe and its shortcomings has already been assessed in report D3.5 of the TradeRES project, called ”Market design for a reliable ∼100% renewable electricity system” [7]. In this report, the design and regulation of electricity markets have been analysed and the respects which need to be improved to facilitate a transition towards a decarbonised electricity system identified.

In the European electricity markets, the local transmission system operator (TSO) is responsible for maintaining operational security and security of supply in the area, i.e. keeping the supply and demand balanced in the system at all times. There are several bidding zones in the European market defined as the geographical areas within the market, in most bidding zones there is one TSO responsible, so there is no structural congestion. This means the wholesale electricity prices are uniform within each bidding zone and the electricity can be traded without needing to consider grid constraints of other zones.

The electricity in the bidding zones can be traded in two ways, either via bilateral over-the-counter (OTC) contracts or on organised marketplaces (power exchanges). On these marketplaces the products traded differ not only in size, but also in time horizons. The markets within the power exchanges are divided into four timeframes; the (physical) forward and (financial) futures market, the day-ahead market, the intraday market, and the reserve market. On the forward and futures market, participants can buy or sell long-term products, which enables the participants to hedge long-term price risks. On the day-ahead market the energy one day prior to delivery can be bought or sold, which offers a certain flexibility to the participants. The intraday market offers balancing opportunities by closing only one hour prior to delivery. Finally, if there are still imbalances in the system after the intraday market has closed, TSOs can activate balancing products, which are procured in reserve markets for example.

1.1.1 Wholesale market design

On the wholesale market usually large amounts of electricity are traded, so active participants on the market are generally energy suppliers and large (industrial) consumers. The participants can actively trade electricity within the wholesale market on the forward and futures market, the day-ahead market, and the intraday market.

On the forward and futures market buying and selling electricity up to several years before delivery is enabled. The trades can take place either via bilateral over-the-counter (OTC) contracts or on the power exchanges, of which the prices are based on expected future spot prices plus or minus a risk premium.

The day-ahead market (DAM) is the most used and liquid of the three markets. The main European exchange markets are Nordpool, EPEX and MIBEL, of which EPEX is the one Dutch buyers and sellers use. On these exchange markets the trading takes place through an implicit auction, where an algorithm called EUPHEMIA (Pan-European Hybrid Electricity Market Integration Algorithm) computes the price and quantity for every hour of the next day. EUPHEMIA defines the day-ahead flows between bidding zones by computing the price and quantity for each bidding zone. This is done by considering the system marginal pricing theory and simple and complex bids from both supply and demand sides. In addition the algorithm takes the physical constraints of the cross-zonal capacity in account.

Like the DAMs, the intraday market (IDM) involves auctions, however, these take place in several sessions or continuously. The electricity is either traded using bilateral contracts or, when it was auctioned, using pay-as-bid schemes.

TSOs need to schedule the real-time operation of the system, for which they consider the market results of the day-ahead markets, intraday markets and bilateral contracts.

The way the electricity prices on the wholesale market will be determined will change in the coming years as the market is hit with an increasing penetration of variable renewable energy sources (VREs). In a power system consisting mostly of conventional power plants, the generation capacity is more or less fixed. But in a low carbon, high-VRE energy system, both supply and demand will vary. The formation of electricity prices will be further offset by an increase in energy storage and demand flexibility. So new forms of flexibility are required from both suppliers and consumers to ensure security in the high-VRE market system, since the price of electricity will no longer be determined by the marginal costs of generation in periods of energy scarcity, but by the marginal willingness to pay of consumers.

This could result in very high prices when there is a scarcity of energy, or even in negative prices at times when there is very high VRE generation and low demand. When sufficient energy storage capacity is installed these peaks could be dampened, however, currently the shortfalls of VRE generation are covered by conventional, fossil fuel-fired, power plants. Storage has, however, still very limited capacity and is not able to deliver energy anymore when the battery is depleted. While conventional power plants are only limited by their capacity and the amount of fossil fuels in stock. But the stockpile of fossil fuels of a power plant can be ”recharged” much more quickly than the energy of a battery.

Another way of ensuring security of supply is through demand shifting, however, this opposes a challenge. Most consumers can only shift their demand for a timespan of several hours. Besides, most residential consumers do not have smart electricity meters and so they do not know when prices are rising, which makes anticipating on energy shortages hard.

These challenges make that the system adequacy is a function of the history of the system. The amount of loads that are shifted in the past and the state of charge of the energy storage facilities determine the ability of the supply to meet demand at a given time. Since the trades on the day-ahead market are only established once every 24 hours, the operation of load shifting and storage cannot be optimally served.

1.1.2 Need for capacity mechanisms

To ensure sufficient generation capacity in electricity systems, capacity mechanisms could be implemented as policy instruments. Whereas policies in the past only concerned generation, in the future their objectives consist of ensuring an optimal balance of variable renewable generation, controllable generation, storage and demand response, and an optimal combination between these market-driven investments and network capacity. The objective of these instruments in the long-term market is to provide sufficient incentive for adequate investment in generation capacity to ensure system adequacy, which is mostly needed due to the risk of the wholesale market not providing sufficient incentive through long-term contracts with risk-hedging options. The main cause for the market not being able to provide the sufficient incentive is the fact that variable renewable generators have very low marginal costs, when these generators are setting the price the inframarginal rents become close to zero.

Furthermore, the markets not reaching a long-term equilibrium is an issue for conventional power markets, which causes investment cycles due to the long permitting, construction and life cycle times of conventional power plants [8]. These investment cycles can be harmful to society as they can raise electricity prices for consumers as a consequence, due to periods of under investment. Given the high social costs of scarcity periods, society as a whole is better off investing a little too much in generation capacity to prevent shortages [9], [10]. This is, however, not in the interest of the generation companies, as the price of electricity in the wholesale market might be pushed below the operational costs due to excess capacity.

As long as existing conventional power plants make more money than their variable and short-term fixed costs, their operation makes economic sense. But this is only the case for new plants if it is expected their full investment costs can be recovered. So energy generation companies owning conventional power plants could distort the investment equilibrium during the energy transition, by stalling investments in renewables to keep the profits of their operational conventional power plants higher. Therefore, fossil fuel-fired power plants could delay the introduction of renewable energy sources, as well as introducing the risk of an investment cycle [11].

However, a new equilibrium may develop on the long-term when the goal of a low-emission power system has been achieved. In such a scenario the market could respond to supply shortages better, due to the shorter lead times of installing technologies such as solar PV and batteries, which will reduce the social impact.

The biggest challenge in this scenario is the weather dependence of the renewable energy sources. Not only the daily and seasonally weather variations, but mainly the year-on-year variations. The total annual generation of wind and solar energy can vary significantly as well as their peak load contribution. If enough renewable generation capacity is installed to withstand periodic weather extremes, there will be an excess of capacity during most of the years with average weather conditions. This could cause prices to drop below the price needed to recover investments during these years. This contributes to the risk investors have to take, next to the unknown probability of the extreme weather occurrences, which is affected by the further changing climate. Nevertheless, society expects system adequacy at all times, even during rare extreme weather events. So investing in excess capacity is, in the perspective of society, a cheap form of insurance against the much higher costs of possible supply shortages [9]. For this reason, research is required to determine whether the wholesale market could offer sufficient investment incentive on the long-term for investors in generation capacity, or some form of a capacity remuneration mechanism is needed to guarantee this incentive [12].

1.2 Context

This thesis is written as part of the TradeRES project [13]. This project is funded by the EU framework programme for research and innovation Horizon 2020 and aims to find new market designs for the European energy market that are economically efficient.

The TradeRES project is called to life with the purpose of developing and testing innovative electricity market designs that can meet society's needs of a (near) 100% renewable power system. The increasing share of VRE sources should be the leading characteristic of the future electricity system, this should, however, be supported by a long-term sustainable market design in which there is enough efficient operational and investment incentive provided for both renewable energy sources and controllable conventional power plants. This way the market design should provide security of supply through ensuring generation capacity that can be controlled in an economically efficient way. Finally, the market should prevent extreme electricity price swings for consumers by allocating the risks in an efficient and socially accepted manner.

1.3 Research questions

During the energy transition the penetration of renewable energy sources in the market will increase, which leads to concerns about the stability of the energy system and prices of energy in the future. To respond to the concerns of the investors, this study will investigate if a reformation of the Dutch electricity market, by adding a capacity mechanism, can resolve them.

The high penetration of renewable energy sources will lead to an electricity system which is more dependent on uncontrollable weather conditions. This means ”dunkelflaute” scenarios, a scenario in which there is little sun and wind, while the energy demand is high, could oppose more of a threat to the stability of the energy system than it is today. Therefore, this thesis will focus on keeping sufficient incentive for investors to invest in controllable conventional power plants during the energy transition. In this changing market, conventional power plants will be needed in periods of electricity scarcity to maintain a certain level of security of supply.

So the main research question that will be answered in this thesis is:

How to maintain security of supply in the Netherlands during the transition to a zero-carbon energy system?

To get to the answer of the main research question, three supportive research questions have been established. These questions will be answered by doing an extensive literature study and simulating models. The established questions are:

1. *What is a realistic energy generation scenario for the Netherlands in 2050?*

   Firstly, a realistic expected scenario for the Dutch energy system will be defined, this will be done by a literature study. Afterwards, the simulations of the Dutch energy system can be compared to this scenario, to examine if the simulations result in similar scenarios. Because the outcomes of the simulations will be more useful when they are similar to the expected energy system scenario.

2. *What is the energy shortage at peak times in the realistic energy scenario, when there is no capacity mechanism in place?*

   Secondly, the energy shortages at peak times need to be quantified, this means running the simulations without any form of capacity mechanism in place in a so called ”dunkelflaute” scenario.

3. *What is the least costly capacity mechanism for the entire society for providing sufficient security of supply?*

   Thirdly, the simulations will be done with the different forms of capacity remuneration mechanisms in place. From these results can be concluded which capacity mechanism results in the highest level of security of supply and at what costs to society. The security of supply will be measured by the installed capacity of controllable energy sources and the yearly loss of load expectation. The costs to society will be measured by the total yearly price paid for electricity by consumers.

1.4 Outline of the thesis

In Chapter 2 the current Dutch electricity market will be elaborated upon. The different exchanges within the wholesale electricity market will be described in detail. Next up, Chapter 3 goes in-depth in the need for capacity remuneration mechanisms and four capacity mechanisms, which could be implemented in the future Dutch electricity market to possibly attain system adequacy, will be clarified. In Chapter 4 an overview of the models used for the simulations to answer the research questions will be given. Chapter 5 will give an overview of different possible energy scenarios for the Netherlands in 2050. In Chapter 6 the coupling of the models will be described and how the simulations were set up. This is accompanied by the description of how power plant data is updated and a baseline scenario is established, which will be used as input for the simulations. Chapter 7 goes in-depth on the creation of the different capacity mechanisms in Python. The results of the simulations will be presented in Chapter 8. Finally, Chapter 9 will conclude the thesis and in Chapter 10 the findings are discussed, furthermore, potential future work will be described.

2

Dutch Electricity Market

In this chapter the current Dutch electricity market mechanisms will be explained. Firstly, it is important to note that this thesis will only focus on the wholesale electricity market. In the wholesale market the generators of electricity sell to electricity suppliers and (large) industrial consumers. However, there also exists a market in which the electricity suppliers sell to the final consumers, called the retail market [14]. But the retail market is not in the focus of this thesis.

2.1 Wholesale electricity market

The Dutch wholesale electricity market consists of three separate markets; the forward and futures market, the day-ahead market and the intraday market. An overview of the chronological sequence and the interaction of market participants can be seen in Figure 2.1. The different markets will be described in detail in the following sections.

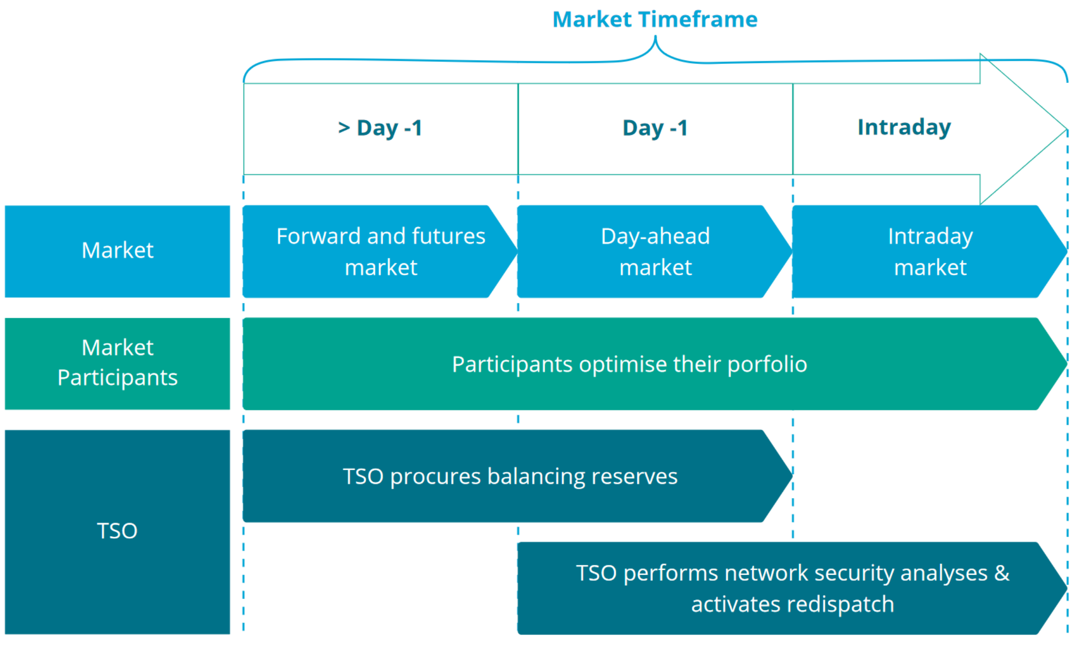

Figure 2.1: Relation between the different timeframes of the wholesale market [14].

2.1.1 Trading platforms

The liberalisation of the Dutch electricity market, which started in the 1990s [15], has led to the creation of energy exchanges. The current energy exchanges in the Netherlands are the ICE Endex for the forward and futures market and the EPEX SPOT for the day-ahead and intraday markets. These are internal European energy markets on which the production, trading, marketing, transmission and supply of electricity is organised for large companies [16]. The European rules define how national markets are linked to the platform and what fair trade is.

Besides the organised markets, energy can also be traded over-the-counter (OTC), similar to financial products. The main difference between OTC contracts and exchange-traded energy is that the energy traded via the exchange is regulated and standardised according to the European rules [17]. In an OTC trade there is no involvement of a central authority and the terms of the transaction are only agreed upon by the involved parties. However, to protect the off-exchange transaction against counterparty risk it is still possible to register the trade on the stock exchange [18].

Both forms of energy trading have their own advantages. Trading on the central exchange increases transparency, which could provide valuable information about trading prices for other participants on the market, leading to lower transaction costs [19]. On the other hand, OTC trading offers a high degree of flexibility, which could be used, for example, to hedge custom defined load profiles. Furthermore, the contractual obligations of OTC trades can be kept confidential, since only trading volumes registered on a stock exchange are publicly known.

2.1.2 Forward and futures market

On the ICE Endex, the forward and futures market, energy products can be traded for longer periods of time. Not only the duration of the contract can be several days, weeks, months or even years, but also the time between signing and fulfilment of the contract. Two types of contract categories exist within the market, these are the conditional and unconditional contracts [20]. When a transaction is conditional, e.g. an option, the fulfilment of the contract can be enforced by the contracting party, but the party does not have the obligation to do so. When a transaction is unconditional, e.g. a futures contract, the contract must always be executed, since both parties have entered a binding obligation by signing the contract. In case the contract cannot physically be fulfilled, by for example supplying the electricity, a financial compensation payment must be made.

The foremost reason for companies to trade on the forward and futures market is to hedge against financial risks [17]. This is, therefore, also extensively done by market participants, what results in the fact that trading volumes are significantly larger than the day-ahead and intraday market combined. Electricity suppliers are able to optimise their medium- to long-term portfolio through trading on this market, by selling energy their power plants will generate in the future.

In contrast to physical commodities, the price of electricity futures is not based on the current spot price and cost of storage, but the price is determined by the expected spot price in the period the energy will be delivered plus or minus a risk premium [21].

2.1.3 Day-ahead market

On the EPEX SPOT short-term energy products can be traded with delivery on the following day. On this day-ahead market especially individual hours can be traded, instead of the mostly peak load or base load products traded on the forward and futures market. Therefore, traders on this market consist for a large part of utilities trying to optimise their portfolio, whether it be the supply contracts with their customers or their available generation capacities. Other participants active on the day-ahead market are large industrial companies attempting to purchase electricity at the best price, or pure traders like banks and market makers, who exploit the price differences, just as they do on the financial exchange markets. Finally, the TSOs are also active market participants, as they might need to compensate grid losses or to supply the expected electricity feed-in from renewable energy sources. The trading volumes on the day-ahead market are significantly lower than the volumes traded on the forward and futures market, however, the number of participants in the market is comparable [18].

Auctions

On the EPEX SPOT the trading normally takes place in the framework of a single auction, but in rare cases a second price auction could take place according to the current rules of the EPEX SPOT. In the first auction bids can be submitted until 12:00 a.m. on the day before the electricity physically has to be delivered. On the trading platform bids can be placed for every of the 24 hours of the next day, since power plants already have most of the required information to optimise dispatch available at this point for the next day [18].

EUPHEMIA calculates the outcome of the market with its market clearing algorithm after all bids have been placed and assigns an identical price for each hour to all accepted bids in the market [16]. The resulting price from the uniform-price-auction is relevant for both the participants of the day-ahead market and the traders on the forward and futures market, because the base or peak spot price forms for a large part the basis of forward and futures contracts. This price is, furthermore, also used to determine the market premium for renewable energy sources [18].

In rare cases a second auction can be held, but only when the market is in imbalance after the first auction or the prices of the first auction are considered abnormal. This could be, for example, when a single or more hours have a significant different price from the other hours of the current day [16]. If needed, this second auction will take place immediately after the first, because the auction results need to be published at 12:42 p.m..

Block bids

Next to the hourly bids, bids can also be submitted in blocks [22]. A block bid is a bid for a certain number of consecutive hours within a day, which needs to be accepted for all hours or rejected altogether, this is called an all-or-nothing condition. Block bids can be used to sell energy for an average price over a pre-defined period of time. This eliminates the risk of single hourly bids being rejected and therefore partial costs not covered, as a consequence a lower price could be offered for delivery of energy in consecutive hours. The assurance energy has been sold for multiple consecutive hours also ensures complementary costs of electricity generation can be covered, such as start-up costs of power plants [23].

Besides the standard block bids there are two types of smart block bids available on the market, these are linked and exclusive block bids [16]. Linked block bids are meant to offer the market participants a way of incorporating the financial and technical constraints. By using linked blocks the start up costs of a power plant can be offered in the first block and in another block the fuel costs, for example. Exclusive block bids are meant to pursue different strategies for a power plant to trade energy within the same delivery day. By using exclusive blocks a base load generation profile could be offered at a lower price and a peak load profile at a higher price, for example, but the market rules only allow one of the offers to be executed.

Despite offering a wide range of possibilities to market participants to better reflect their financial and technical constraints, the use of block bids is still restricted currently on the EPEX SPOT. This is foremost due to the fact the market clearing algorithm complexity significantly increases when more block bids are traded [24]. When only blocks bids are traded with an all-or-nothing condition and static bid quantities, for example, the market can only be cleared if the demand and supply volumes exactly match.

Negative prices

Currently it is also possible to place bids with negative prices on the day-ahead market, this is generally only done in the case of an oversupply. Negative prices lead to more efficient auction results and provide an increased incentive for investing in flexible system components and storage options [25]. The occurrence of negative prices is heavily influenced by the prioritisation of the renewable energy sources increasing in the generation mix, which ensures that fossil fuel-fired power plants primarily have to adjust their generation.

Negative prices may seem counterintuitive, but economically they are very reasonable. Since electricity storage capacity is very limited and short-term demand relatively inelastic, due to the majority of household consumers not being able to respond to price signals, electricity generation must be reduced in order not to compromise grid stability [18].

Power plants could have technical or economic reasons to accept lower or even negative prices, or lower their generation [26], [27]. Reasons could be, for instance, technical restrictions such as slow change speeds or start up costs. A power plant cannot, for example, immediately return to generation at full capacity after is has been partially or fully shut down. If high market prices are expected to follow, the power plant operator could, therefore, be willing to accept losses for a short period of time, if earnings in the subsequent period are expected to make up these losses.

Other reasons for power plant operators accepting negative prices could be contractual obligations. Power plants providing negative balancing power or hydroelectricity plants, which run-of-the-river, for example, must remain in operation [28]. Furthermore, there exist combined heat and power plants in which the generated electricity is regarded as a by-product and the main source of income is the supply of heat, used for the heating of buildings or industrial processes. Interrupting the supply of heat could impose financial penalties higher than the losses of the negative electricity prices [29].

2.1.4 Intraday market

The intraday market also takes place on the EPEX SPOT and uses the EUPHEMIA algorithm to carry out the market clearing, but the volumes traded on the market are much smaller compared to the forward and futures or day-ahead markets. On the intraday market, products can be traded in between the day-ahead market and the physical gate closure, by which the point in time is meant at which the system operator no longer permits changes to the schedule to be submitted [30]. Participants of this market use it especially to make last minute changes to their schedule, for example when their demand or supply is higher than could be foreseen when submitting their bids on the day-ahead market at 12:00 a.m. on the previous day.

Trading on the intraday market is continuous, from 4:00 p.m. on the previous day until closure of the gate. The gate closure time is determined by the TSO, since the schedules need to be transmitted to the TSO to execute the deliveries. The lead time between the closure of the intraday market and physical delivery has been reduced in 2011 from 75 minutes to 45 minutes, and again in 2015 to 30 minutes, this was possible due to technical improvements. Since 2017 it is even permitted to submit trades within an individual control area 5 minutes before delivery [16]. This enabled a higher resolution of portfolio management for market participants, which is especially useful for responding to short-term changes in the electricity production of renewable energy sources.

During the continuous trading on the intraday market trades are immediately carried out when a corresponding counterpart is found, this enables participants to obtain new information constantly [31]. Besides the single hourly contracts it is, since December 2011, also possible to trade quarter-hourly contracts. This feature was particularly implemented to stimulate generation from renewable energy sources, such as photovoltaics which can have strong variations even within the hour. Furthermore, on the intraday market also standardised blocks can be traded and there is a possibility to trade orders under an execution condition, this means it is ensured a bid will be either executed immediately or entirely cancelled.

Next to the continuous trading there is also a uniform price auction, this was introduced in December 2014 to increase the market liquidity [16]. The uniform price auction provides an initial price signal for the continuous trading by taking place daily at 3:00 p.m., one hour before the trading on the continuous intraday market opens. On the auction all quarter hours of the next day can be traded.

2.2 Merit order curve

On the electricity exchange markets the trades will be cleared according to the merit order curve, a mechanism to determine the clearing price and volumes. The merit order curve is an aggregation of generation bids to one supply curve, on which the bids are ranked on price in ascending order. On the left side of the curve are the generation technologies with the lowest marginal costs, in most cases renewable energy sources can be found here. The expected order of technologies on the merit order curve, corresponding to their increasing marginal costs, is firstly renewables, secondly nuclear, thirdly coal, followed by gas and lastly are peak plants, running on for example diesel or gasoline. In Figure 2.2 an illustration of the merit order curve can be seen.

The market operator also forms a demand curve from the submitted demand bids. The place where the supply and demand curve intersect determines the market clearing price and volume. All generating units participating in the market that will be dispatched according to the merit order curve will receive the market clearing price. On the other hand, the market participants taking off electricity will all have to pay that clearing price.

When every power plant receives the same price for delivering electricity, it means that the market clearing power plant receives its marginal costs, while for other dispatched plants this price is higher than their marginal costs. This difference between the marginal costs of generators and the clearing price is needed for the power plants to recover fixed generation costs and is called the inframarginal rent. Thus investing in generation technologies is only economically viable for investors if the market clearing price is higher than the fixed operating costs plus the marginal costs of the power plant for most of the time.

The increasing penetration of renewable energy sources on the merit order curve will drive the market clearing price down, as can be seen in the bottom graph of Figure 2.2. When the demand stays the same, the generating units with the highest marginal costs will be pushed out of the market. This makes fossil fuel-fired power plants vulnerable to being pushed out of the market when the prices of the fuels rise, as they then cannot compete at the lower prices. Due to the penetration of renewable energy sources the wholesale electricity prices have decreased in Europe since the beginning of the energy transition. However, this decrease in price was not necessarily seen in the energy bill of the end-consumer, because only one-third of the energy bill is made up by the energy component, the rest is made up by taxes, levies and network tariffs [32].

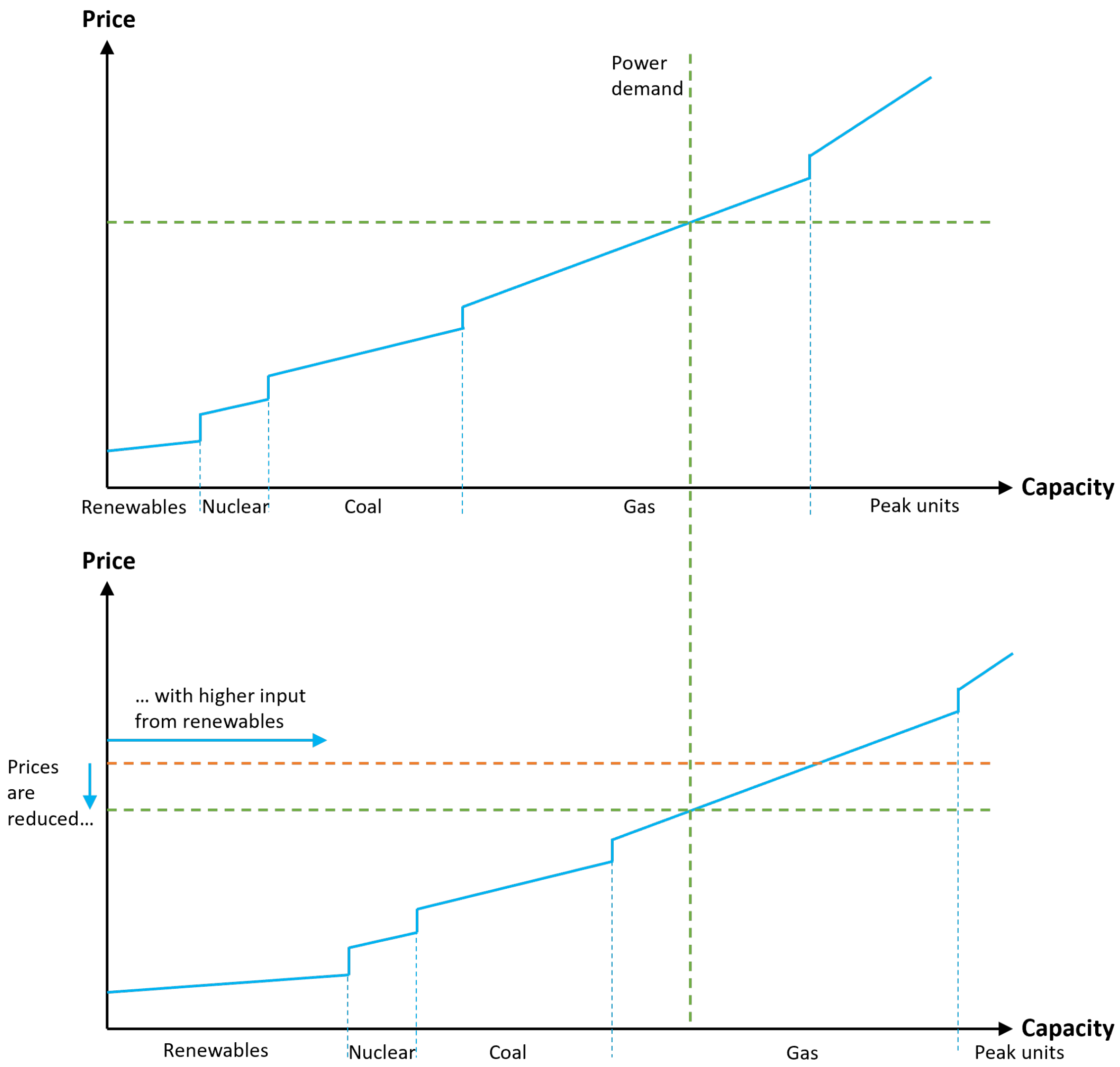

Figure 2.2: Illustration of electricity price fluctuations due to the merit order effect.

3

Capacity Remuneration Mechanisms

In a future energy scenario, consisting almost only of renewable energy sources, system adequacy is a key issue of concern [33], [34]. When most of the energy is generated by variable renewable energy sources, investments in controllable power generators is only needed to maintain balance in the energy system [7]. When the balance cannot be maintained anymore, a rolling blackout could occur in which not all demand can be served, even when all generators are producing at maximum capacity and prices going sky-high.

Capacity remuneration mechanisms are generally designed to encourage investments in such a way generation adequacy will be improved. Via these mechanisms market participants, that can provide capacity, are offered an income on top of their regular sales on the electricity markets [35]. The determination of the required capacity quantities that needs to be supplied and the corresponding capacity prices, however, does vary per mechanism [36]. The European Commission categorises the capacity mechanisms into volume-based mechanisms and price-based mechanisms [18]. Volume-based mechanisms set the amount of capacity required to guarantee a certain level of generation adequacy, for which the price is determined in a market. Price-based mechanisms set a target price and the amount of capacity that will be procured is steered by this price.

A range of capacity mechanisms could be implemented, such as strategic reserves, capacity markets and capacity subscriptions. None of these capacity mechanisms does have a standard form, but a large number of design options creating a continuum of options between the named main types.

One thing that needs to be determined when evaluating the different capacity mechanisms is how to value the contribution to system adequacy. For the valuation of capacity the Value of Lost Load (VoLL) can be defined, this is the price consumers are willing to pay to prevent their electricity supply being interrupted during blackouts. Due to technological advancements it becomes increasingly possible to differentiate the provided security of supply to consumers and system adequacy can be turned from a public into a private good [37]. This has as a consequence that consumers which are flexible with their demand can choose to pay less. However, none of the named capacity mechanisms are currently capable of including commercially operated storage facilities, which can be used during shortages, so all mechanisms still need to be innovated further before they can be implemented in a fully renewable energy system [7]. On the other hand, the aim of all the models is the same, which is to ensure investors of efficient valuations so they can successfully recover all components of their costs and enter and leave the market in the optimum amounts and at the appropriate time, this will be provided by sufficient prices for energy and capacity [38].

Furthermore, there is still no real practical experience of implemented capacity mechanisms in European near zero emission energy markets. This means, to determine which capacity mechanism will work best for the future Dutch energy system, models have to be simulated, instead of doing a survey of already existing capacity mechanisms.

In this chapter different forms of capacity remuneration mechanisms will be investigated. Firstly, the energy-only market will be explained, of which the question still lingers whether it will be capable of providing sufficient system adequacy. Next up, a couple of capacity mechanisms, which could be implemented in the future Dutch electricity market to possibly attain system adequacy, will be clarified.

3.1 Energy-only market

Energy-only markets are a form of price-based capacity mechanisms. In an energy-only market generators need to recover their operating and fixed costs exclusively through the electricity prices on the market and, in some cases, through paid ancillary services. Since there is no system in place providing payments for capacity services of generators, their only income is through electricity trading on the wholesale market [39]. Most of the time generation capacity in the market will be sufficient to meet demand and the price of electricity will be determined according to the merit order on the wholesale market. During times the market price is above the operating costs of the power plant, it is able to recover inframarginal rents, which can be used to cover fixed costs, in addition to recovering its operational costs [38].

During times of generation scarcity the market price will rise, in a normal market operation. In (almost) any other market the market will always clear when demand exceeds supply and prices are rising, however, in an electricity market it would result in prices rising without a limit. This is due to the fact that most of the demand is very inelastic, typically only large consumers have real-time electricity meters and can interrupt their demand, but the average household consumer is not able to respond to the market. To protect consumers from suppliers exercising market power, the energy price is capped [40]. The VoLL reflects the average price consumers are willing to pay for their electricity consumption, so if the electricity price is capped by the regulator at the VoLL, the market will achieve the second-best outcome.

Investors will react to the VoLL by building additional capacity until the market reaches the point where the costs of building an extra MW of capacity are equal to the VoLL earnings during periods of blackouts. So when the VoLL times the expected duration of blackouts equals the investment costs of the last MW of capacity, investment stops. However, this VoLL × duration is actually the price average consumers are willing to pay for serving a load that would have gone unserved. This means the value for consumers of an extra MW of capacity only declines beyond this point, so capacity becomes less valuable as the system becomes more reliable [40]. As a result the market only builds the second-best ”optimal” amount of capacity when it is led by the VoLL pricing rule [41], [42].

In theory, if the VoLL can be determined accurately, a well designed energy-only market could avoid forcing all customers to pay a high price for system adequacy, irrespective of the value they place on that level of reliability [43]. One problem with this approach is the difficulty of estimating the VoLL. Since most consumers cannot react to electricity prices and be individually interrupted, because the electricity flow going to individual customers cannot be controlled by system operators, the market has hardly any access currently to information how customers value reliability. Only for large consumers with real-time meters, of which the electricity flow can be interrupted, can the VoLL be determined [42].

Since the market prices will be capped in a real energy market, due to extreme prices being deemed politically unacceptable, the high prices during energy scarcity periods necessary to provide sufficient incentive for investments will likely be avoided. If the prices are capped too low, the market will not be able to recover investment costs, which will lead to the ”missing money” problem [44]. The proper operation of energy-only markets will likely be prevented by the poor understanding of politicians, general public and industry.

A well functioning energy-only market will only be possible in predictable and stable situations in which market participants can make timely decisions about new investments [38]. However, energy-only markets always have a risk of not having sufficient installed capacity, leading to blackouts, due to the markets not being able to provide any guarantee that sufficient capacity will be installed as long as there is no security investments will be covered by high prices during energy scarcity periods [43].

3.2 Strategic reserve

A strategic reserve is a form of volume-based capacity mechanisms, of which the volume is set by the central authority, and can be implemented alongside an energy market. In a strategic reserve a certain back-up generation capacity is established and directly contracted by the system operator. This capacity is a small portion of the generator’s total capacity, which will provide an additional reserve that can be dispatched by the system operator. Only when all other available capacity in the market is already operating and the market response is insufficient to meet all demand, then the capacity in the strategic reserve can be called upon by the system operator [38]. The reduced available capacity should lead to a price increase, which should incentivise new investments. This will lead to the available capacity on the market reaching similar levels as before, after a certain time, plus a certain amount of additional reserve [45].

Generally the system operator determines the amount of capacity which should be separated from the wholesale market and stand available as strategic reserve. The needed capacity is then also procured by the system operator, either via auction-based mechanisms, which is typically the case, or via bilateral negotiations and contracts. The generators then get a fixed payment through the strategic reserve mechanism, providing them with a certain income and a compensation for not being able to sell electricity from that part of their capacity on the wholesale market. Thus when the generators are dispatched, their marginal costs of generation are paid by the system operator and the system operator will keep the profits when the reserve is dispatched. These profits should cover the fixed costs of the strategic reserve to the system operator, however, the operator takes the financial risk of keeping the commissioned strategic reserve available. If the operator is unable to recover all of the expenses of the strategic reserve, the operator will socialise the remaining costs as part of the network or system tariffs [8].

The price paid for the capacity can be determined in two ways, either via a fixed strike price or via a strike price equal to the highest supply bid plus potentially a mark-up.

In the setting of a fixed strike price, all market participants know in advance above what predetermined strike price the strategic reserve will start operating. So, whenever there is a period of energy scarcity and the day-ahead prices rise above the strike price, the strategic reserve will be activated. This means that the set strike price should, in theory, be higher than a potential competitive bid in the energy market, because otherwise flexible demand offering to reduce consumption during scarcity could be ruled out. But the set strike price should also be lower than the VoLL, since it would make more sense from an economic point of view to shed loads instead of activating the strategic reserve when prices are higher than the VoLL.

When the strike price is set equal to the highest supply bid in the market plus a potential mark-up, it is guaranteed that market-based solutions to the energy scarcity will not be overruled by the strategic reserve. This is because the price of the strategic reserve is set equal to the highest bid in the market, which is the bid on the last commercial unit that is being dispatched [38].

On the short-term a strategic reserve is not very efficient. On the other hand, on long-term investments a strategic reserve could have a ”slippery slope” effect, which means generation units that are still marginally profitable try to become eligible for strategic reserves by claiming they plan to decommission. Furthermore, when the strike price is set too low the strategic reserve results in a reduced investment in the energy market, because a low strike price essentially means a low price cap. This results in an unstable mechanism for the long-term that leads to the system operator having to manage all capacity [46]. By keeping the prices low and reducing the price volatility, a strategic reserve could prevent a provision of incentive for the investment in development and deployment of new generator technologies, which could be more efficient than the current generators that are kept alive through the mechanism [47]. The more polluting power plants, which should normally be dismantled, could be supported by the distorted merit order. This phenomena is called ”the dismantling paradox” [8].

On the other hand, a strategic reserve has relatively limited impact on the operation of the wholesale market on the short-term. Since a strategic reserve adds a new product and segment to the market, it does not directly impact the market, which makes the introduction of this mechanism relatively easy, as well as the regulatory reversion. When the regulator expects the generation capacity to be sufficient to sustain reliability on the long-term in the power system, the strategic reserve can be phased out with enough notice time for investors to prepare for re-entering the wholesale market.

A strategic reserve will not provide the highest level of economic efficiency, but will secure a certain level of installed capacity. By withdrawing generation capacity from the market and only dispatching this capacity when all other capacity is in use, the power plants are withheld from getting the market price if this is above their marginal costs. So the most economically efficient dispatch according to the merit order will in many situations not be maintained. However, if security of supply is the top priority, the economic inefficiency does not have to be a major issue.

Both Germany and Sweden already have a strategic reserve mechanism in place in their electricity markets, but both mechanisms differ in their characteristics. In the following sections will be described how both mechanisms are characterised and how they differ from the basic strategic reserve model and from each other.

3.2.1 German strategic reserve

In the German strategic reserve model only conventional power plants can participate [48]. Because the model aims to support the least profitable power plants, with the highest costs per MWh, the model has some strict conditions for plants entering the strategic reserve. If a plant wants to be contracted into the strategic reserve it is, in all probability, not profitable anymore.

Therefore, when a plant has entered the strategic reserve, it is not allowed to leave until the end of its lifetime and can never return to the normal electricity spot market. Furthermore, if a power plants gets contracted into the strategic reserve, it has to be decommissioned within a couple of years, because it is economically not interesting to keep loss making power plants alive for too long. This feature of the German strategic reserve model automatically tackles the dismantling paradox.

3.2.2 Swedish strategic reserve

The Swedish model for the strategic reserve has stricter environmental rules, which allow only renewable power plants to enter the strategic reserve [48]. In the basic and German strategic reserve models power plants with the highest costs per MWh will be contracted first, however, in the Swedish model the power plants with the lowest costs get accepted first. Furthermore, the model only considers the variable costs of the power plants when ordering the bids. Unlike the German model, the Swedish strategic reserve model only offers contracts for one year, so power plants have to be re-accepted into the reserve every year. This also means the power plants in the Swedish model do not have to be decommissioned at the end of the contracted period.

3.3 Capacity market

A capacity market is a volume-based capacity mechanism. The term ”capacity market” can be used for various designs of capacity mechanisms, since it generally does not describe one specific model. However, in this report the term is used for the market where participants with a capacity deficit can buy capacity credits through a market from participants with a surplus. Large electricity consumers and parties representing the smaller consumers are obligated to buy capacity credits on the capacity market, of which the quantity corresponds to an equivalent of their expected peak demand plus a reserve margin. The reserve margin is meant to ensure generation capacity and more stable electricity prices, by providing a stronger and earlier investment signal [8]. These credits can be traded either via an auction or via bilateral trades between a producer and a consumer [40].

The capacity credits available on the capacity market can be seen as capacity obligations, which are necessary to ensure system adequacy. A central authority determines the total amount of capacity that should be made available in the market, then the load serving entities (LSEs) are obliged to procure their portion of the total capacity in the capacity market. It is expected the LSEs pass their procuring costs on to their customers. The credits which are traded in the market could also be obtained through demand side response, besides the obvious generation capacity. For these obligations a specific timeframe is set, that could range from daily to seasonally to annually, and may be locational [38].

The amount of capacity sold through the capacity credits must be made available at the time of the peak demand per obligation period. These peak times could be, for example, a seasonal peak in the summer or winter. The volume of the traded capacity is, therefore, dependent on expected weather conditions, not only from the demand side, but also from the generation side. If an LSE cannot meet its obligation, penalties will be applied, whose strength will have a large impact on the investment incentive created by the mechanism. This effect is comparable to the price cap applied in energy-only markets.

By clearly defining the required capacity volume a capacity market can ensure system adequacy through the obligations. The investment incentive for the long-term can be assured through adequate penalties for LSEs not meeting their obligations. Furthermore, the responsible party for procuring the capacity is defined and the mechanism to assign capacity.

Two capacity markets are defined and will be elaborated in the following sections. These are the yearly capacity market and the forward capacity market [8].

3.3.1 Yearly capacity market

In a yearly capacity market auctions are conducted annually for capacity credits for the following year. This form of capacity market has a relative simple design. In the yearly capacity market unforced capacity is offered by generators and the system operator contracts capacity on behalf of LSEs, which makes consumers participate automatically. The LSEs are then obligated to buy an amount of capacity credits corresponding to the minimum unforced capacity assigned to them by the system operator. Consumers can react to their seasonally capacity needs via the capability period auctions. There are two capability periods in each year, the summer and the winter capability period.

The annual auctions are cleared by a sloping demand curve, which reduces price volatility by providing more predictable revenues to generators and lower costs for consumers [49]. The amount of capacity credits LSEs are forced to purchase are determined by the product of the Installed Reserve Margin (IRM) and the forecasted peak demand. The IRM is calculated by the regulator, which tries to achieve a loss of load expectation of once in 10 years. When the market is cleared, the generation units clearing the capacity market are paid the market-clearing price.

This form of capacity market has already been implemented by the New York Independent System Operator (NYISO) in the United States [50].

3.3.2 Forward capacity market

In a forward capacity market capacity credits are auctioned for the following year or a few years in the future. The amount of capacity that must be available on the market in a future year is determined by the amount of capacity that clears the market in the current year. This means every generation unit can participate in the capacity market if they expect to be available in the reference year, regardless of whether they already exist or are being built now.

The period of the signed contract is dependent on the state of the power plant, only new and refurbished plants are provided with long-term contracts, existing plants can only get a one-year contract at a time. New plants are awarded with 15-year contracts and refurbished plants may obtain 3-year contracts. Power plant operators may not participate in the capacity market for the duration of their contact, however, after the long-term contract they may participate in the market again as existing capacity and are eligible for one-year contracts. Renewable energy plants receiving supportive subsidies are not eligible to participate in the capacity market.

The price the generators receive for clearing the market is the current capacity market-clearing price, in case of a one-year contract. When a long-term contract is signed the generators will receive payments for the period of the long-term contract at a price fixed at the current year's market-clearing price.

This form of capacity market has already been implemented in the United Kingdom as part of their Electricity Market Reforms policy.

3.4 Capacity subscription

A capacity subscription is again a volume-based capacity mechanism, but it is fundamentally different from the other models [38]. A capacity subscription model is the only mechanism in which customers determine the amount of capacity they wish to procure themselves. This can be technically made possible through the use of Load Limiting Devices (LLDs), which act as a controllable fuse that gets activated when there is a shortage of capacity in the system. An LLD can be implemented as an extended functionality of a smart meter. In normal conditions the LLD will be inactive, since capacity will not be constrained in the power system, but during scarcity conditions the LLD can be activated by the system operator to limit the consumer's demand to the level of capacity the consumer is subscribed to. For the capacity subscription mechanism to work properly it is necessary each consumer's demand can be limited by an LLD.

Since the consumers are themselves responsible for procuring enough capacity, it becomes very important the consumers have enough information to determine the right amount for their needs. The consumers need to know the height of their own peak demand and by how much they are willing to lower it, at the cost of what comfort, if the capacity price becomes too high. In this decision process present technologies, such as websites and apps, can provide the consumers with support based on a few key inputs about demand.

When a consumer's demand exceeds its subscribed capacity there are two ways the capacity subscription mechanism can exercise its power. Either the LLD gets activated and disconnects the consumer, which means the consumer is then without electricity until demand is reduced and the LLD resets. By connecting or integrating the LLD with a smart controller, the demand of the consumer could be kept below the limit whenever the LLD is activated. Or the consumer could get financially penalised for exceeding its limit. Instead of limiting the consumer's demand, a (very) high price will be accounted to the consumer when its demand exceeds its subscribed capacity.

To trade capacity subscriptions a market needs to be established. On this market, producers are able to offer their available capacity during scarcity conditions and consumers are able to buy subscriptions to capacity, either directly or through intermediaries. When the LLDs get activated producers should be obliged to deliver the amount of capacity equal to the subscriptions they have sold. If the producers are not able to provide the contracted capacity during scarcity situations they will be penalised to prevent free riding. When the capacity subscription mechanism is implemented correctly, a sufficient level of capacity to supply the subscribed load should be ensured. Due to competition on the market the capacity prices should be low in case of plentiful supply of capacity. However, when capacity supply is scarce, prices will rise and consumers will be forced to look for alternatives, like storage. This system is economically attractive, because it turns quality of supply into a private good instead of a public good, matching demand and supply in an optimal way [51].

3.5 Incentives versus control

There exist more forms of capacity remuneration mechanisms, but the proposed four are nicely distributed when they are placed on a graph showing the relation between the reliance upon financial incentives and the control over capacity reliability of the mechanisms. Figure 3.1 shows the reliance upon financial incentives versus control over reliability relation of the four proposed mechanisms, or it can be called the relation between prices and quantities.

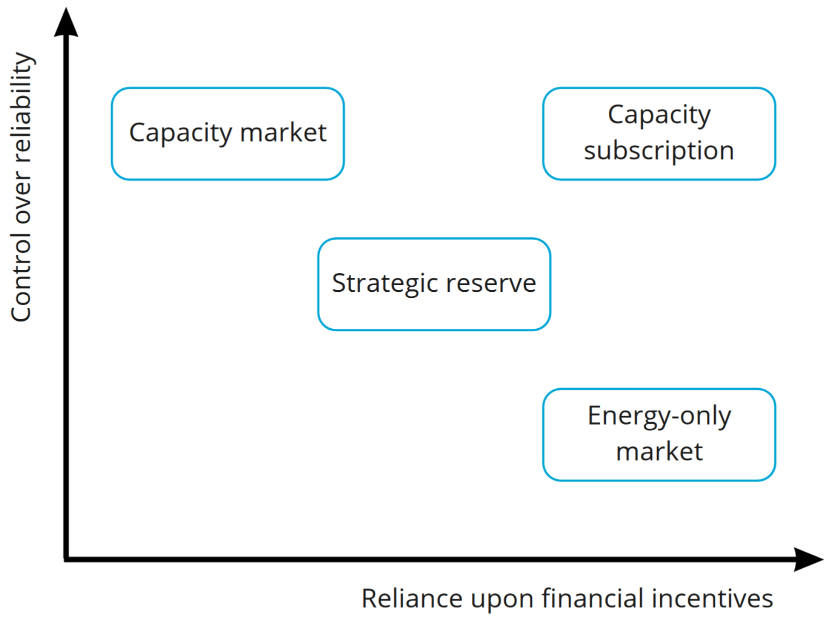

Figure 3.1: Financial incentives versus the control of the different capacity mechanisms.

The four proposed capacity remuneration mechanisms all have their own distinctive features, but in all four mechanisms the recurring theme is that the effectiveness of the capacity reliability improvements heavily depend on the investment signal that is sent to the market.

An energy-only market will not provide security of supply, unless investors are guaranteed to earn sufficiently high prices during scarcity periods to cover investments. On the contrary, in a capacity market the security of supply is guaranteed through the capacity obligations, but not whether the investors will be able to recover their investments in the capacity.

A strategic reserve will turn reliability into a public good. By adding an extra volume of generating capacity to the reserve the reliability will be improved, this gives direct control over the security of supply to the operator. Consumers will pay for the strategic reserve, for example, through an excise tax on electricity, which makes them expect to benefit from the increased security of supply. However, in a decentralised, interconnected market, scarcity in neighbouring systems could lead to high prices in the system at hand, but there is no possibility for system operators to direct the electricity to its own system. This means there still could be scenarios in which the consumers would be let down and the strategic reserve is not effective, but these are the risks of such a public good [52].

On the other hand, a capacity subscription turns reliability into a private good. The capacity subscription mechanism has as advantages that it provides an incentive for consumers to limit their peak demand and it produces a clear signal for the amount of capacity the consumers reliably wish to have available. Furthermore, the mechanism turns reliable capacity into a product with a steady revenue stream for power plant operators, in contrast to an energy-only market, which turns capacity into a speculative investment [52].

So the four proposed capacity remuneration mechanisms cover all the vertices of the playing field on the spectrum of capacity price versus available quantities. As a result, by implementing these mechanisms in models and running those simulations for the electricity system in the future, a correct conclusion can be drawn about which capacity remuneration mechanism would work best in the Dutch energy system.

4

Models

To simulate different energy market scenarios models have to be used. There are certain challenges to creating a model that needs to run an accurate simulation of the complex energy generation and trading system. Since there are many different entities active in the system with each their own behaviour, a central controller would not suffice. Each entity needs to be modelled according to its behaviour and should be able to effect other entities in its environment with the decisions it makes. Therefore, the model should be run in a step-wise manner, so at every step the new decision to be taken by the entities can be influenced by the outcome of the previous actions taken.

There are many different kinds of models available, like optimisation, equilibrium or agent-based models. The challenges mentioned above can best be solved using an agent-based modelling (ABM) approach, this approach found its origin in the field of artificial intelligence, but has since been used to model complex systems in the economic and energy system domains, amongst other domains [53]. The model approach uses actors of which the interrelationships and their influences on their environment form the basis of the modelling [54]. This approach enables the description of complex relations between entities within the system, which is done through a set of attributes, behavioural rules and their effects on behaviour of other entities in the environment, and an environment itself [55]. The model allows for the relationships to develop through an evolutionary path, since the analysis has a step by step execution [56]. The data is saved at every step so the evolutionary behavioural changes can be traced back to specific events happening in the simulated timeframe.

Because of these characteristics of agent-based models, they are particularly suitable to simulate complex systems, in which multiple actors behave in an autonomous way. The system evolves in a bottom-up mechanism, which means the behaviour is not centrally determined. This bottom-up evolvement follows from the individual actions taken by entities in the system, which leads to a complex system with emergent structures [57]. Agent-based models do not assume the power sector to be in a long-term equilibrium, which, on the contrary, is done in optimisation or equilibrium models [58].

Agent-based models are proven to be adequate to analyse the complex electricity grids and markets [59], [60], so it can be seen as an adequate testbed for analysing innovative concepts and paradigms within these fields of study. There are three main advantages associated with the general ABM approach, these are [61];

- *Ability to capture emergent phenomena.*

Interactions between individual entities can lead to emergent phenomena; the whole is more than the sum of its parts. These phenomena can only be observed when the individual entities can exercise their own behaviour and influence other entities through interactions that will lead to properties that are decoupled from the properties of the single entity.

- *Ability to provide natural description of the system.*

  By looking at a process from the viewpoint of a single entity inside of the system, instead of looking at it from top down, the model leads to a more natural description of the system. Simulating the behaviour of the single entities will create a model closer to reality than trying to come up with equations that govern the dynamics of the entire system.

- *Ability to offer flexibility.*

  The ABM approach is flexible along multiple dimensions. Firstly, it is possible to add more agents to the model. Secondly, the complexity of the agents can be tuned. Thirdly, the levels of description and aggregation of the agents can be edited.

The models that will be used to analyse the effects in the development of power plants and the energy market are the Energy Modelling Laboratory (EMLab) and AMIRIS. These two will be used together to increase the accuracy of the outcomes. The models will be further explained in the following sections.

4.1 Energy Modelling Laboratory (EMLab)

EMLab is a model developed by the Technical University of Delft at the faculty of Technology, Policy and Management [62]. It was developed to study the long-term effects of interacting energy and climate policies. The model is supposed to simulate evolving energy infrastructure systems, which should aid in the strategic decision-making of public and private actors in the electricity generation sector. By simulating power companies investing in generation capacity, the model should help to anticipate what effects certain decisions will have on the long term [63]. Since it is an agent-based model, the heterogeneity of actors can be explored, as well as imperfect expectations, consequences and investment behaviour in non-ideal conditions [64]. The model offers a new way of modelling policy effects in electricity markets, by providing insight in the behaviour of the actors and the system over time.

4.1.1 Model concept

The EMLab model is able to capture uncertainties by modelling the explicit policy and exploration of transition pathways [58]. The core of the model can simulate processes of the electricity sector, investments and dismantling on the long-term, while being specific enough to show results within short-term processes, such as market clearing and dispatch [63]. The simulation of the long-term processes is enabled by the use of a model within a model, this method can asses the profitability of investments in plant capacities on a business perspective. The model does this by forecasting the merit order of the electricity prices in future years and analysing the net present values (NPV) for every generation type. Since it assumes the power sector is not in a long-term equilibrium, it is possible the agents operating in the system do not have a perfect foresight and can make bad investments or errors. This makes for a system that is in constant flow and a power plant capacity mix evolving through the time steps of the simulation.

4.1.2 Model overview

The EMLab model consist of two interconnected electricity markets, which could be two countries such as the Netherlands and Germany, that are linked trough an interconnector [64]. The modelled agents acting in the system are the power generation companies, these agents can bid on energy and invest in power plants. The investments could be in various generation technologies and are based on the prospective NPV of the investments in power plants. Monte-Carlo simulations are enabled in the model by reducing the simulation time, through representing load as a load-duration curve that is divided into segments.

The overview of the model structure can be seen in Figure 4.1. Looking at the structure, it can be seen that at the start of a simulation a scenario has to be chosen. In the scenario the active agents, behaviour, data, exogenous variables and policies have to be selected. The model iterates with steps through the simulation, controlled by the time controller. Every step the behaviour of the agents will be determined, categorised in three different time scales. On the short-term scale the fuel mix, market coupling and dispatch of generators will be determined. On the medium-term scale the dispatch plan of the power plants will be determined and the CO_2 auction and electricity spot market will be cleared, as well as the fuel markets. On the long-term scale long-term electricity contracts will be signed between agents and agents will decide to invest in new generation capacity or dismantle a part of their generation capacity.

4.1.3 Input

The inputs which can be given in the EMLab model determine the scenario. In the following list all inputs that can be changed are given. These inputs can be configured in multiple Excel files.

- The length of the simulation (in years)
- Whether CO_2 emissions trading is implemented
- Electricity demand growth
- Fuel price trends
- Whether there are one or two countries/markets, possibly also the interconnector capacity (in MW)
- The load demand curve for each country
- Power generation company agents and their properties and preferences
- A CO_2 tax, how the CO_2 cap changes over time and a minimum CO_2-price
- The properties for power generating technologies and how they change over time
- Power plants at the start of the simulation

4.1.4 Model mechanics

In the EMLab model two electricity markets are interconnected through an interconnector. The main agents in the model are the various power generation companies. The power companies bid on power and they invest in various technologies based on the NPV of prospective power plant investments, which are based on scenarios from the IEA World Energy Outlook 2011. The demand load in the model is represented as a load-duration curve, which has to be defined as an input. The load-duration curve is divided into 20 segments to reduce simulation time and thus enabling to do Monte-Carlo simulations of the entire model.

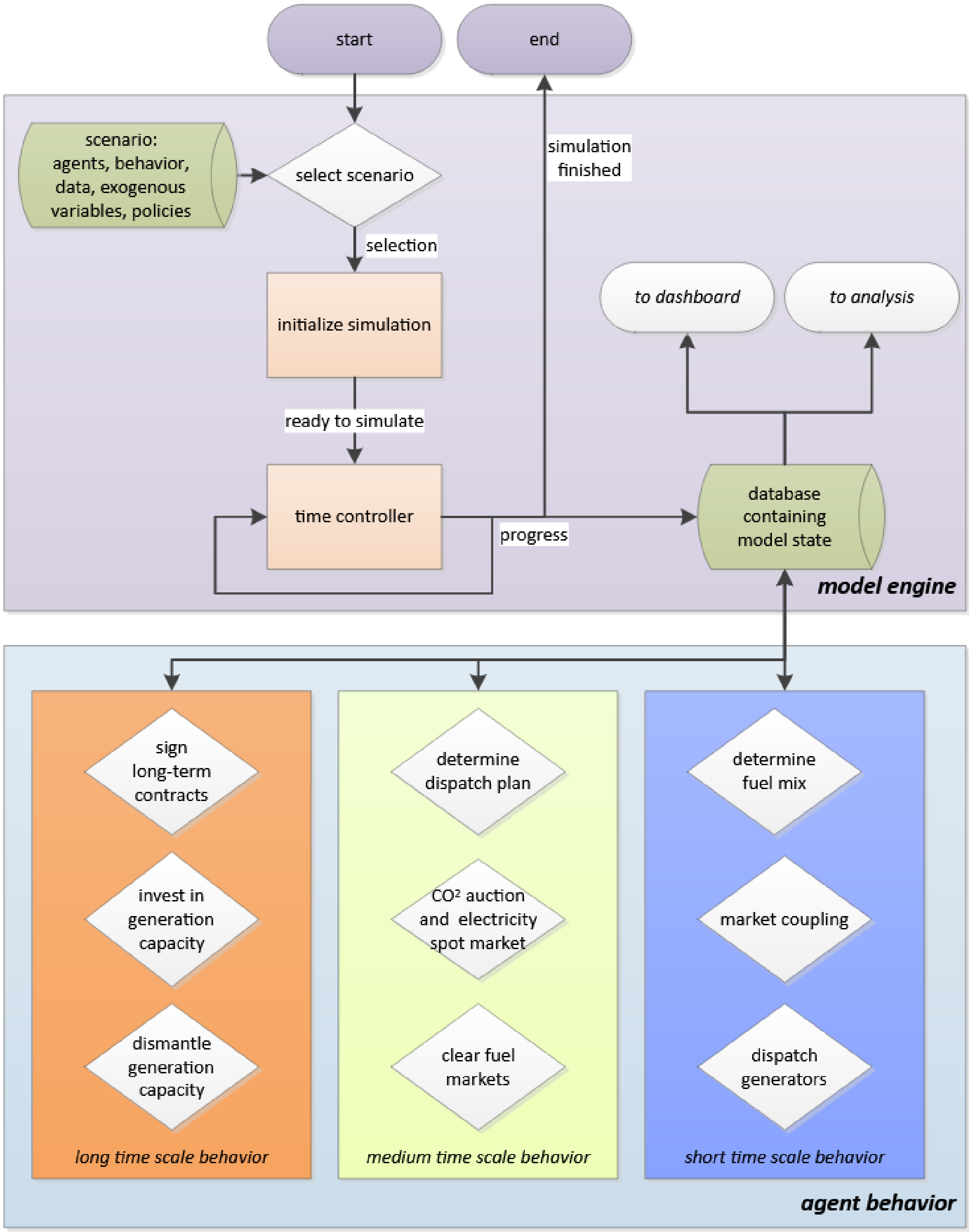

Figure 4.1: Overview of the EMLab model structure [64].

In the model, energy producers are modelled as separate agents, so they are able to make their own decisions on investments. The agents influence each other with the investment decisions they make, because they interact through the market. The decisions of all agents combined form the system-wide developments and performance. This is because the electricity prices in the market are influenced by the bids of the participants, which in turn are based on their generation portfolio, which is something that follows from their investment decisions [65].

4.2 AMIRIS

AMIRIS (Agentenbasiertes Modell zur Integration Regenerativer In den Strommarkt / Agent-based Market model for the Investigation of Renewable and Integrated energy Systems) is a model developed by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt (DLR)) [57]. The model was developed to analyse the adequacy of energy policy and remuneration instruments and to evaluate their impact on the market actors involved in the system on both micro- and macrolevel. Specifically the effects of policy schemes on the integration of renewable energy sources and flexibility options in the electricity system can be simulated using the model. By modelling the actors on a micro-level the model tries to reflect reality more adequately than the conventional equilibrium models based on classical economic theory [66].

4.2.1 Model concept

The AMIRIS model is able to model the micro-behaviour and economic successes of the actors in the complex system. By simulating the interactions between the different entities, such as power plant operators and marketeers, their successes can be determined on micro level [58]. The actions on micro level will have an impact on the macro level of the system through the bottom-up structure. This enables the assessment of policies on renewable energy expansion goals and whether they can be achieved by implementing certain policies or market designs. The economic successes of the agents active in the market can be monitored through the development of the electricity prices, which is a central variable.

4.2.2 Model overview

The AMIRIS model consists of differently prototyped intermediaries that are able to contract renewable energy plant operators and to accomodate their generated energy to the electricity markets or sell it directly to customers [66]. These intermediaries are central figures in the overview of the model depicted in Figure 4.2. There is a techno-economic regime that constraints the decision making of the actors by encompassing all available technologies in the energy system and their costs [67]. The interactions between the actors are coordinated by mechanisms such as the spot market and the control energy market. The regulatory framework influences these system elements by influencing the remuneration mechanisms and feed-in tariffs, for example.

Every iteration step the model calculates the electricity prices, power plant dispatch plans, the market values, emissions and system costs. Before running the simulation the scenario has to be specified with external data. This data consists of feed-in of renewables, the temperature, the balance energy price, marginal costs of conventional generators and the load demand curve.

The AMIRIS model only considers a single country in the simulation, which is Germany by default. However, in the model the module of the day-ahead market is connected to a market coupling agent. This agent makes it possible to import and export electricity in the modelled country.

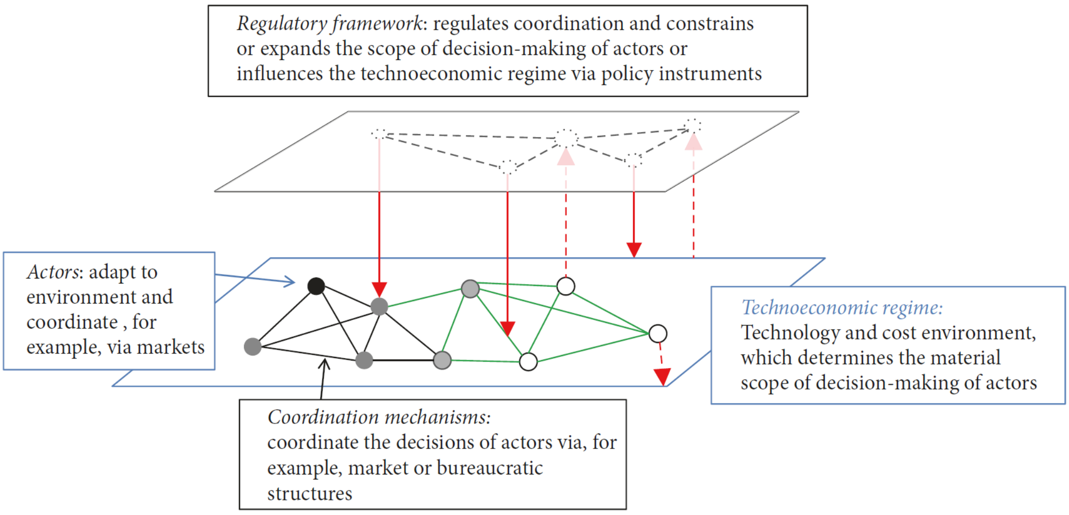

Figure 4.2: Overview of the conceptual framework of the AMIRIS model [57].

4.2.3 Input

To run a complete simulation of AMIRIS input data files have to be passed to the program code. There is an input data file that determines the scenario and an agent configuration file that parametrises the agents in the simulation [67]. The variables that are needed for the model are:

- Capacity per generation technology
- Generation potential for renewable technologies
- Load demand curve
- Prices for coal, gas, oil and CO_2 in the form of time series
- Efficiencies of power plants
- Average sizes of power plants
- The markups on top of the marginal bids of each power plant (minimum and maximum)
- Unavailability of power plants (planned and unplanned)
- Potential of load demand shedding

4.2.4 Model mechanics

To get results the model needs to process the input data, the structure in which AMIRIS operates is depicted in Figure 4.3. In the model the decisions of the active actors will be simulated in an hourly resolution.

The central mechanism in the model simulates the competitive bidding on the electricity market, which results in the electricity market prices and the dispatch plans for the power plants consequently. The market price is not determined per power plant in the model, but per technology. The individual power plants are parametrised inside of the technology class as their average size. A power plant operator agent implements the technology class and is linked to a trader agent, who can offer the available generation capacity of the power plant on the wholesale market in the form of a bid. The power plant operators are able to add a certain markup or markdown to the bid, when a certain technology receives feed-in tariffs for example. The trader agent can instruct the power plant to produce the amount of sold electricity. Contracts in the form of exchange objects take care of the communication and record the delivered energy at specified marginal costs for every hour [67].

When all traders have send in their list of supply bids to the energy exchange, the supply bids are stored in an order book and then sorted by price. In the same way demand traders send in demand bids to the energy exchange. Then the intersection of supply and demand is determined by the exchange and in both the supply and demand order books the accepted bids will be marked. The traders will pass the results of the exchange on to the power plant operators, so only when the power plant is awarded in the competitive bidding it is instructed to run.

The full topology of the AMIRIS model, depicted in Figure 4.3, shows all the agents in boxes. These agents in the system are encapsulated entities that are all equipped with their own set of attributes and behavioural rules. Due to the ABM approach of the model, it is possible to describe the complex relationships between the entities by identifying their attributes, behaviour and the environment in which they operate [57]. This concretely means that for every power plant technology there is at least one trader agent that contains the bidding behaviour of that technology class. The traders are connected to their respective power plant operators through exchange objects. The policy providers form the regulatory framework as is depicted in Figure 4.2, they e.g. track the value of renewables in the market and specify the height of the feed-in tariffs for the renewable generation technologies. The renewables traders take these remunerations into consideration in their bidding and lower their bid with a markdown equal to the height of the premium they receive. However, these remunerations will be paid to the renewables traders ex-post on a monthly basis, so the traders need to forecast the amount they will receive, for this they take the value of the past month market premium [67].

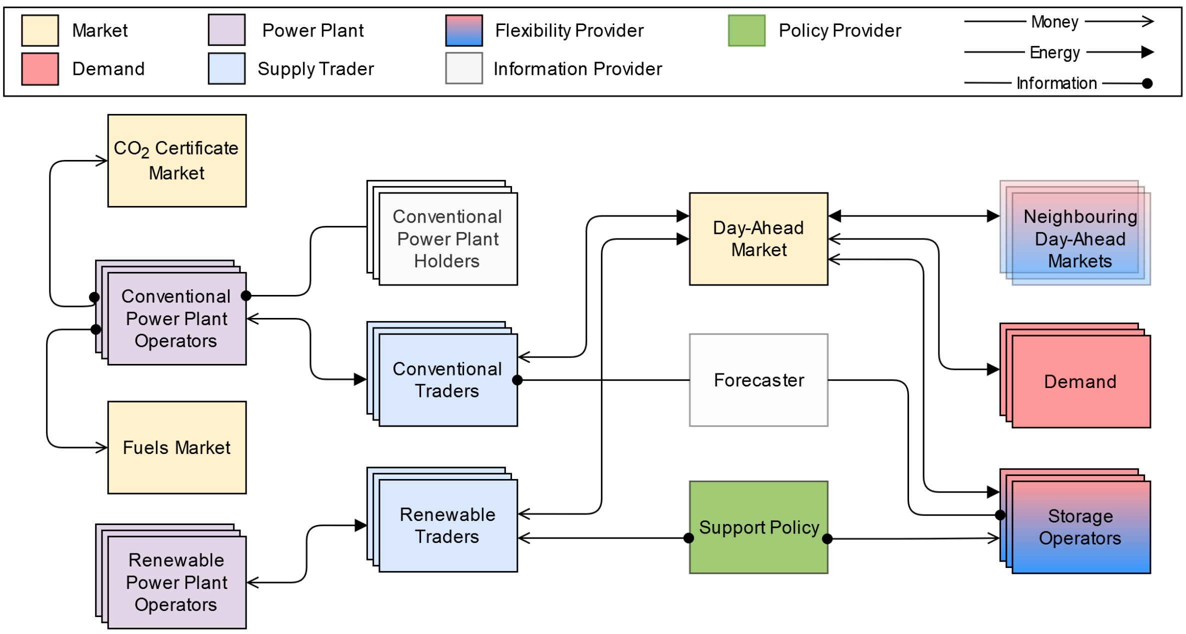

Figure 4.3: Overview of the full AMIRIS model structure [66].

5

Future Dutch Electricity Mix

Answering what could be a realistic energy generation scenario for the Netherlands in 2050 will not be left to the simulations, but will be done by an extensive literature study. It would be desirable that the simulations end up in a similar energy generation scenario to achieve the most useful results. However, nobody can look into the future and know for sure how the energy generation mix will look like in 2050. Therefore, it is impossible to define one scenario, but an attempt can be made to mark the borders within which the scenario is expected to fall.

In the ”Klimaatneutrale energiescenario’s 2050” (Climate-neutral energy scenarios 2050) report written by Berenschot [68], four future energy scenarios are given, which all have the objective to lower the CO_2-emissions as much as possible. These scenarios sketch the vertices of the playing field of the electricity generation mix that will probably be installed in the year 2050. This gives some flexibility for the net operators for the changes needed in the infrastructure.

The scenarios are created in the Energy Transition Model developed by Quintel Intelligence. This online tool enables users to get an overview of regional CO_2-emissions, build scenarios for certain regions, gain insight of different options and see how different sectors interact [69]. All the scenarios use the same base parameters, such as the number of inhabitants in the Netherlands and the number of households, which are 18.4 million and 8.8 million respectively in 2050. The four scenarios are called regional governance, national governance, European CO_2-governance and international governance. The following sections will explain the scenarios shortly and their characteristic electricity generation mix will be given. Afterwards the feasibility of the scenarios will be discussed.

5.1 Regional governance

In this scenario the focus lies on the governance from local communities and autonomous systems [70]. Heat is delivered through heat networks and generated through geothermal energy. Heavy electrification is present due to a big growth in solar- and wind-energy, which together with a decline in industrial activities lead to a country self-sufficient in energy. In case of energy demand peaks gas will still be used, but in the form of green gas from local biomass and ”green” hydrogen from solar- and wind-energy through electrolysis.

In Table 5.1 the installed generation capacity of the regional governance scenario in 2050 is presented.

Technology	Marginal costs	Installed capacity	Availability	Full load hours
	€/MWh	MW	%	Hr
Solar PV (buildings)	-	18,711.81	98	867
Solar PV (households)	-	40,442.15	98	867
Solar PV (ground-mount)	-	66,918	98	867
Wind (offshore)	-	31,000	92	4,500
Wind (onshore)	-	20,000	89	3,000
Hydro (river)	-	37	98	2,515
Import	50.04	14,800	30	475.81
Hydrogen plant (CCGT)	66.61	18,500	90	869.02
Gas CCGT CCS	107.46	2,500	87	187.99
Hydrogen turbine	117.48	12,000	90	39.06

Table 5.1: Installed electricity generation mix in 2050 in the regional scenario [70].

5.2 National governance

In this scenario the national government controls the energy systems [71]. There is less growth in heat networks, but a stronger growth in electrification in all consumption sectors. The energy generated by wind and solar is highest of all scenarios. The industrial sector is stable and becomes more sustainable due to heavy electrification, therefore import of energy is needed. As backup for the industrial sector gas will still be needed in the form of green gas and ”green” hydrogen.

In Table 5.2 the installed generation capacity of the national governance scenario in 2050 is presented.

Technology	Marginal costs	Installed capacity	Availability	Full load hours
	€/MWh	MW	%	Hr
Solar PV (buildings)	-	9,355.91	98	867
Solar PV (households)	-	40,442.15	98	867
Solar PV (ground-mount)	-	57,600	98	867
Wind (offshore)	-	51,500	92	4,500
Wind (onshore)	-	20,000	89	3,000
Hydro (river)	-	37	98	2,515
Import	50.44	14,800	50	699.82
Waste CHP	64.93	363	90	1,142.76
Hydrogen plant (CCGT)	66.61	17,000	90	738.34
Hydrogen turbine	117.48	18,000	90	57
Gas engine CHP (small-scale)	124	330	95	0

Table 5.2: Installed electricity generation mix in 2050 in the national scenario [71].

5.3 European CO_2-governance

In this scenario the energy is controlled by the European CO_2-tax, which applies to all sectors [72]. This CO_2-tax leads to an increase in the use of green gas in multiple sectors. There is again a big growth in solar- and wind-energy. The industrial sector also grows in this scenario, however, there is no CO_2-emission due to a combination of hybrid electrification and carbon capture and storage (CCS), including the production of ”blue” hydrogen. There is a moderate electricity peak demand in this scenario, partly because of the hybridisation. There will be more import of energy than in the previous two scenarios and gas will still be present in neighbourhoods and other sectors, this will be in the form of green gas and a mix of ”blue” and imported ”green” hydrogen.

In Table 5.3 the installed generation capacity of the European governance scenario in 2050 is presented.

Technology	**Marginal costs**	**Installed capacity**	**Availability**	**Full load hours**
	€/MWh	**MW**	**%**	**Hr**
Solar PV (buildings)	-	7,484.73	98	867
Solar PV (households)	-	16,176.86	98	867
Solar PV (ground-mount)	-	34,588	98	867
Wind (offshore)	-	30,000	92	4,500
Wind (onshore)	-	10,000	89	3,000
Hydro (river)	-	37	98	2,515
Import	49	14,800	100	3,537
Waste CHP	64.93	726	90	2,291.61
Gas CCGT	84.94	15,155.04	90	1,189.77
Gas CCGT CCS	107.46	1,844.96	87	228.41
Gas turbine	149.84	19,000	90	30.81

Table 5.3: Installed electricity generation mix in 2050 in the European scenario [72].

5.4 International governance

In this scenario the energy is controlled by the market and internationally the cheapest option is searched for [73]. A lot of hydrogen is imported in this scenario from countries where it could possibly be produced more easily. Green gas is used less, but there is a lot of hybridisation with hydrogen as back-up, this is because of the growth of the industrial sector in this scenario. Due to the import of hydrogen, less wind-energy is needed for the national electrolysis and, therefore, this scenario has the lowest sustainable electricity production.

In Table 5.4 the installed generation capacity of the international governance scenario in 2050 is presented.

Technology	Marginal costs	Installed capacity	Availability	Full load hours
	€/MWh	MW	%	Hr
Solar PV (buildings)	-	5,613.54	98	867
Solar PV (households)	-	12,132.65	98	867
Solar PV (ground-mount)	-	34,588	98	867
Wind (offshore)	-	27,500	92	4,500
Wind (onshore)	-	10,000	89	3,000
Hydro (river)	-	37	98	2,515
Import	48.66	14,800	100	3,824.82
Waste CHP	64.93	726	90	2,465.55
Hydrogen plant (CCGT)	66.61	11,000	90	1,534.79
Gas CCGT CCS	107.46	5,000	87	415.35
Hydrogen turbine	117.48	18,000	90	49.38
Gas engine CHP (small-scale)	124	1,650	95	0

Table 5.4: Installed electricity generation mix in 2050 in the international scenario [73].

5.5 Feasibility of the scenarios

In the regional governance scenario there is a large decline in industrial activities, which results in the largest energy usage decline of the four scenarios, as can be seen in Table 5.5. This makes reaching the climate targets a lot easier, but the feasibility of such a large decline in industrial activities is debatable. By having the lowest energy usage of the scenarios, it also makes sense that the annual energy costs and Loss of Load Expectation (LOLE) are relatively low.

In the national governance scenario the industrial activities remain stable, but due to heavy electrification and by installing relatively a lot of offshore wind, the climate targets can still be reached. However, the share of renewable electricity is the highest of the scenarios at 177.3%, which means there is heavy over-investment. How realistic such a high over-investment is, is also debatable.

The European CO_2-governance scenario seems to be the least ambitious and so the most feasible of the four, due to the increasing industrial activities, increasing energy import and a share of renewable energy below 100%. However, the climate goals of the EU will not be reached, since the CO_2-emissions will be 92.3% lower in 2050 compared to 1990, while the goal is to achieve a reduction of at least 95%.

In the international governance scenario the market dictates the scenario and the cheapest form of energy will prevail. However, this scenario will probably lead to the technology that gets most heavily subsidised by a government in a certain European country to be used the most. Which means that specific country will have losses, since they are selling electricity to other countries at a price lower than their subsidy support costs. This leads to a scenario that is not very stable on the long-term.

2050	Regional	National	European	International
Energy usage compared to 2015	-48.5 %	-34.8 %	-11.7 %	-12.1 %
CO_2 compared to 1990	-99.4 %	-98.1 %	-92.3 %	-95.2%
Renewable electricity share	160.7 %	177.3 %	92.8 %	80.7 %
Annual energy costs	€ 49.7 bln	€ 55.4 bln	€ 52.6 bln	€ 56.4 bln
Loss of Load Expectation (LOLE)	23 hr	20 hr	103 hr	128 hr
Installed VRE capacity	32985.1 MW	40862.2 MW	22886.3 MW	21131.0 MW
Installed controllable capacity	1987.7 MW	2028.8 MW	8101.2 MW	8678.0 MW

Table 5.5: Key parameters of the four scenarios [70]–[73]. The installed capacities are a result of the summed installed capacities multiplied with their availability and full load hours.

6

Simulations

The following sections describe how the AMIRIS and EMLab models were combined to create a functioning simulation. Next up, it is explained how the data was gathered that was used as input data for the simulations and the way the simulations were set up is described.

6.1 Coupling of AMIRIS and EMLab

To create a model that will deliver simulations that are more accurate than the simulation of either EMLab or AMIRIS, the two models will be coupled. To create one model that is better than the sum of its two parts, the models have to be coupled in a way that the strongest attributes from both models will be used. EMLab strongest attributes are its investment and decommissioning decisions, while AMIRIS has a more accurate market clearing module. Therefore EMLab will be used for long-term decisions and AMIRIS to clear the electricity spot market. Figure 6.1 depicts how the two models are coupled.

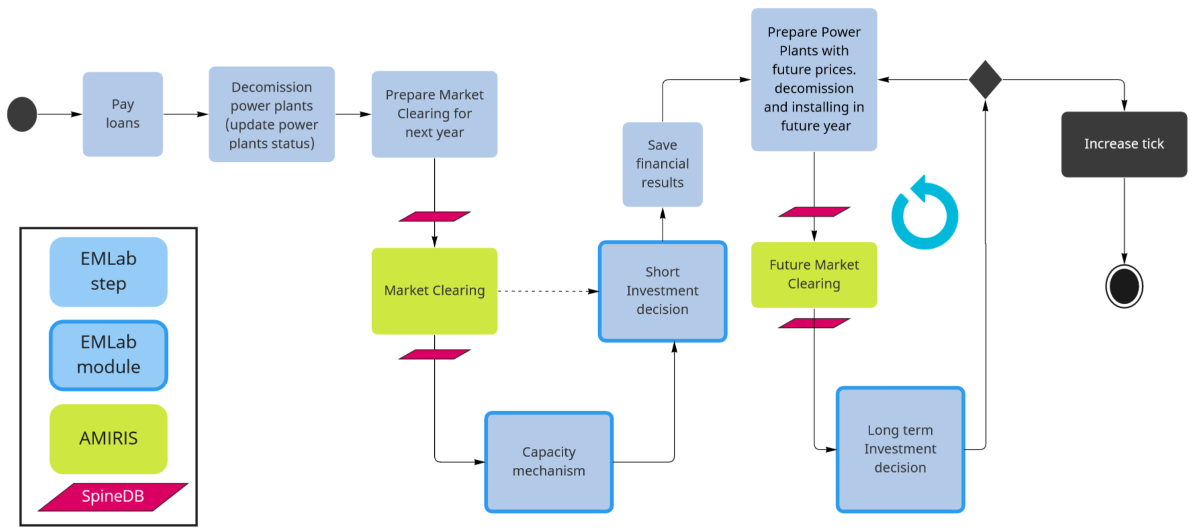

Figure 6.1: Flowchart depicting the coupling of AMIRIS and EMLab.

As can be seen in Figure 6.1, there are multiple different steps that get executed by EMLab, while AMIRIS is only responsible for the market clearing. This is because it is possible to make changes to the functionalities of EMLab, but not to AMIRIS. So AMIRIS is seen as a blackbox that can clear the market, to which inputs can be fed and market results will come out.

The coupled model starts with paying the loans to power plants and the decommissioning of power plants that are past their expiration date and not profitable anymore for the last few years. Then the market clearing will be prepared, which means that a list will be constructed with the plants that are operational and will participate in the market. This list contains data about each participating power plant, like its fuel type, variable operating costs, efficiency and capacity. These first steps were done in EMLab, so the data now has to be prepared in SpineDB to be readable by AMIRIS.

Next up AMIRIS will clear the market and the data will be prepared by SpineDB again to be readable by EMLab. The output data from AMIRIS contains the total variable costs, revenues and production in MWh of each power plant that participated in the market.

When a capacity mechanism is activated EMLab will execute the capacity mechanism module, otherwise the model will skip to the short investment module. Next up, the financial results are saved, from which can be determined whether the operation of a power plant is profitable. Then EMLab will prepare the future prices of power plants and determine which power plants will be decommissioned in the future or what candidate power plants would be available in the future. In the model it is also assumed that the power plants that are in the strategic reserve in the current year will still be operational and in the strategic reserve in the future year. For the long-term investment decisions module a loop will be initiated in which future markets are cleared by AMIRIS. The market will be cleared 4 years into the future, to be able to predict whether an investment in a power plant would be profitable when it becomes operational. Long-term investment decisions on the decommissioning or the installing of power plants will be based on these results. The loop will be initiated for the decision on a single investment, when the investment is profitable the loop will start again. Only when the investment in more power plants is not profitable anymore, the loop is finished and the tick will be increased so the next year will be initiated.

6.1.1 The Spine Toolbox

To realise running simulations of the coupled AMIRIS-EMLab model all the modules of the models were connected in the Spine Toolbox [74]. The Spine Toolbox is a modular tool which provides a skeleton for bringing models and data together. By combining the models and their data the Spine Toolbox is able to make a visual representation of the whole chain of data processing. The tool is meant to define, manage and execute increasingly complex energy system models. Therefore, the Spine Toolbox is a suitable tool for providing the skeleton along which AMIRIS and EMLab are coupled.

In Figure 6.2 the coupling of AMIRIS and EMLab in the Spine Toolbox can be seen. On the left side the blue data connection items load in excel files, which define the scenario. These data connections are connected to purple data importers, which will import the data from the excel files and load them into the pink data storage item. Items further along the chain will be able to read and write data to the data storage, when they are connected to it. When the data is loaded into the EmlabDB data storage item, the scenario is set and the simulation can be started. The first step in the simulation is the initialisation of the clock, which happens in a red tool item. Next up, the power plants get initialised and decommissioned according to financial results of the previous years. This is followed by the preparation of the data for AMIRIS. After AMIRIS has run, the data will be imported in the AMIRIS DB storage item. The specify year tool is there to make sure all the data is handled and specified correctly before going into the capacity mechanism. In the capacity mechanism tool can be defined which capacity mechanism gets executed. The create results tool saves data to an excel to be able to analyse the results

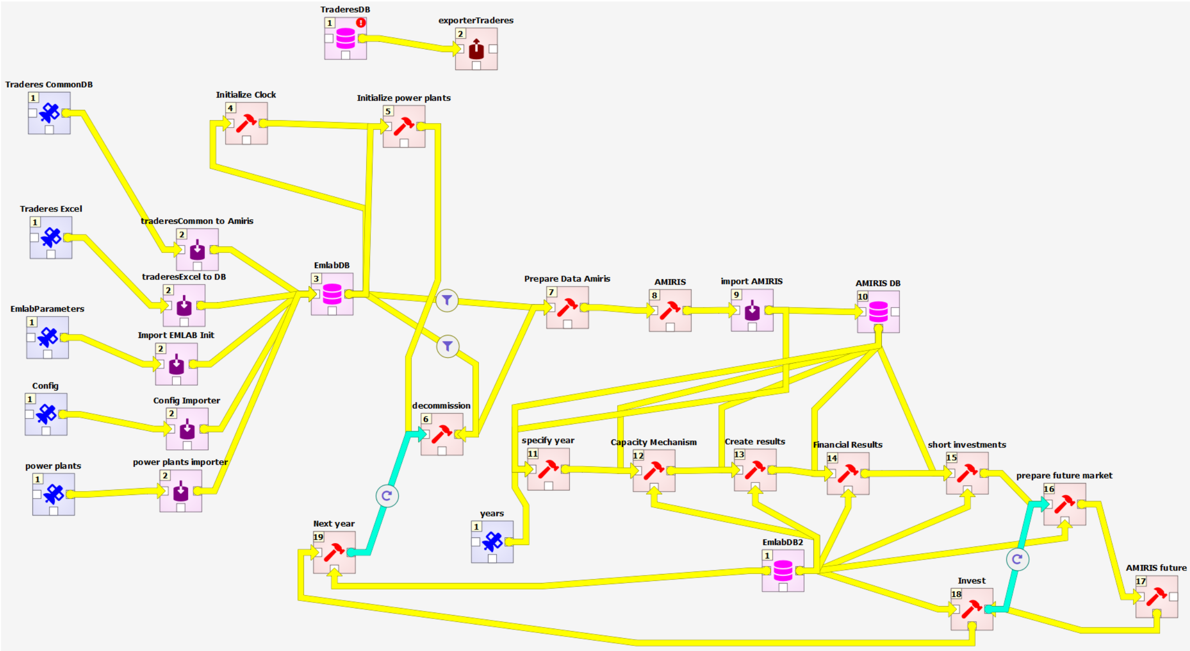

Figure 6.2: Flowchart depicting the coupling of AMIRIS and EMLab in the Spine Toolbox.

from the market. Next up, the financial results tool gathers the financial results of the power plants, so they can be later on decommissioned, not only on age, but also on profits. When the market results are known, the short investment tool will make short investment decisions for the installation of PV utility systems or lithium ion batteries. Then the long-term investment decisions will be made by the invest tool, after AMIRIS future has simulated the market until 4 years into the future, to determine if the investments will be profitable. AMIRIS future looks 4 years ahead, because the longest permit and build time of the power plants within the available long-term investments is 4 years. For every investment that will be made the investment loop has to be run one time. Lastly, the next year will be initialised and the whole chain starts again.

Instructions for running the simulations can be found in Appendix B.

6.2 Power plant database update

EMLab already had a database of power plants to be used as input for the model, but the database was never updated since 2015 and only contained German power plants. So to be able to create realistic simulations of the Dutch energy market the database had to be updated. The German plants had to be updated to the current situation and Dutch plants had to be added to the database. For the simulation it is very important to have not only the capacity of the installed power plants, but also their age, technology and efficiency. Therefore, databases had to be found that are first of all complete, secondly up-to-date and thirdly, contain all these specifications.

6.2.1 Dutch power plants

A list of Dutch power plants was not yet present in the database, so they had to be added.

Conventional plants

For the conventional power plants in the Netherlands Wikipedia [75] was used. The list of power plants was up-to-date and contained the specifications needed for the database, such as the capacity and commissioning year.

Renewable energy plants

For both the onshore and offshore wind farms in the Netherlands Wikipedia [76] was used, as well as for the solar installations [77]. Also for these renewable power plants the available data on Wikipedia was adequate for the database.

To do a sanity check the total installed capacity of the renewable power plants were compared to the data of the Statistics Netherlands (CBS) [78]. According to CBS the total installed capacity of wind energy is 6.6 GW, however, the total installed capacity from the gathered data sums up to 5.6 GW. So the total capacity of wind energy is 15% lower than it should be. The total installed solar capacity, according to CBS, is 14 GW, but the gathered data only sums up to 1.7 GW. This large difference, of nearly a factor 10, can be explained due to the fact that only data was listed from solar energy farms with a minimal nominal capacity of 0.5 MW, but there are a lot of little solar installations in the Netherlands on, for example, rooftops of houses. These little installations are very hard to track and do not really participate on the energy market, therefore only the bigger installations will be used in the database for the models.

6.2.2 German power plants

German power plants were already present in the database, but the conventional plants were outdated and the renewable plants were not accurately depicted.

Conventional plants

For the conventional power plants in Germany the Open Power System Data platform [79] was used to gather the data. This is a data package containing data on German conventional power plants as well as neighbouring European countries. The data contains specifications and technical characteristics of individual power plants. However, the quality of the publicly available data varies per country and not all information is provided for each country. This database is, therefore, very appropriate for the German power plants, but not for the Dutch ones.

Renewable energy plants

For the onshore wind farms and installed solar energy capacity the Global Power Plant Database [80] from the World Research Institute was used, due to it being the only available database with the age of the installed energy sources. The data was very comprehensive and, therefore, grouped per age of installation instead of name or owner.

For the offshore wind farms Wikipedia [81] is used to group the data of the Global Power Plant Database to their real names and owners. The combination of these databases results in a list of offshore wind farms that is very comprehensive and has all the technical specifications of the farms.

To sanity check if the total installed capacity of the list of renewable plants is in the correct order of magnitude, the total capacity was compared to the capacity data of Germany's Bundesnetzagentur [82]. According to the Bundesnetzagentur the total installed capacity of renewable power plants is 138.6 GW and the gathered data sums up to 114.6 GW, so this is a difference of 17%. This difference in capacity is this time not mostly related to the installed solar capacity, since according to the Bundesnetzagentur it should be 59.3 GW, but the gathered data sums up to 51.9 GW. Furthermore, the onshore wind farm capacity is 56.1 GW and the offshore capacity is 7.7 GW according to the Bundesnetzagentur, but the gathered data sums up to 45.0 GW and 7.3 GW respectively.

6.2.3 Grouping of power plants

Since the list of power plants in the database is very long, the power plants are grouped together if they have the same technology and the same age. So the grouped power plant has the capacity of the power plants with the same technology and age summed together. The power plants can be grouped together in this way, because the model would have treated those power plants in the same way. When power plants have the same technology and age, their cost modifier would have been the same in the model and they would have been decommissioned in the same year.

By grouping power plants together the simulation time will be less. When the simulation makes a lot of loops through the power plants, decreasing the number of plants will result in faster simulations. However, when the power plants are grouped together, the accuracy of the results will of course also decrease, but this accuracy decrease is not significant due to the previously mentioned reasons.

6.3 The baseline scenario

As a realistic energy generation scenario for the Netherlands in 2050 a baseline scenario will be chosen to which the results from the simulations will be compared.

The baseline scenario should lie somewhere in between sketched vertices in the previous section, therefore it will be somewhat of an average of the four given scenarios. If the averages of the key parameters of the four scenarios are taken, it will result in the average key parameters given in Table 6.1. The results of the simulations will be realistic if the key parameters of the finished simulations will be in the same order of magnitude as these average values.

	Average	International
Energy usage in 2050 compared to 2015	-26.8 %	-12.1 %
CO_2 in 2050 compared to 1990	-96.3 %	-95.2 %
Renewable electricity share in 2050	127.9 %	80.7 %
Annual energy costs	€ 53.5 bln	€ 56.4 bln
Loss of Load Expectation (LOLE) in 2050	68.5 hr	128 hr
Installed VRE capacity in 2050	29466.1 MW	21131.0 MW
Installed controllable capacity in 2050	5198.9 MW	8678.0 MW

Table 6.1: The key parameters of the average of the four scenarios and of the international governance scenario.

However, since the EMLab model will make all investment and dismantle decisions based on total profits made by the power plants, the simulations have most in common with the international governance scenario. Therefore, a simulation scenario will be created in which the energy demand decreases linearly to -12.1% in 2050, as is the case in the international governance scenario. The standard version of AMIRIS-EMLab has no trend incorporated for the demand, so the load demand curve of 2020 is used for every year. To compare what happens when a trend is applied to the demand, simulations will be run for both the demand staying equal through the years and for a descending demand trend replicating the international governance scenario.

6.3.1 Load demand curve

For the start of the simulations an hourly load demand curve is generated from the Energy Transition Model data for the Netherlands in 2020 [83]. The Energy Transition Model offers CSV files containing the energy usage per application per sector in the Netherlands. So the data of the electricity usage was processed using Microsoft Excel and turntables were used to get the total hourly electricity demand in the Netherlands. Then the data was formatted so it can be read by AMIRIS as input for the simulation. The hourly load demand input will be the same for all the simulations, so the results can be compared with each other in the correct way.

In Figure 6.3 the total demand curve per day can be seen, it was summed per day for the sake of visualisation.

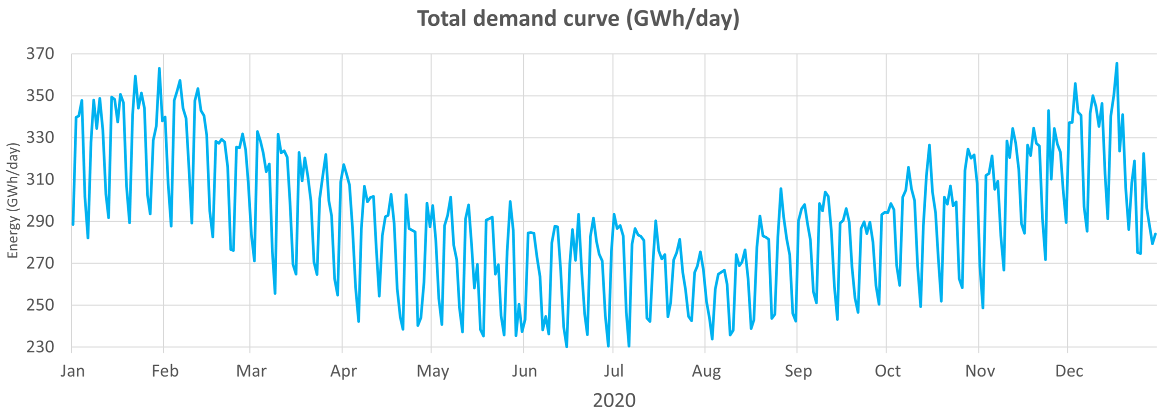

Figure 6.3: Demand curve of the total load demand in the year 2020 in GWh per day. The hourly demand data was summed to represent the daily energy demand.

The total demand curve in Figure 6.3 is the summed total of the demand curve per sector. The demand curve per sector can be seen in Figure 6.4. In the figure of the demand per sector can be seen that the energy demand dips in the weekends are caused mostly by the buildings and agriculture sector.

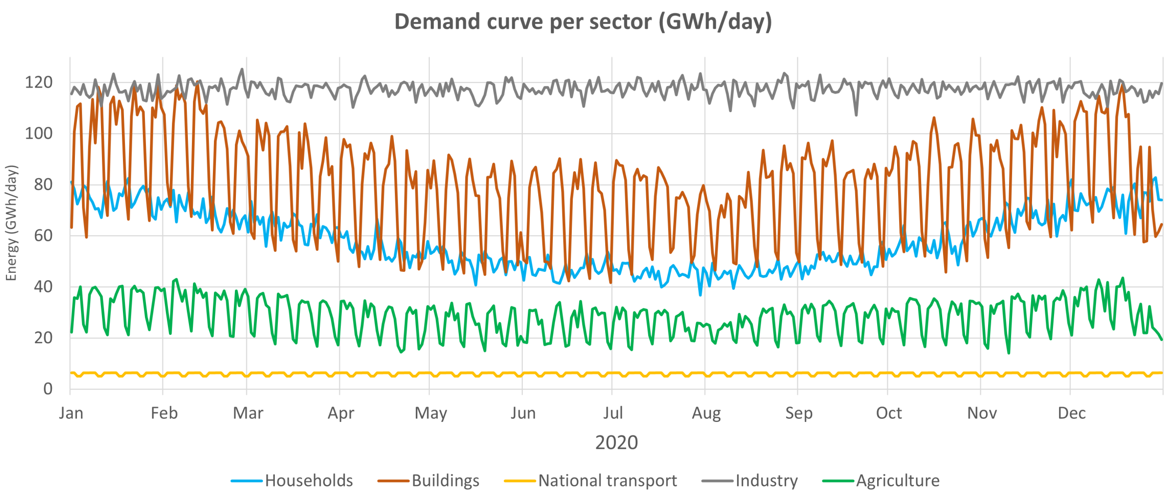

Figure 6.4: Demand curve of the load demand per sector in the year 2020 in GWh per day. The hourly demand data was summed to represent the daily energy demand.

To test the adequacy of the installed power system in the Netherlands in 2050, a single simulation year will be run with the expected demand curve of 2050 as input as well as the installed power plants in 2050. For the installed power plants the installed power plants as result of the simulation in 2050 will be used. For the expected hourly demand curve of 2050 a so called "dunkelflaute" scenario is used to test the adequacy of the installed power plants. A "dunkelflaute" scenario is a scenario in which the demand is higher than usual for longer periods of time and during this period there will be no wind or solar energy available. In this scenario the Netherlands suffers a very harsh winter with an exceptionally cold period, with an average temperature of -6.5°Celsius from January 6 until January 21. This will cause a significant increase in demand for heat. The hourly load demand curve summed per day can be seen in Figure 6.5.

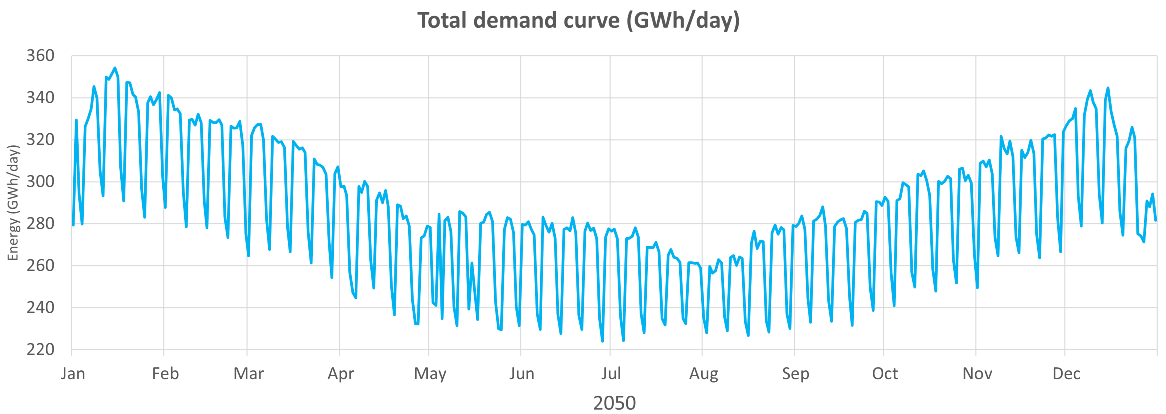

Figure 6.5: Demand curve of the total load demand in a "dunkelflaute" scenario in the year 2050 in GWh per day. The hourly demand data was summed to represent the daily energy demand.

The total demand curve in Figure 6.5 is the summed total of the demand curve per sector. The demand curve per sector can be seen in Figure 6.6.

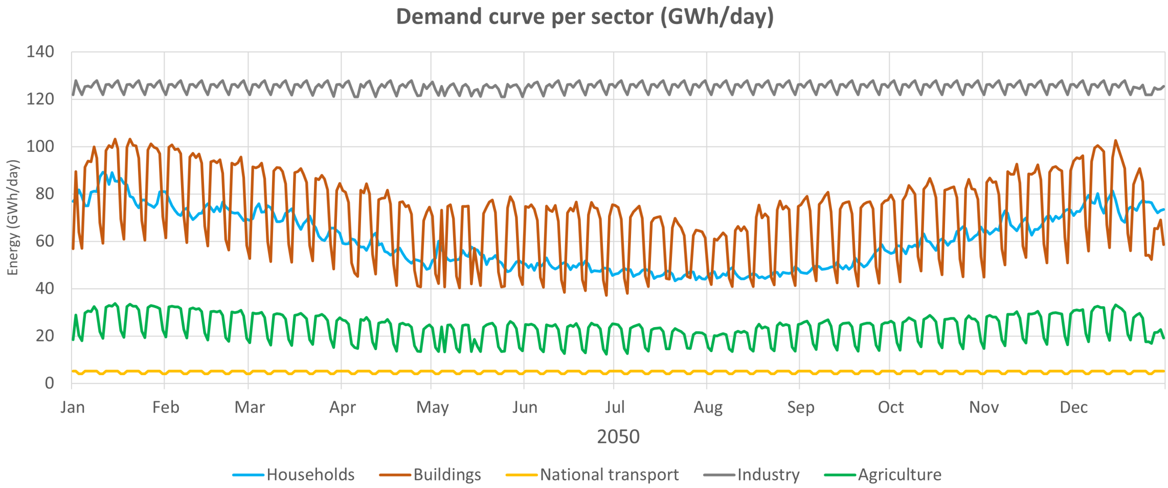

Figure 6.6: Demand curve of the load demand per sector in a "dunkelflaute" scenario in the year 2050 in GWh per day. The hourly demand data was summed to represent the daily energy demand.

When comparing Figure 6.4 with Figure 6.6, the most notable difference is the increase in electricity usage in the industrial sector. This could be due to the expectation that the industry will undergo a heavy electrification.

In addition, from Figure 6.6 can be seen that the trend that more energy will be consumed in the winter is mostly due to the household consumption of electricity. Since in all the scenarios there is heavy electrification in houses, the colder periods result in significant increases in electricity use. This is partly because there is less light available during the day, so the lights are on more hours per day, but mostly because of the heat pumps heating up the houses. Although heat pumps are advertised as the sustainable alternative to the gas-heated boiler, they still need serious amounts of electrical energy to get a house heated up to a comfortable temperature in the winter months. Therefore, heat pumps will only be sustainable when the used electricity is generated by renewable energy sources.

7

Implementation of the Capacity Mechanisms

To be able to test which capacity remuneration mechanism would ensure the highest level of security of supply, the different mechanisms should be implemented in the coupled model of AMIRIS and EMLab. P. Bhagwat already made implementations of the strategic reserve and the yearly capacity market in Java for EMLab in his doctoral research [8]. However, these mechanisms should be rebuilt to fit inside the project of AMIRIS-EMLab running in Python.The implementation for the capacity subscription mechanism still has to be made from scratch.

7.1 Strategic reserve

The following sections firstly describe how the behaviour of the basic strategic reserve is modelled and what parameters need to be defined in the model. Then the description of the modelling of both the German and the Swedish model for the strategic reserve follows.

In the script the available power plants start by bidding their full capacity at cost price to the strategic reserve market. The cost price is determined by dividing the fixed costs by the capacity and adding it to the marginal costs to have a normalised price per MWh. These bids get sorted in descending order, since the most expensive power plants are contracted first, because they would have made the lowest bids and are least likely to run, therefore, the costs of withdrawing these plants from the market are the smallest.

Next up, the volume of the strategic reserve is determined by multiplying the total capacity in the market with the strategic reserve fraction. Now the operator starts with contracting the power plants with the highest normalised costs for the strategic reserve. When a power plant is contracted into the strategic reserve that means its full capacity is contracted. The process of contracting power plants is iterative and continues until the contracted capacity is equal to the predetermined strategic reserve volume.

The contracted power plants get their annual fixed operating costs paid by the operator and the operator offers the available plants on the electricity spot market at the strategic reserve dispatch price (P_{SR}). The operator of the strategic reserve can cover the costs of the strategic reserve by offering the available capacity within the strategic reserve on the market. When the capacity of generating units is sold on the market and dispatched, the revenue of the strategic reserve operator (R_{SR}) is the revenue of the generating units (R_{GR}) above their marginal generating costs (VC).

$$R_{SR} = R_{GR} - VC \tag{7.1}$$

In case the strategic reserve operator cannot recover the full costs of the strategic reserve, the operator will end the simulation with a negative amount of cash. This negative cash amount would normally be passed on to the consumers via the network of system tariffs. However, in this model this is not possible to implement directly, but can be shown in the results.

An electricity shortage will occur when the full capacity of the strategic reserve and all non-contracted generators are running and the combined capacity is not enough to meet demand. When this happens the model sets the market price equal to the VoLL.

Thus summarised the steps the model takes are;

1. Power plants bid their full capacity at cost price to the strategic reserve market
2. The bids get sorted in descending order (on price)
3. Contract energy from power plants with highest operating costs
4. Pay contracted power plants their annual operating costs
5. Offer this energy to the market with price P_{SR}, which is higher than the marginal costs
6. If dispatched, pay contracted power plants marginal costs
7. If not profitable for TSO, costs of the strategic reserve can be seen as a result of negative cash

In Figure 7.1 the flowchart of the implemented strategic reserve can be observed.

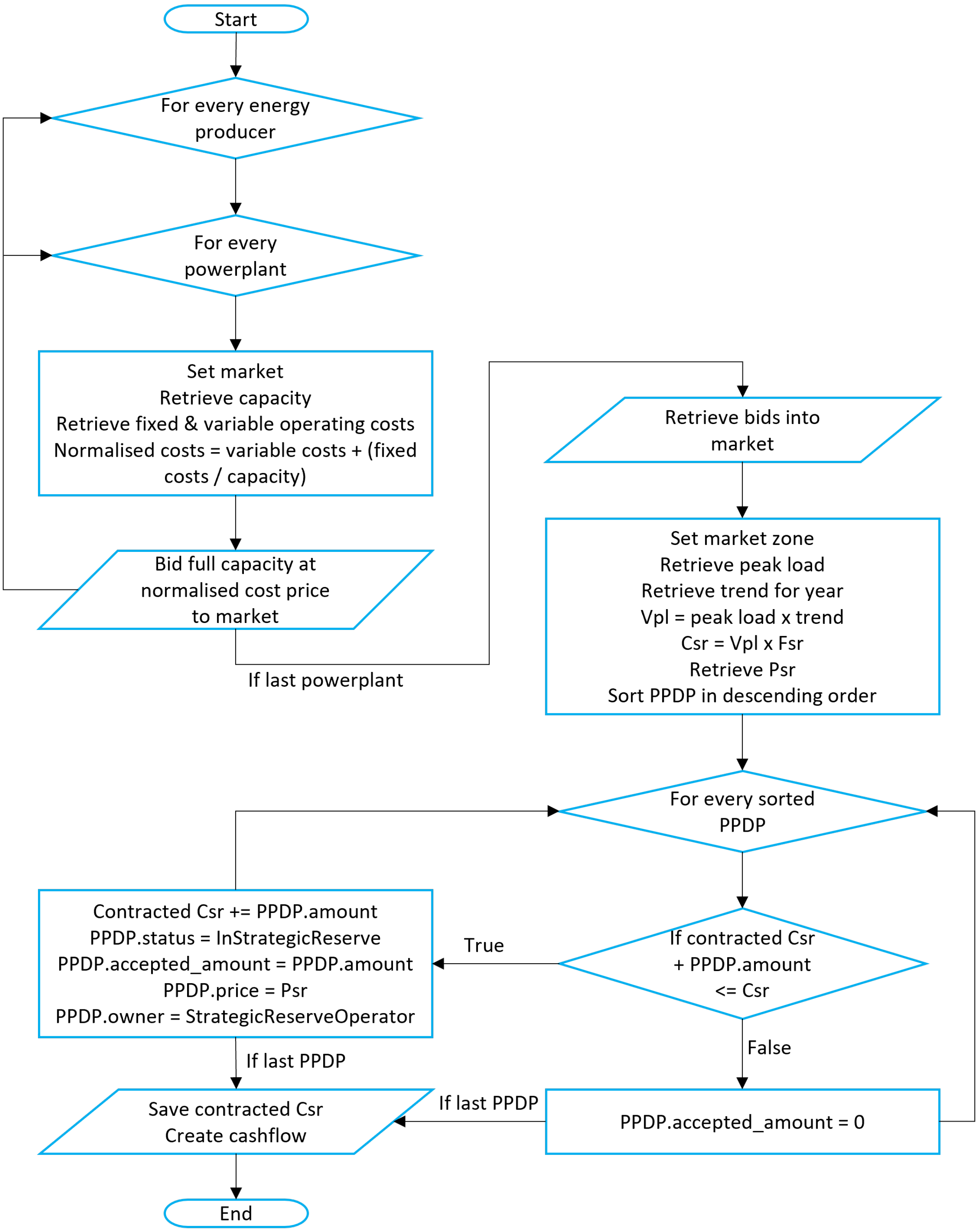

Figure 7.1: Strategic reserve flowchart.

Parameter definitions

The key parameters for the strategic reserve model are;

- *Fraction strategic reserve* (F_{SR})

  The user defines the size of the strategic reserve capacity to be contracted as a fraction

F_{SR} of the expected peak demand. The F_{SR} will be set at 6% with a corresponding dispatch price P_{SR} of € 800/MWh, as these values were established to be the most effective for a strategic reserve [84].

- *Total contracted capacity (C_{SR})*

  The total capacity contracted into the strategic reserve (C_{SR}) is calculated in every time step. It is calculated by multiplying the fraction of the strategic reserve volume (F_{SR}) with the peak load volume (V_{PL}) of the corresponding year.

$$C_{SR} = F_{SR} \cdot V_{PL} \tag{7.2}$$

7.1.1 German strategic reserve

The German strategic reserve implementation is built off of the basic strategic reserve with a few additions. Firstly, only conventional power plant are allowed to participate in the strategic reserve, so only those are able to place bids on the strategic reserve market. Secondly, when a power plant gets accepted into the strategic reserve it has to be decommissioned in a few years. When the model updates the power plant status it, therefore, also increases the age of the power plant to an age 4 years before its expected lifetime. This means the power plant should get decommissioned after being in the strategic reserve for 4 years. Furthermore, when a power plant gets accepted into the strategic reserve it will be in there for the rest of its lifetime. Thus the model checks if the power plant was already in the strategic reserve and if it was, it automatically accepts it in again.

The flowchart of the German strategic reserve implementation can be seen in Figure 7.2.

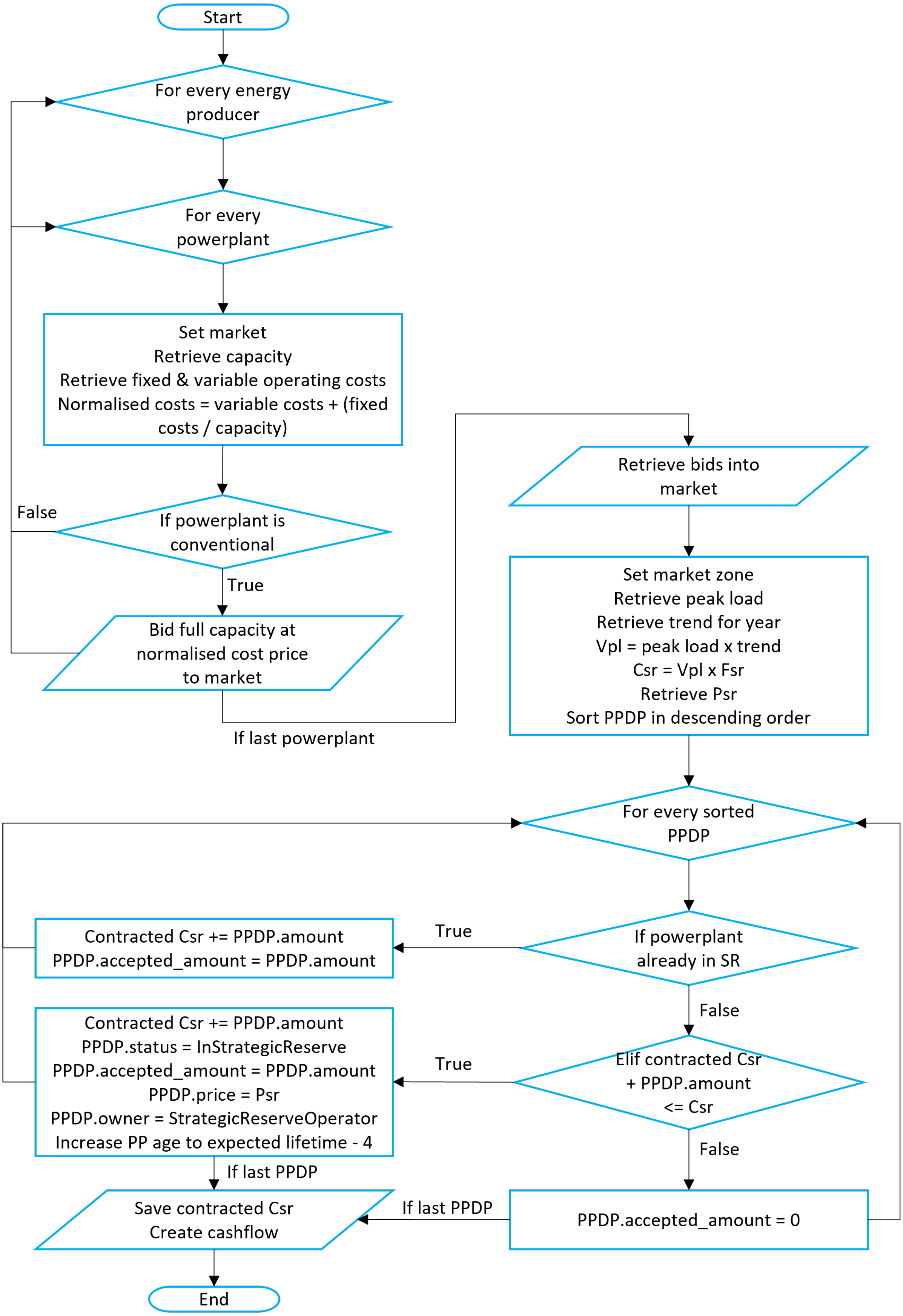

Figure 7.2: German strategic reserve flowchart.

7.1.2 Swedish strategic reserve

The Swedish strategic reserve implementation is again built off of the basic strategic reserve with a few additions. In the Swedish model the bids are not based on the total costs of the power plant, but only on the variable costs. Only renewable power plants are allowed to participate in the strategic reserve, so only those plants are able to place bids. In contrast to the basic and German strategic reserve, in the Swedish version the bids will be sorted in ascending order to price, so the power plants with the lowest variable costs will be accepted first.

The flowchart of the Swedish strategic reserve implementation can be seen in Figure 7.3.

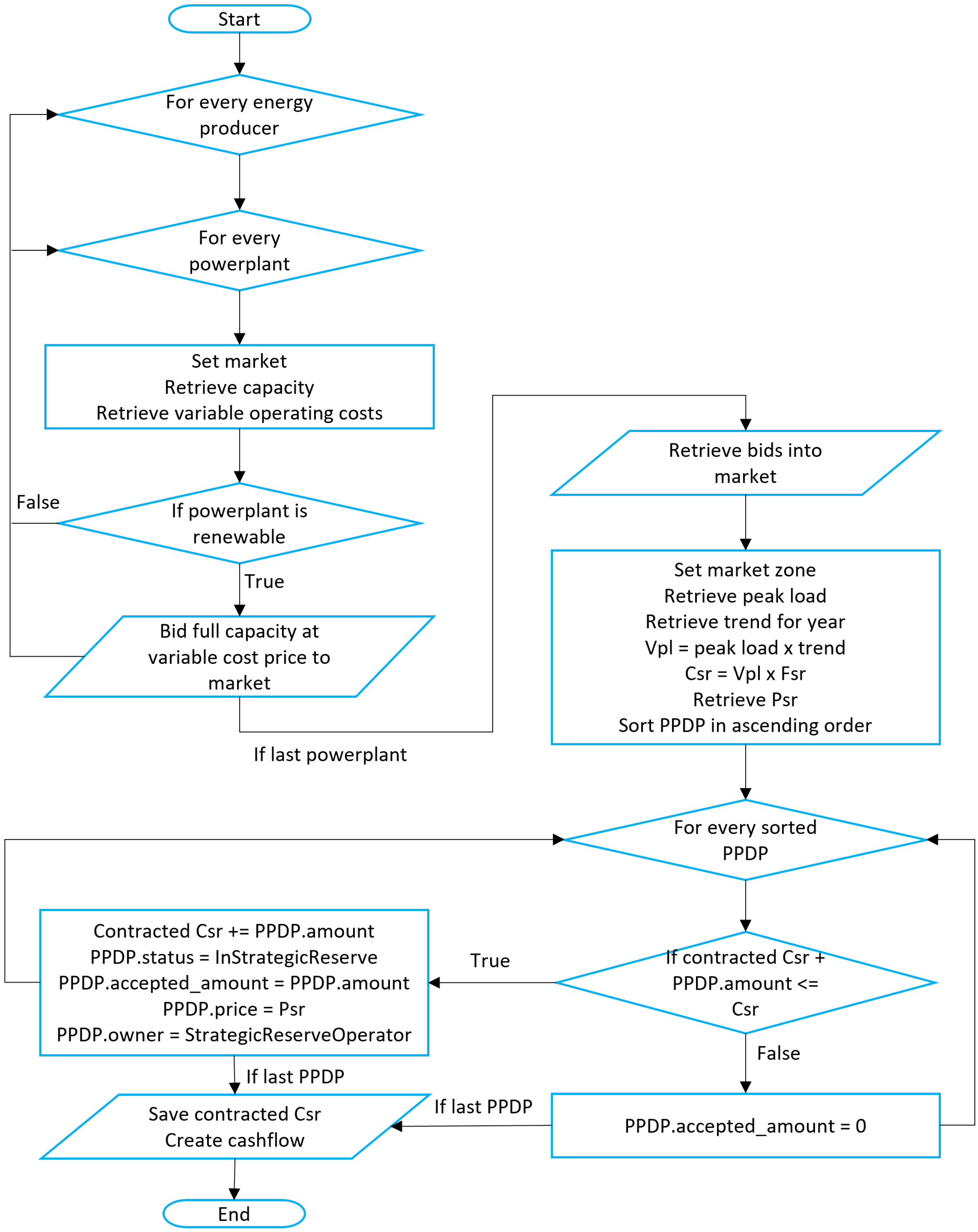

Figure 7.3: Swedish strategic reserve flowchart.

7.2 Capacity market

The following sections describe how the behaviour of the yearly and the forward capacity market is modelled and what parameters need to be defined in the model.

7.2.1 Yearly capacity market

The yearly capacity market model is modelled similar to the NYISO-ICAP model, since it has a relatively simple design [50]. In the model generators start by offering unforced capacity (UCAP) for the coming year in an annual auction, which is administered by the capacity market regulator. The demand requirement for the coming year is calculated by the regulator and then a sloping demand curve of the available capacity in the market is calculated. This sloping demand curve results in more stable capacity market prices, since changes in offered capacity volume only result in small price changes.

The power plants submit bid pairs for price and volume of their available capacity, which form the supply curve. The available volume that is bid in the market is based on the expected available capacity of the generation unit in the peak segment of the load-duration curve for a given year. The bid price is based on the marginal costs of producing energy for the generation unit. If the expected revenues from the energy-only market alone are not sufficient to cover the fixed operating and marginal costs of a power plant, the bid price will be set to the difference between the fixed costs and the expected revenue. Otherwise, if the expected revenue from the energy-only market is adequate to stay online for the power plant, the bid price will be set to zero.

Next up, the submitted bids by the generators will be sorted in an ascending order by price, so the market-clearing algorithm, based on uniform price clearing, can clear the market according to the sloping demand curve. A sloping demand curve is depicted in Figure 7.4. The market-clearing price will be paid to the generating units that clear the capacity market.

Thus summarised the steps the model takes are;

1. Auction offered unforced capacity (UCAP) by generators:
   (a) Volume is the available capacity at peak load
   (b) Price is based on expected revenues from the electricity market (0 if the EOM covers all operating costs, otherwise the difference in revenue and operating costs)
2. Calculate the sloping demand curve, see Figure 7.4
3. Sort bids in ascending order (on price)
4. Select and pay bids

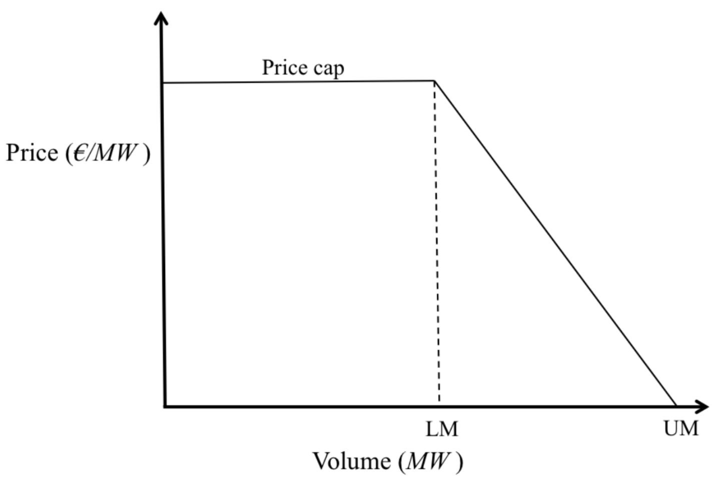

Figure 7.4: Sloping Demand Curve [8].

In Figure 7.5 the flowchart of the implemented yearly capacity market can be observed.

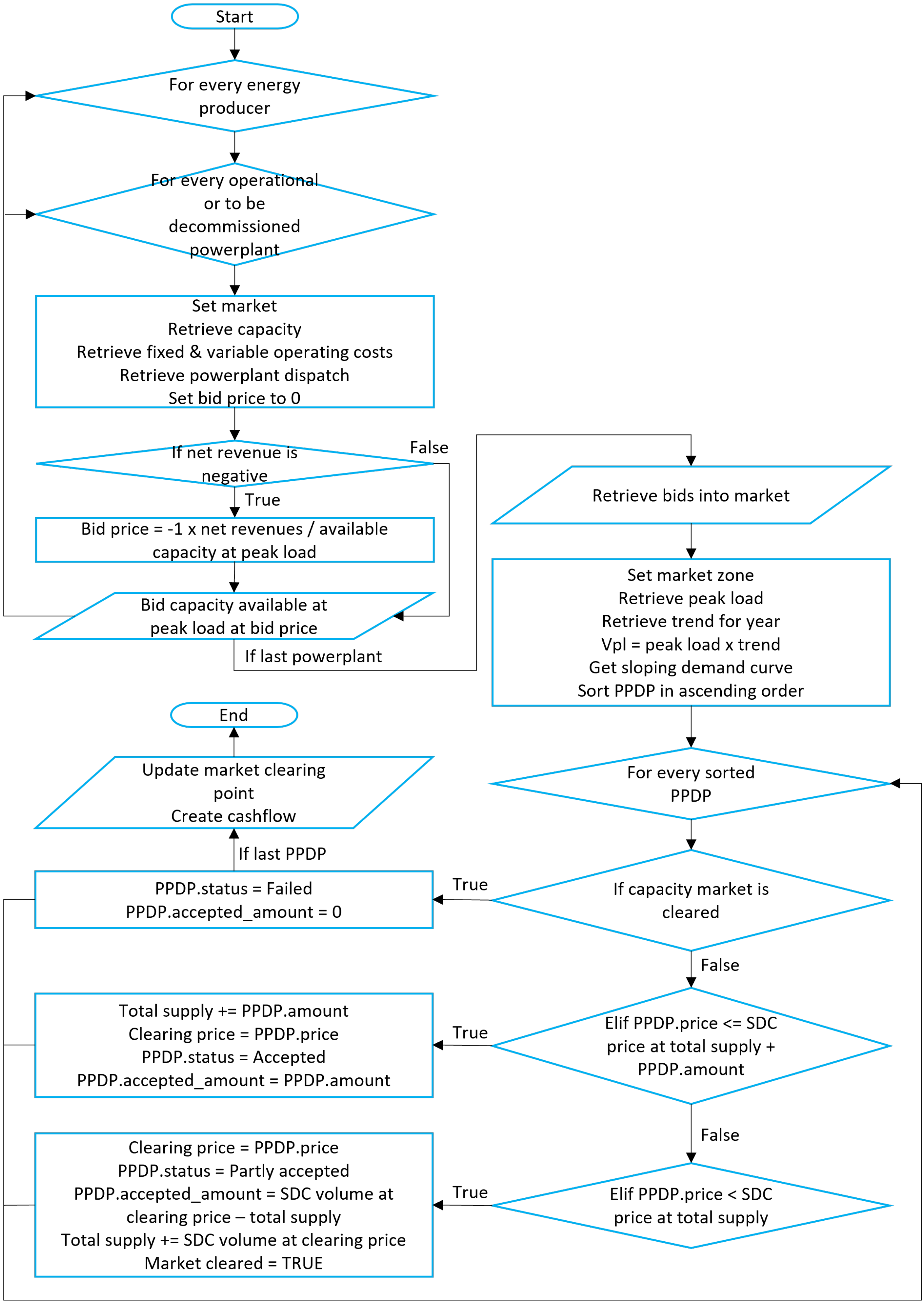

Figure 7.5: Yearly capacity market flowchart.

Parameter definitions

The key parameters for the yearly capacity market model are;

- *Value unforced capacity*

  The value of the unforced capacity is the product of the IRM and the forecast peak demand. The value of the IRM (r) is set to 10% and the forecast peak demand is a result of the peak of the current load demand curve with the defined electricity demand trend applied to it.

- *Sloping demand curve (Figure 7.4)*

  The sloping demand curve consists of two lines, a horizontal and a sloping line. The horizontal line is placed at the capacity market price cap (P_c) and the sloping line intersects the horizontal line and the X-axis. The price cap is set to € 75000. The slope (m) is dependent on the lower margin (lm) and the upper margin (um), which are user defined maximum flexibility boundaries above and below the IRM, given in percentages. The margins are both set to 3.5%. The slope (m) is calculated using the following equation.

  $$m = \frac{P_c}{LM - UM} \tag{7.3}$$

  Since the lower (lm) and upper margin (um) are given in percentages, they need to be converted to volumes (LM and UM) using the following equations.

  $$LM = D_{peak} \cdot (1 + r - lm) \tag{7.4}$$

  $$UM = D_{peak} \cdot (1 + r + um) \tag{7.5}$$

7.2.2 Forward capacity market

The implemented forward capacity market model is similar to the capacity market implemented by the UK [85]. The capacity that clears the forward capacity market in the current year needs to be available in the reference year in the future. Therefore, not only existing power plants, but also power plants under construction that expect to be up and running in the reference year can participate in the market. This also means that power plants that expect to be decommissioned before the reference year cannot participate in the market.

Contracts in the market will be awarded according to the flowchart in Figure 7.6. New power plants can be awarded with 15-year contracts and existing plants only with one-year contracts. In the actual forward capacity market refurbished power plants can be awarded with 3-year contracts, however, in the used models power plants do not get refurbished, so this function is not added in the model for the forward capacity market. During the duration of their long-term contract, power plants cannot participate in the capacity market, but they are eligible for one-year contracts at the end of their long-term contract as existing capacity. In the model renewable energy capacity is not eligible to participate in the market, so only conventional power plants are able to place bids.

The eligible power plants submit bid pairs for price and capacity volume to the capacity market. The available capacity volume of a power plant is determined by its available capacity during peak load in the reference year. The price bids are different for existing and new plants. For existing plants the price is based on the marginal costs of producing energy for the generation unit, just as in the yearly capacity market, the price will be zero if the plant expects to earn adequate revenues from the energy-only market to cover the fixed operating and maintenance costs, and when it expects the earnings not to be sufficient to cover the fixed costs the price will be the difference between the fixed costs and the expected electricity market revenue. For new power plants the price will be set at its fixed operating costs, this will be the minimum required revenue for the power plant to remain online without any revenue being earned from the wholesale electricity market.

Next up, the submitted bids by the generators will be sorted in an ascending order by price, so the market-clearing algorithm, based on a uniform price auction, can clear the market according to the sloping demand curve. The auction forward period is four years and the long-term contract length is set at 15 years. Power plants that clear the market either get awarded a one-year contract or a long-term 15-year contract, depending on the fact that they are either existing or in pipeline. Since power plant operators are not able to refurbish their plants in the model, this contract option is also not considered.

Existing plants with a one-year contract get paid the current capacity market-clearing price, after the market is cleared. New plants with a long-term contract that clear the market will receive payments for the duration of their contract fixed at the current year's market-clearing price. Furthermore, the remaining plants with long-term contracts awarded in previous years get remunerated based on the contracted market-clearing price of the corresponding earlier year.

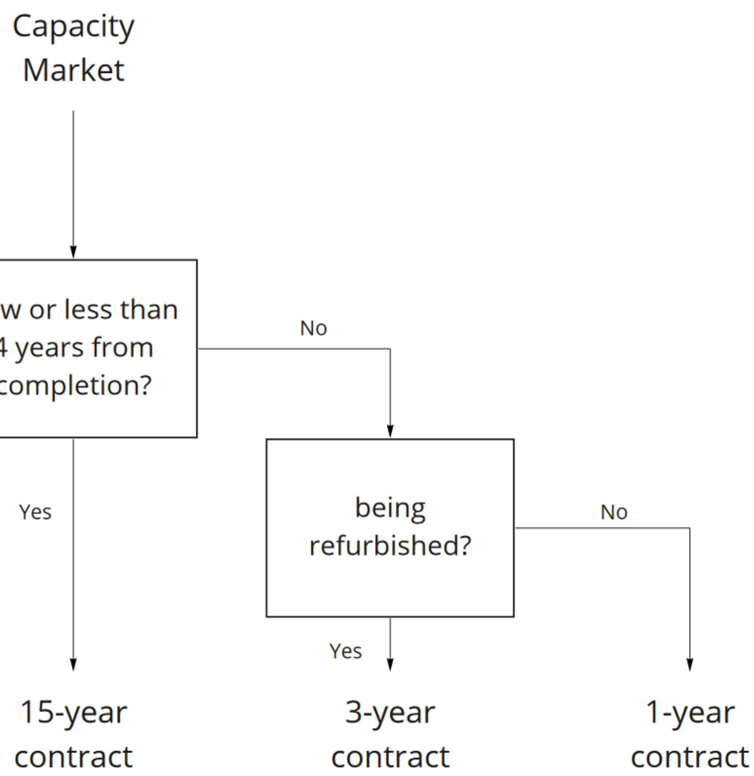

Figure 7.6: Flowchart for offered contract duration in the forward capacity market.

Thus summarised the steps the model takes are;

1. Producers submit bids for plants that are not already participating
   (a) Volume is the available capacity at peak load
   (b) Price in bid is based on:
      - Expected revenues if power plant is already existing (0 if the EOM covers all operating costs, otherwise the difference in revenue and operating costs)
      - Fixed operating costs of power plant if it is in pipeline

2. Create sloping demand curve
3. Sort bids in ascending order (on price)
4. Contracts will be offered according to the flowchart depicted in Figure 7.6
5. Pay:
    (a) Existing units get current market-clearing price
    (b) New units get price fixed at this year's market-clearing price
    (c) Previously awarded contracts get their contract price

The flowchart of the implementation of the forward capacity market can be seen in Figure 7.7.

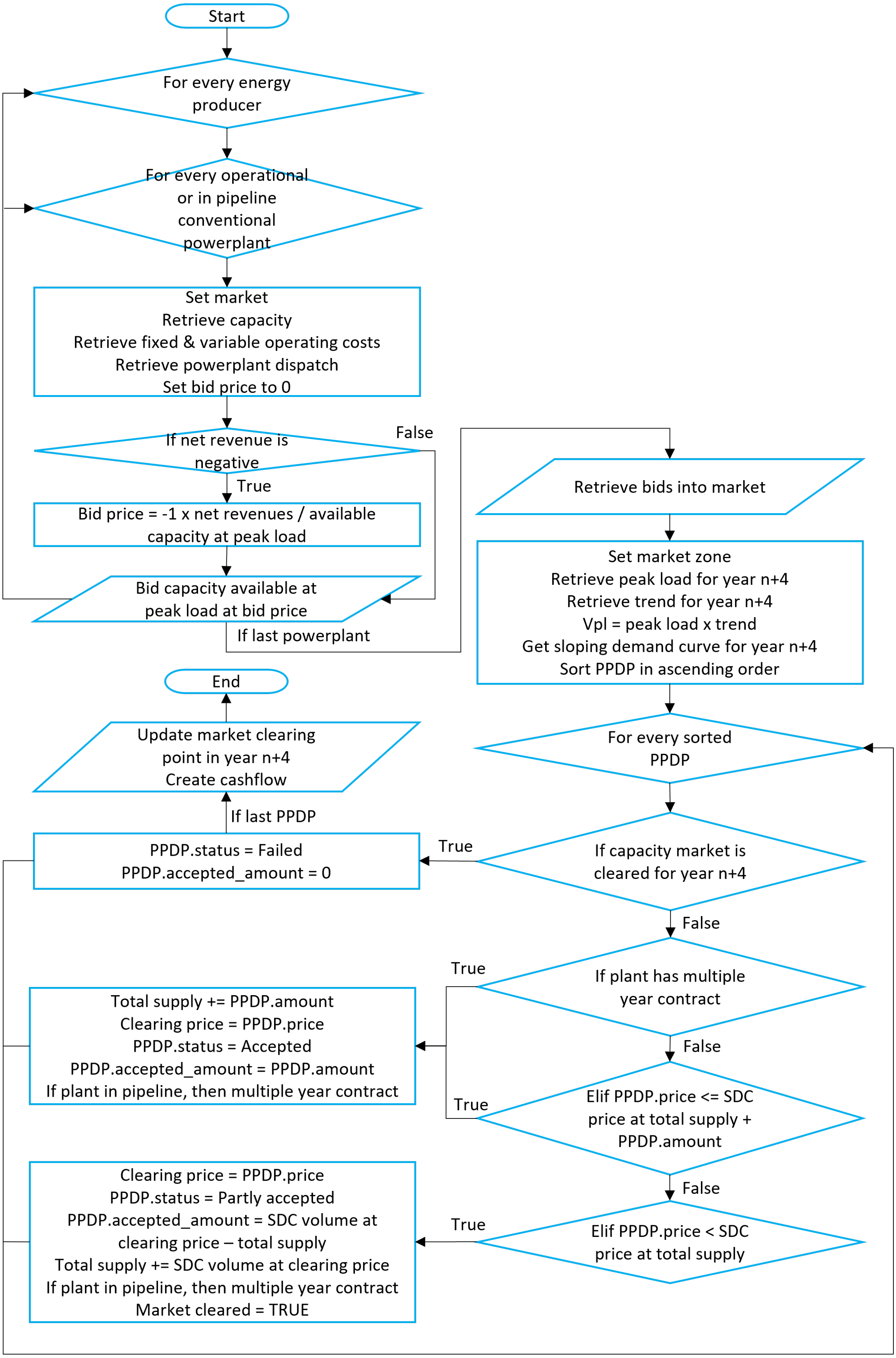

Figure 7.7: Forward capacity market flowchart.

7.3 Capacity subscription

Finally the module for the capacity subscription mechanism still has to be made. So lets start with defining the steps the algorithm has to make. For this simulation model it is assumed all market participants have an LLD installed and have perfect insight in the capacity they need, furthermore, the consumers will get cut off when they exceed their contracted amount of capacity during peak periods. However, their consumption is not limited the rest of the time.

In the capacity subscription model each consumer wants to obtain the permission to use a certain amount of installed capacity during scarcity periods. By bidding certain prices in the market consumers show their preference for the amount of capacity they wish to subscribe to, paying more money leads to higher subscriptions and in turn to higher levels of capacity. Since the consumer bids will be sorted in descending order, higher bids will be selected first and, therefore, will be firstly secured of capacity. The volume each consumer will bid on will be based on their peak demand of the previous year plus an uncertainty margin.

In the model the generation units start by voicing their available capacity to the market. The system operator gathers the data of offered capacity and starts the capacity bids at a basic price. If this price is high, consumers will buy less, so their amount of subscribed capacity will be less.

When the basic capacity price set by the operator is too low and the summed total optimal subscribed capacity level for all consumers is higher than the level of available capacity, the operator will increase the price and repeat the procedure. The market will be cleared at a price where the total subscribed capacity is equal to the available capacity [86]. This means all consumers buy capacity at the same price, but their bids determine the amount of capacity they subscribe to and if they will subscribe to any capacity at all or the capacity will be too expensive for them. In the model the basic price will be based on the marginal costs of the generators and the market clearing price will be at the intersection of the supply and demand curve, as can be seen in Figure 7.8.

Thus summarised the steps the model takes are;

1. Operator determines available capacity and sets basic price
2. Consumers submit bids for capacity subscriptions
    (a) Volume is based on peak demand in previous year
    (b) Price in bid is based on VoLL
3. Sort consumer bids in descending order (on price)
4. Calculate the sloping demand curve, see Figure 7.8
5. Match supply and demand curve and pay bids

Parameter definitions

The key parameters for the capacity subscription model are;

- *The Installed Reserve Margin (IRM)*

  The IRM is defined by the regulator.

- *Demand requirement per consumer (D_{rc})*

  The required demand per consumer (D_{rc}) for the current year is calculated using the IRM (r) and the expected peak demand (D_{peak}). The expected peak demand is a result

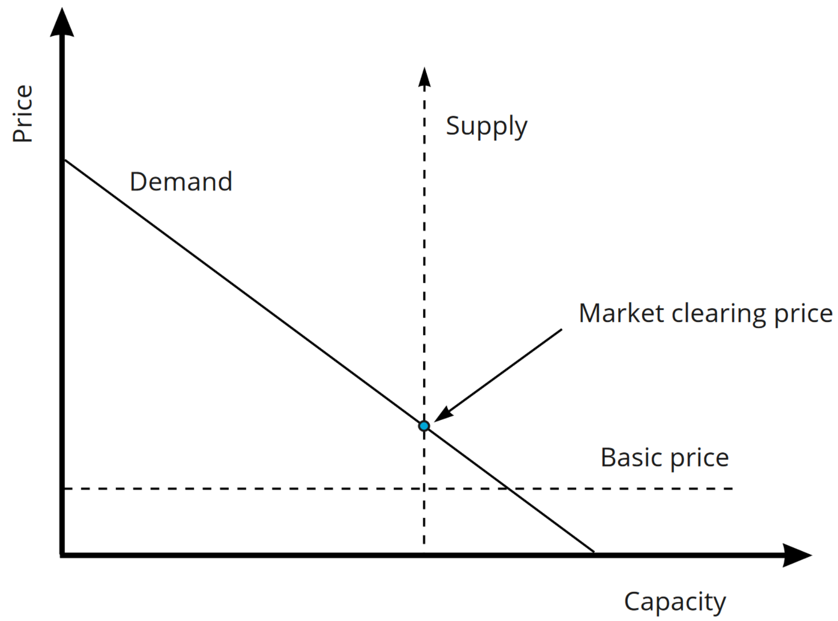

Figure 7.8: Capacity demand versus supply in a capacity subscription mechanism.

of the peak of the current load demand curve with the defined electricity demand trend applied to it.

$$D_r = D_{peak} \cdot (1 + r) \tag{7.6}$$

- *The basic price (P_B)*

  The basic price (P_B) is based on the marginal costs of the generators.

- *The consumer bid price (P_{bid})*

  The height of the bid of the consumer (P_{bid}) is based on the VoLL of the consumer.

Issues

Building the capacity subscription mechanism into the AMIRIS-EMLab model is, however, a problem. Since both models are agent-based models, with the producers and power plants as the decision making agents, it is not possible to submit bids from consumers into the market. There are currently no consumers as agents modelled in the system, the consumers are only represented by a load demand curve that represents all the consumers together. So the key step in the capacity subscription mechanism of consumers submitting bids for subscriptions is not possible, since the energy needs are not defined for single consumers. Furthermore, the model currently is not able to cut off certain consumers exceeding their contracted amount of capacity during peak periods, since they are represented as one single entity. Another way how the capacity subscription could function is to penalise consumers, instead of cutting them off, when they exceed their contracted amount of capacity, but because of the previously mentioned reasons this is also not possible.

So, for these reasons it is not possible to create a capacity subscription mechanism in the current version of the AMIRIS-EMLab project.

8

Results

Twelve different simulations were run, all with the same configuration as input, as described in the previous chapters, from 2020 unto 2050. But first all six capacity mechanisms were run without an energy demand trend and then the six mechanisms were run again with a descending demand trend, equal to the international governance scenario. The simulations are configured so they will run from 2020 until 2050 with a time step of 1 year. The maximum investment capacity per year is set to 20,000 MW, a value that will never be reached, so the investments are not limited. The start year for fuel trends is set beyond 2050, so the fuel prices will increase linearly, without a yearly geometric trend, and will be the same for all scenarios. All the candidate power plants for investment have a capacity of 1000 MW, which is higher than their normal capacity. This will result in some investment overshoots, but due to time constraints running all the simulations with the candidate power plants having their own actual capacity would take much too long.

More explicit results of the simulations can be found in Appendix A, but the following sections show and describe the differences in resulting key parameters between the different implemented capacity mechanisms.

8.1 Simulations without demand trend

Firstly, the results of the scenario without a demand trend will be analysed. In this scenario the energy demand is in every year equal to the load demand curve of 2020 that was used as input. Since all simulations are serving the same energy demand, the total yearly production is the same for all mechanisms. However, the difference in results is in the differences in amounts of energy coming from the different generation technologies.

The following sections analyse the security of supply, the energy prices and the closeness to reality of the simulations.

8.1.1 Security of supply

The first, and most important, metric to test the different capacity mechanisms is their security of supply. The security of supply will be measured by the installed capacity of controllable energy sources and the yearly loss of load expectation. The security of supply is heavily dependent on the total installed generation capacity within the system, but foremost on the controllable energy sources. So the capacity data of the different simulated mechanisms was extracted and processed.

The total installed generation capacity per capacity mechanism can be seen in Figure 8.1.

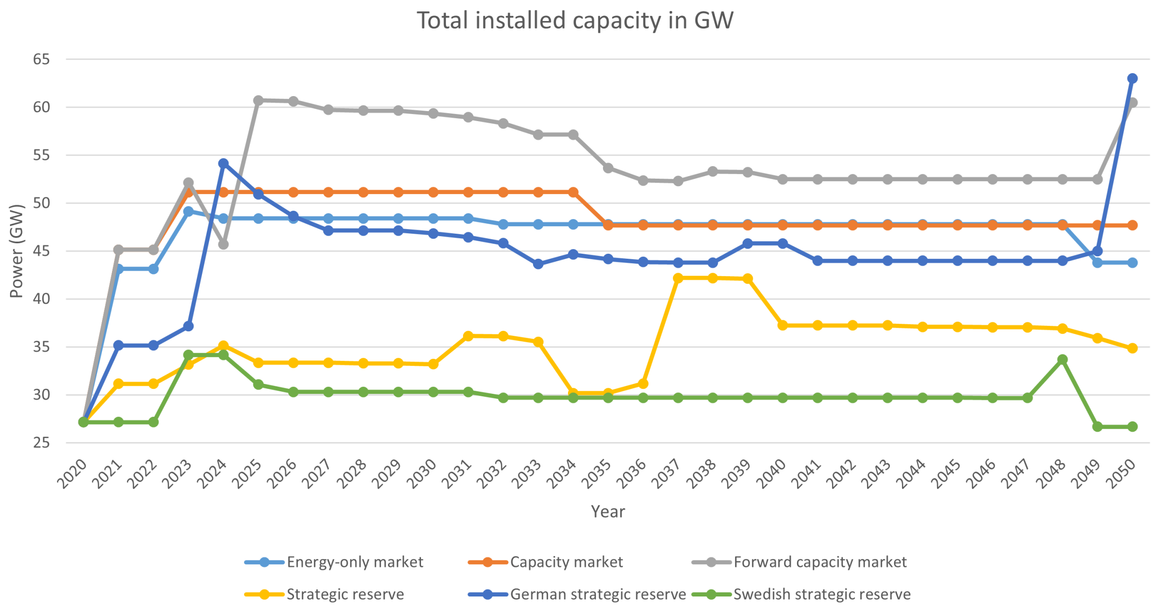

Figure 8.1: Total installed generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

In Figure 8.1 can be seen that all simulations have a large increase in installed capacity in the first few years. This is due to the large investment round that is happening at the beginning of the simulations, a few years later these investments are realised and the power plants are operational. From 2041 unto 2047 all the mechanisms have reached a steady state for a few years, since their installed capacity is constant for that period of time.

The figure shows that the forward capacity market has the highest level of installed capacity through the years, only in the last year it is just overtaken by the German strategic reserve. The Swedish strategic reserve has continuously the lowest total installed capacity.

The corresponding supply ratio can be seen in Figure 8.2, in this figure the total installed capacity is divided by the peak energy demand. All capacity mechanisms have a supply ratio that is above one in all years, so in normal conditions all mechanisms should be able to supply all demand.

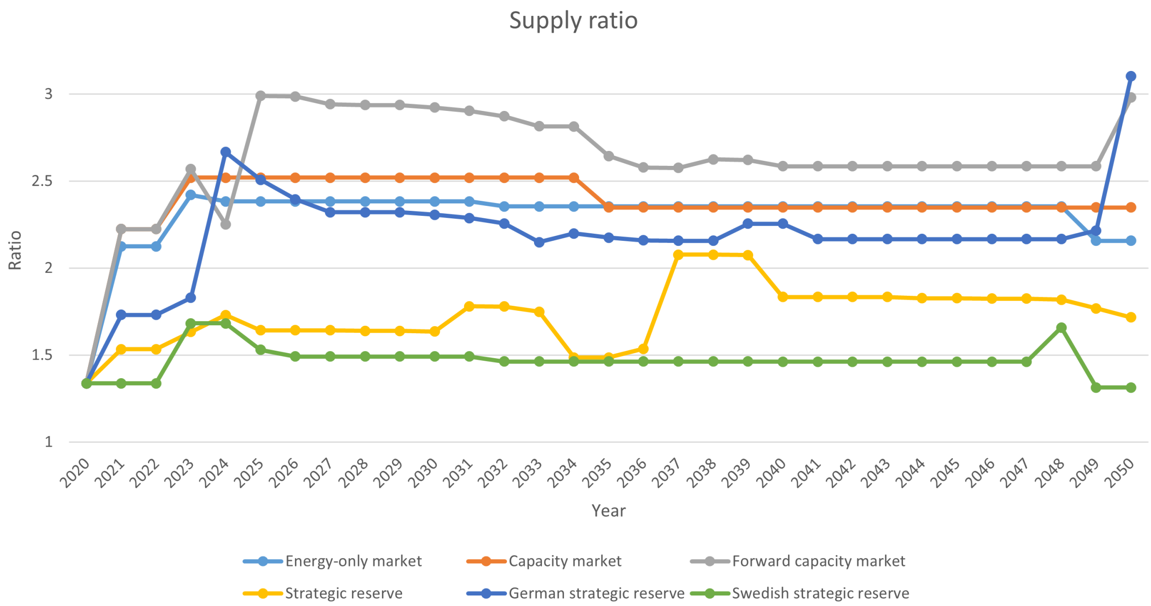

Figure 8.2: Supply ratio per capacity mechanism, calculated by dividing the total installed capacity by the peak energy demand. The represented data are yearly data points extracted from the simulation results.

To see where the differences in installed capacity and supply ratios come from, the data of the variable renewable energy sources, the controllable renewable energy sources and the conventional energy sources was extracted. With this data the installed capacities of different technologies will be analysed in the following sections.

Variable renewable energy sources

The energy sources that count as variable renewable energy sources are on- and offshore wind farms, PV installations and run-of-river hydroelectricity. The installed variable renewable energy capacity per capacity mechanism can be seen in Figure 8.3.

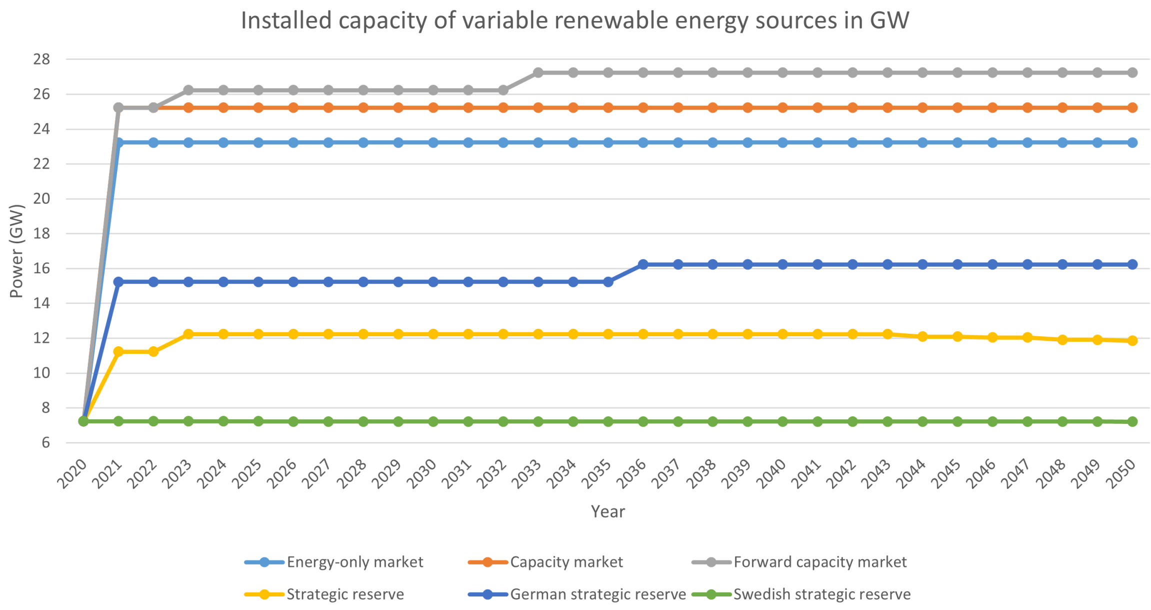

Figure 8.3: Operational variable renewable generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

From Figure 8.3 can be learned that the forward capacity market has the highest level of installed VRE capacity through the years and the Swedish strategic reserve has the lowest. While the Swedish strategic reserve should be promoting investments in renewable energy, what actually happens is that the strategic reserve operator takes the energy sources off of the market and gives them a predetermined price. The strategic reserve will only be activated when the electricity spot market prices reach € 800 per MWh, so this market price is not reached often in the Swedish strategic reserve. This prevents the owners of the energy sources to participate in the market and receive market prices while they are lower than the predetermined strategic reserve price, or to potentially get a higher price when there is high demand.

In Figure 8.4 the consequence can be observed, since there is less installed variable renewable capacity in the Swedish strategic reserve, the yearly produced energy from these sources is also much lower compared to most of the other mechanisms.

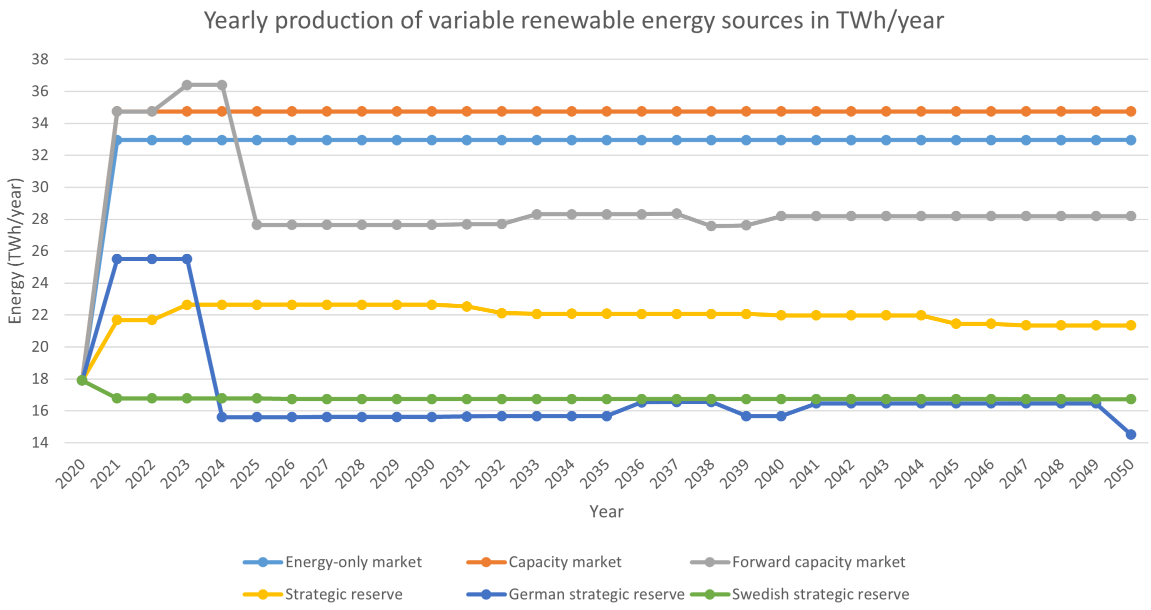

Figure 8.4: Yearly variable renewable energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

In Figure 8.4 can be seen that the energy generated by VRE sources is the lowest for the German strategic reserve. Since the German strategic reserve takes conventional power plants off of the market, it was expected this hole would be filled with VRE, but this is not the case.

Controllable renewable energy sources

Biomass and hydro storage energy are the sources that are counted as controllable renewable energy sources, of which the installed capacity can be seen in Figure 8.5. In this figure the installed capacities of the energy-only market, yearly capacity market and Swedish strategic reserve are the same.

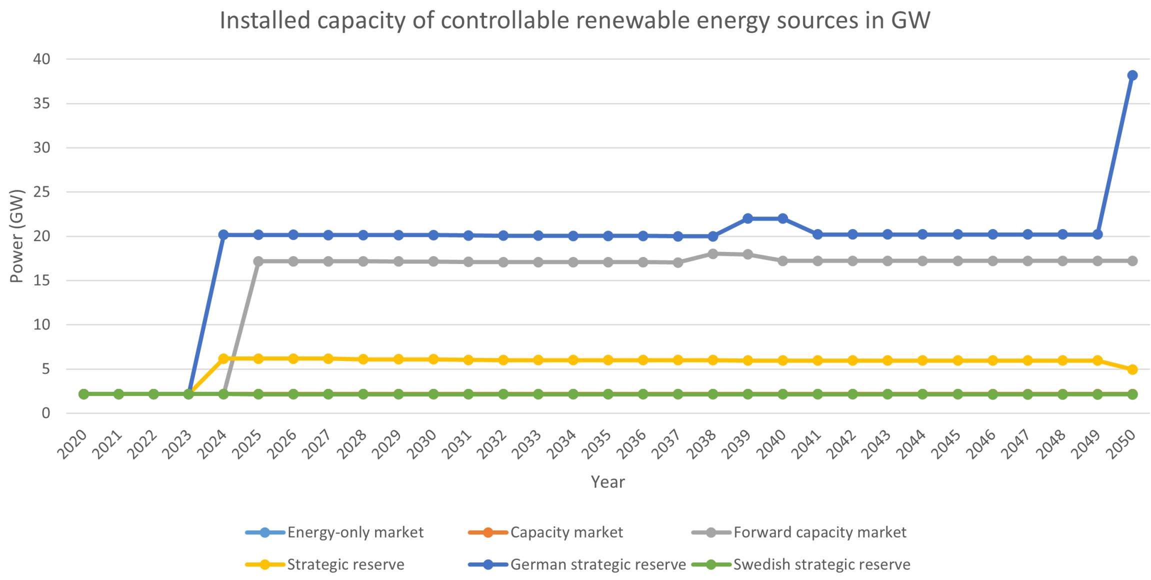

Figure 8.5: Operational controllable renewable generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

For all the mechanisms the controllable renewable energy capacity consists predominantly of biomass power plants. In the energy-only market, yearly capacity market and Swedish strategic reserve the installed biomass power plants are profitable enough not to be decommissioned. However, in these capacity mechanisms they are also not profitable enough to further invest in this technology.

In the German strategic reserve the level of installed CRE capacity is the highest, so the capacity of conventional power plants that are taken off of the market by the mechanism is compensated mostly by controllable renewable power plants. This is also confirmed by the level of yearly CRE production, as can be seen in Figure 8.6.

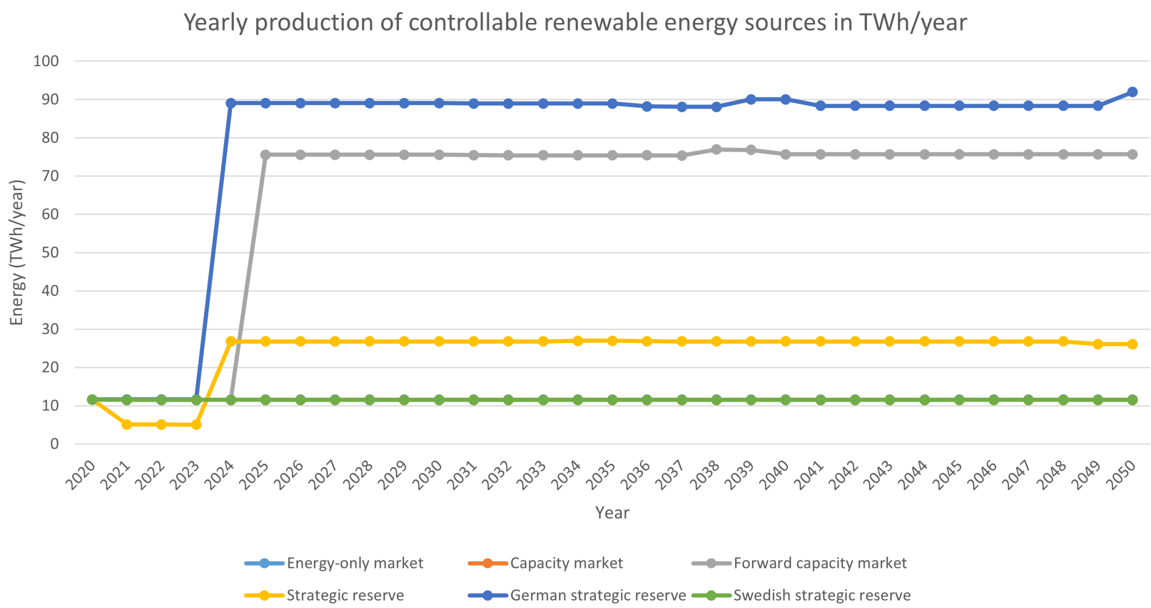

Figure 8.6: Yearly variable controllable energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

Conventional energy sources

The remaining power plants are the conventional energy sources, these are coal, CCGT, OCGT, nuclear, lignite, fuel oil and lithium battery energy sources. The installed capacity through the years of the conventional energy sources can be seen in Figure 8.7.

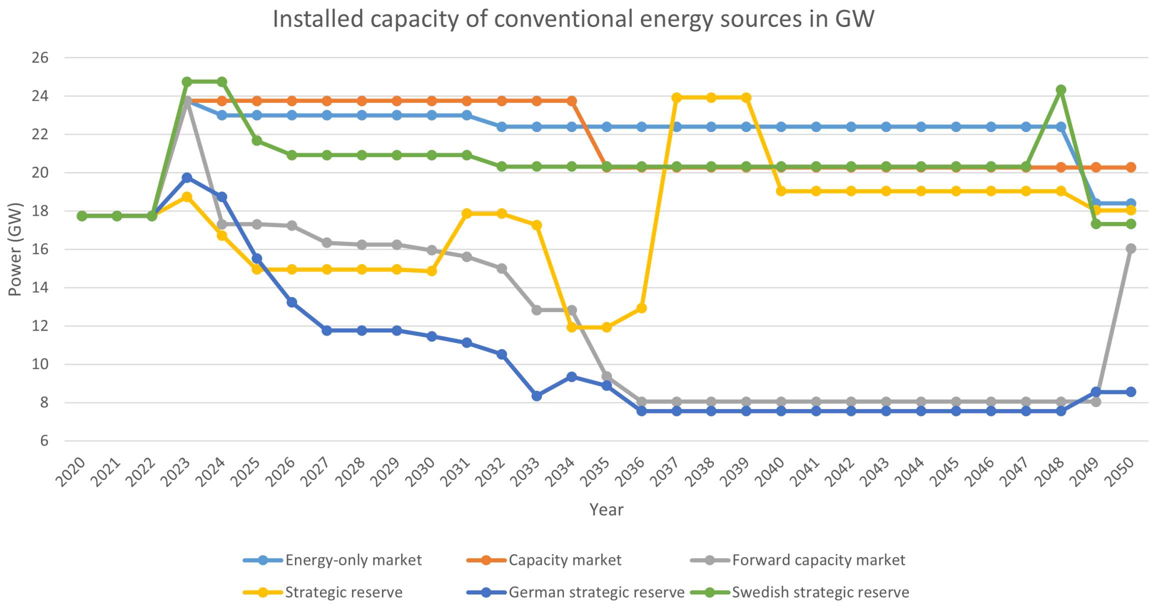

Figure 8.7: Operational conventional generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

Figure 8.7 shows that actually the energy-only market has the highest installed capacity of conventional power plants during the steady state years, but the yearly capacity market ends up with the highest level of conventional capacity in 2050.

As expected, there is a high level of decommissioning of conventional power plants in the German strategic reserve and so it ends up with the lowest level of installed capacity of conventional power plants. Although this is a good thing for the environment, this research is focused on creating security of supply, so in this research it could be a bad thing.

Furthermore, it can be seen that the Swedish strategic reserve has a relatively high capacity of conventional power plants, while this mechanism should be promoting investment in renewable energy sources. The produced energy of conventional energy sources is also highest for the Swedish strategic reserve, as can be seen in Figure 8.8. This makes the Swedish strategic reserve the least green mechanism of the bunch. On the other hand, the forward capacity market and the German strategic have very low levels of conventional energy production.

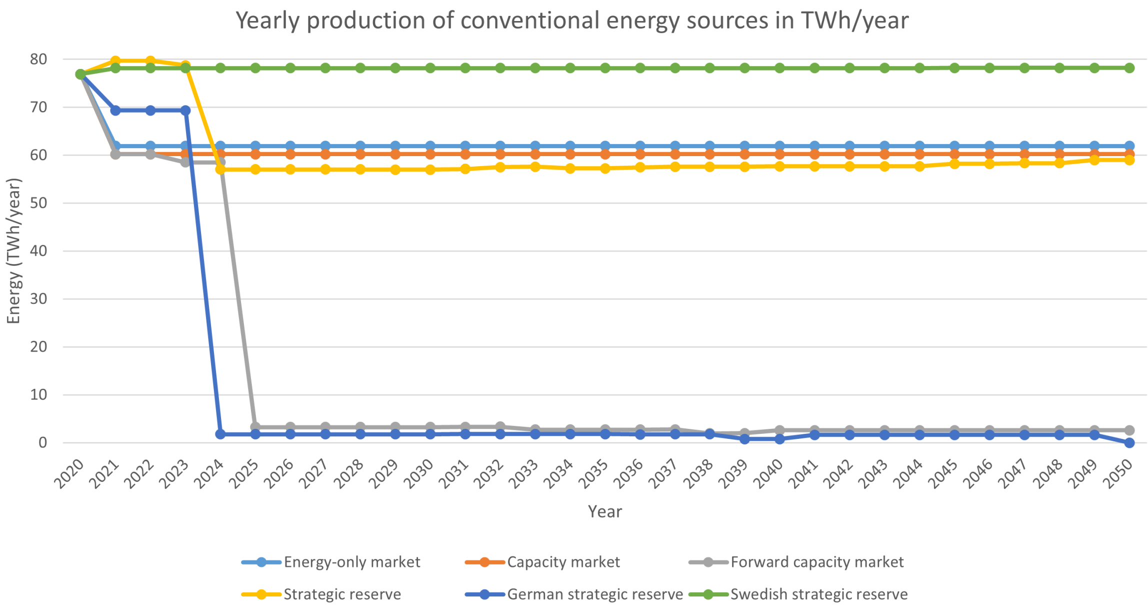

Figure 8.8: Yearly conventional energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

Contracted technologies

The different mechanisms have different results concerning the earnings of different power plant technologies. These differences are caused by the differences in which power plants get their capacity sold on a capacity market or get contracted into a strategic reserve. To see where the difference comes from, the average contracted capacities over the years can be seen in Figure 8.9 and 8.10.

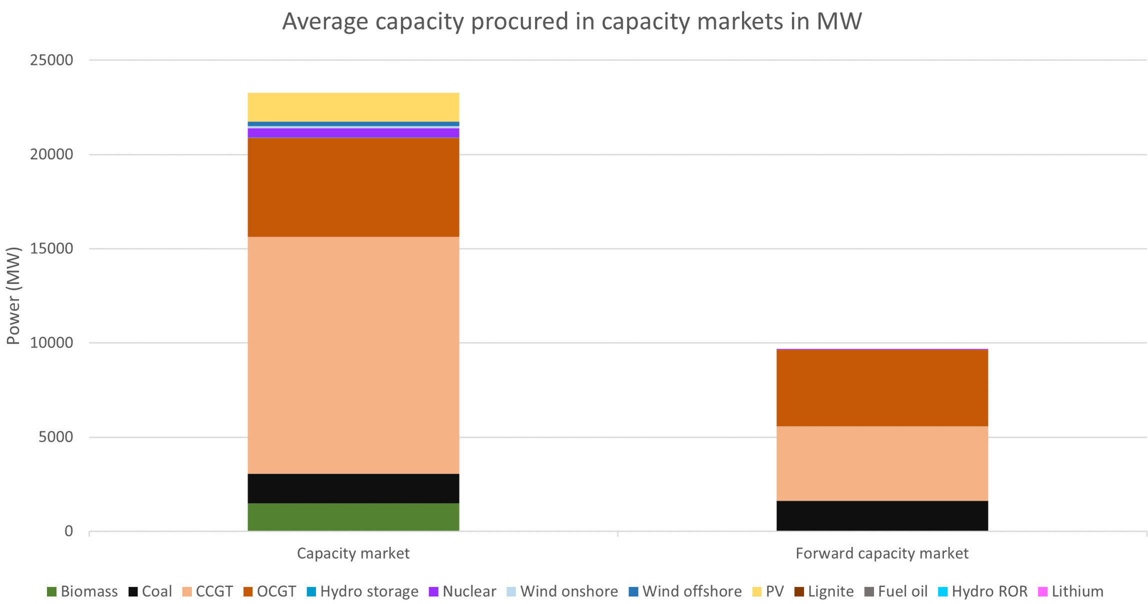

Figure 8.9: Average of the yearly procured capacity in capacity markets over the years 2020 to 2050 in MW.

As can be seen in Figure 8.9 the average total amount of capacity sold on the yearly capacity market is much higher than the average capacity sold on the forward capacity market.

On the yearly capacity market all installed generation technologies are represented, while on the forward capacity market only conventional capacity is sold. This is due to the fact that renewable power plants are not allowed to participate in the forward capacity market if they are receiving supportive subsidies.

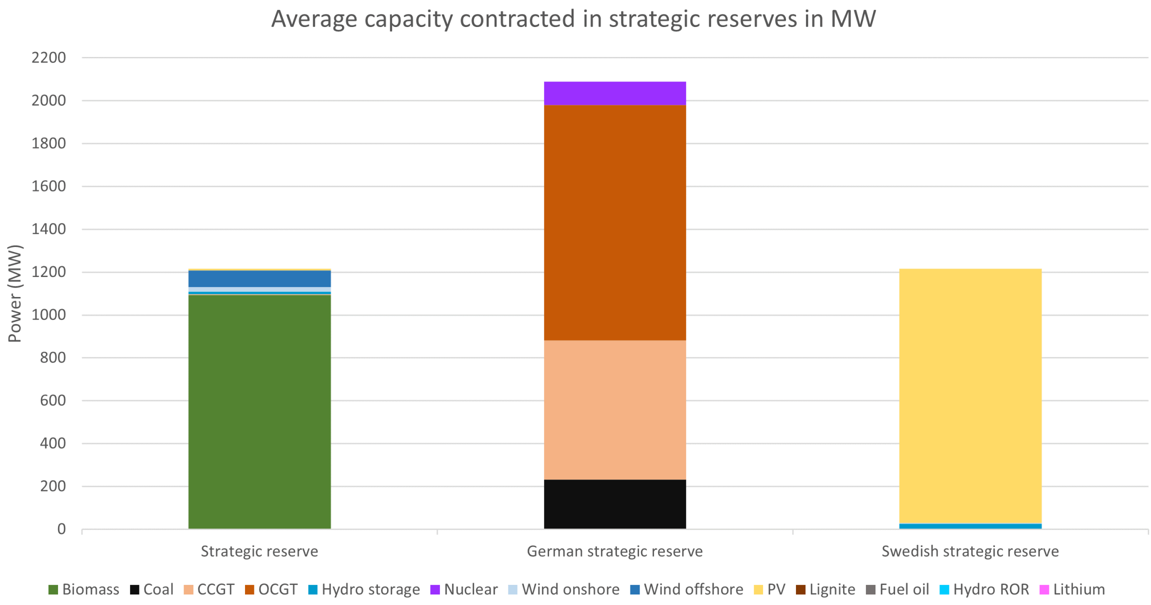

Figure 8.10: Average of the yearly contracted capacity in strategic reserves over the years 2020 to 2050 in MW.

Figure 8.10 shows that the amount of capacity contracted in the German strategic reserve is on average higher than in the other two strategic reserves. This is due to the long term contracts in the German strategic reserve, when a power plant is contracted it is in the strategic reserve until the end of its lifetime.

Although all power plants may participate in the basic strategic reserve, the average contracted capacity almost solely consists of biomass power plants. The basic strategic reserve contracts the power plants with the highest combined fixed and variable costs first, so this means the operating costs of biomass and offshore wind are the highest.

The fact that these power plants are contracted in the strategic reserve does, however, not mean the strategic reserve is always fully dispatched. It is not unrealistic that the strategic reserve is not always fully or partly activated in the simulations, since there is an oversupply of energy in most years. To further back this up, the strategic reserve in Sweden has been activated only five out of the twelve years from 2003 until 2015 [87].

Installed capacity in 2050

The resulting installed capacity at the end of the simulations can be seen in Figure 8.11.

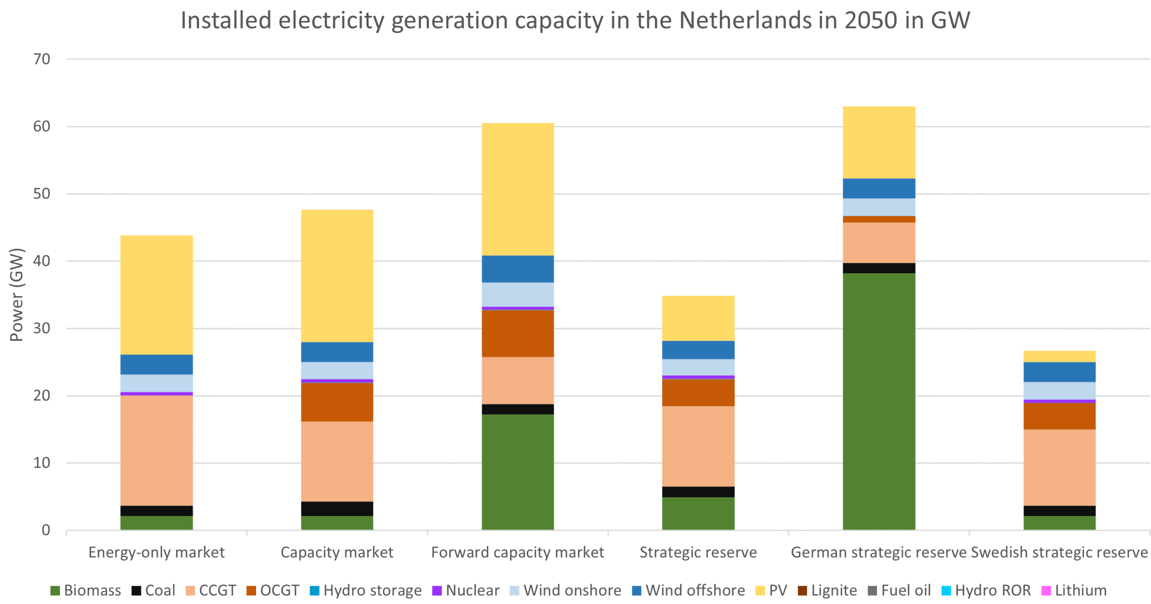

Figure 8.11: Installed and operational generation capacity in the Netherlands in 2050 in GW.

Figure 8.11 learns us that the German strategic reserve has the highest installed capacity, due to the large amount of installed biomass capacity, but it is the only mechanism without any nuclear energy anymore in 2050. Since the nuclear power plant had high costs, it was contracted in the German strategic reserve and decommissioned after a couple of years.

The Swedish strategic reserve not only has the lowest total installed capacity, but also the lowest amount of controllable capacity and the lowest amount of variable renewable capacity. This makes the Swedish strategic reserve to offer the lowest level of security of supply. Which is also confirmed by the amount of energy shortage hours in 2050. Only the Swedish strategic reserve has 11 energy shortage hours in 2050, while all the other mechanisms have zero shortage hours. These hours are measured by the amount of hours the price on the spot market reaches the market price cap at the predefined VoLL, which is set at € 3000 per MWh.

8.1.2 Energy prices

The second metric to test the capacity mechanisms is their costs to society. The costs to society are measured by the total cumulative costs of each mechanism. The cost price of the capacity mechanisms is not only dependent on the electricity price on the spot market, but also the added costs of the operation of the capacity mechanisms. In Figure 8.12 the average electricity prices per MWh per year on the spot market can be seen.

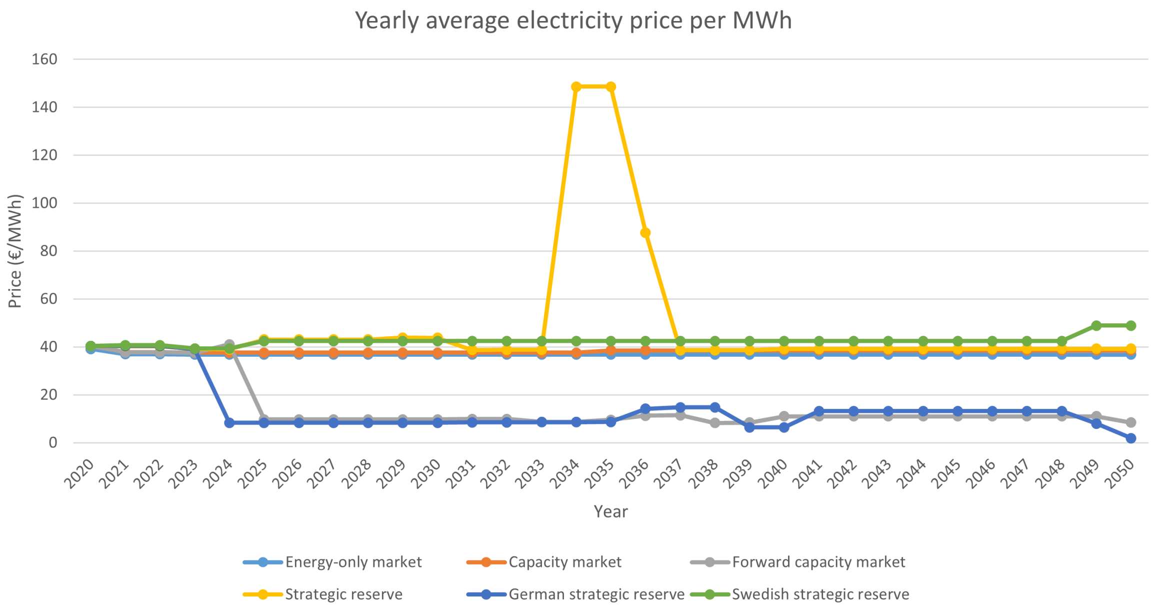

Figure 8.12: The yearly average electricity price on the spot market in Euro per MWh. The represented data are yearly data points extracted from the simulation results.

In Figure 8.12 the results of the large investment round at the beginning of the simulations can be clearly seen in the price drop in the forward capacity market and the German strategic reserve. The forward capacity market and German strategic reserve have much lower spot market prices than the other mechanisms. The price of electricity on the spot market in the forward capacity market and German strategic reserve hovers around € 10 per MWh, this is about four times lower than the price of the other mechanisms, since those prices hover around € 40 per MWh.

Due to a large energy shortage the spot market prices of the basic strategic reserve have a large spike in 2034 and 2035. In each of the two years the strategic reserve is activated for 316 hours and there is an energy shortage for 186 hours. These are the biggest shortages of all mechanisms and of all years. The shortages are caused by the large decommissioning of conventional power plants in the basic strategic reserve from 2033 to 2034, as can be seen in Figure 8.7.

However, to determine the total costs to society, the costs of implementing the mechanism also has to be accounted for. In Figure 8.13 the total cumulative costs per mechanism can be seen. This includes the price of electricity on the spot market and the additional costs for the mechanism, either being it the prices paid on the capacity market or the costs of contracting a strategic reserve.

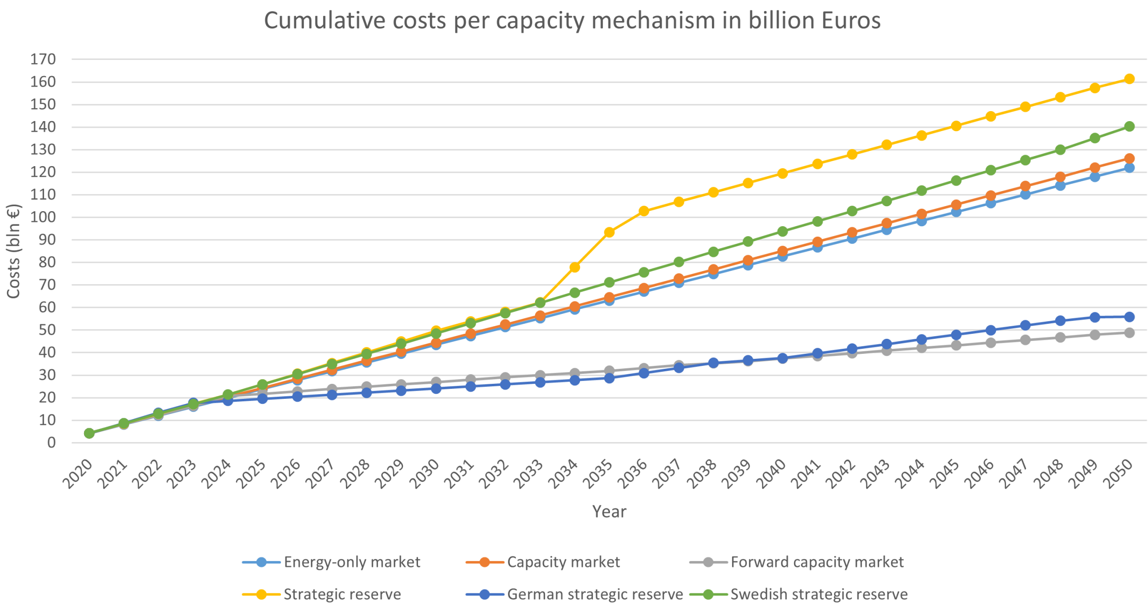

Figure 8.13: Cumulative costs per capacity mechanism in billion Euros. The represented data are yearly data points extracted from the simulation results.

As can be seen in Figure 8.13, due to the low spot market prices the cumulative costs of the forward capacity market and German strategic reserve are much lower than the other mechanisms. The consequence of the large spike on the spot market is also visible for the cumulative costs of the basic strategic reserve, which makes it the most expensive mechanism. So the price differences between the mechanisms are mainly caused by the price differences of energy on the spot market.

To determine whether conclusions regarding costs of the capacity mechanisms can be drawn from these given figures, the capacity mechanism specific additional costs should be examined.

Mechanism specific costs

The implementation of the capacity mechanisms lead to additional costs for electricity. In the case of a capacity market this will be the price the capacity is sold for on the market and in the case of a strategic reserve it will be the contracting of the power plants as a reserve. These yearly costs can be seen in Figure 8.14. When the costs are positive in the figure, it means that the mechanism costs money, but when the costs are negative it means that the mechanism makes profit in that year. In this figure the yearly costs of the yearly and forward capacity markets are mostly overlapped by the costs of the Swedish strategic reserve.

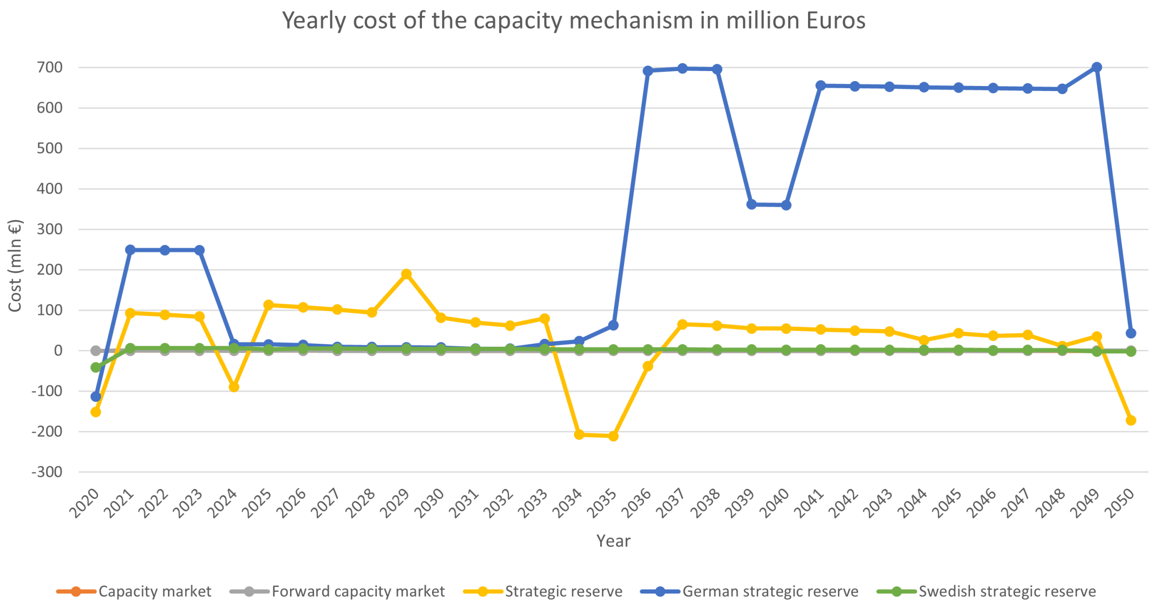

Figure 8.14: Yearly costs per capacity mechanism in million Euros. The represented data are yearly data points extracted from the simulation results.

From Figure 8.14 can be learned that the annual cost price of either of the yearly and forward capacity market is almost nothing compared to the strategic reserve prices.

In the years with an energy shortage in the basic strategic reserve, which are 2034 and 2035, it can be seen that the strategic reserve operator makes profit. Furthermore, the German strategic reserve has very high yearly costs in many years, but it is still one of the cheapest mechanisms on total cumulative costs. So the low prices on the spot market can sufficiently compensate for the higher costs associated to the contracting of the German strategic reserve. While when a strategic reserve operator loses money in a certain year, the costs will be passed on to the consumers via the network or system tariffs.

To have a better view of the profitability of the mechanisms, the cumulative profit per mechanism can be seen in Figure 8.15. The profits in this figure only contain the mechanism specific profits, not the profits of electricity spot market. In this figure the cumulative profits of the yearly and forward capacity markets are mostly overlapped by the costs of the Swedish strategic reserve.

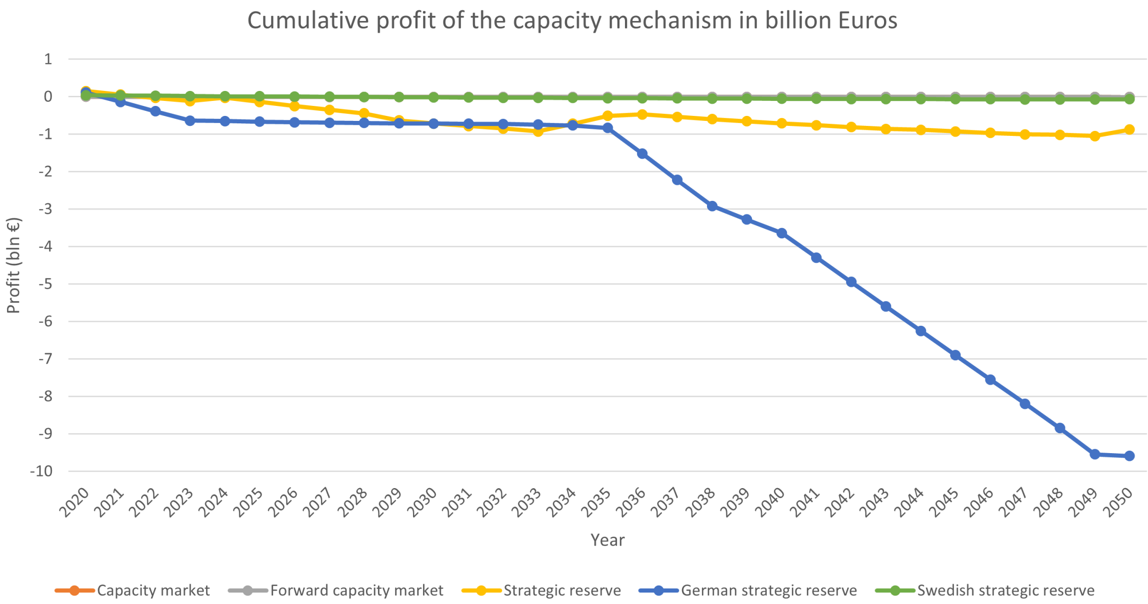

Figure 8.15: Cumulative profit per capacity mechanism in billion Euros. The represented data are yearly data points extracted from the simulation results.

Figure 8.15 shows that the specific cost price of the yearly and forward capacity market is almost nothing compared to the costs of the strategic reserves. Even though the German strategic reserve has very high costs of contracting plants in the reserve, the combination with very low spot market prices still make it one of the least costly mechanisms to society. This is due to the most expensive power plants being contracted in the reserve and decommissioned after a few years. However, the forward capacity market is a little cheaper, since it has relatively very little mechanism specific costs and also low spot market prices. Therefore, in this scenario the forward capacity market is the cheapest mechanism for society.

8.1.3 Closeness to reality

To test how far off the simulations are from the expected future energy scenarios, the results should be compared with the key parameters of the defined scenarios. In Table 8.1 the results of the simulations can be seen. When comparing the results with the key parameters of the average baseline scenario, it can immediately be observed that some of the values differ heavily. The average decrease in energy usage of the scenarios is 26.8%, but in the simulations there is no decrease in energy usage. This is, however, due to the input of the simulations. In the simulations the same input load demand of 2020 is used for every year.

In the scenarios the CO_2-emission is in 2050 on average lowered by 96.3%, when compared to the values of 1990. Since the CO_2-emission of the Netherlands in 1990 was 162.7 Mton, according to the CBS [88], the simulations actually realise quite a significant decrease in CO_2-emissions, despite the still high share of conventional energy. Nonetheless, the goal of reducing the CO_2-emissions with 96% to 99%, as set in the climate goals, is reached only by some of the simulations. The forward capacity market and the German strategic reserve score the best in lowering CO_2-emissions, in the German strategic reserve the emissions are even lowered to zero in 2050. This shows that it is possible to achieve the climate policy goals by 2050 in the Netherlands, but not when only an energy-only market is implemented.

The share of renewable energy sources in the future scenarios is easily reached by some of the simulations. The future scenarios have an average renewable electricity share of 127.9%, while three of the mechanisms reach higher values. This share of renewable electricity is calculated by dividing the capacity of the installed renewable energy sources with the peak load volume, which is 20.31 GW.

Nevertheless, the simulations outperform the predicted future scenarios on annual energy costs and LOLE by far. The average annual energy costs of the scenarios is € 53.5 bln, which is much higher than the annual energy costs of the simulations. Due to the very high installed capacity levels in the forward capacity market and German strategic reserve, the annual electricity costs drop below € 1 bln. This sends off the wrong message to investors, since the goal is to offer sufficient investment incentive on the long-term for investors in generation capacity, to increase the security of supply.

Furthermore, due to the heavy investment in controllable power plants most mechanisms have a LOLE of zero hours in the simulations, except for the Swedish strategic reserve, which has a LOLE of 11 hours. This is still much lower than the average of the expected scenarios, since in the future scenarios it is on average 68.5 hours.

To be able to better compare the simulations with a real scenario, subsequently all the capacity mechanisms are run in a scenario comparable to the international governance scenario.

2050	**Baseline scenario**	**Energy-only market**	**Capacity market**	**Forward capacity market**	**Strategic reserve**	**German strategic reserve**	**Swedish strategic reserve**
Energy usage compared to 2020	-26.80%	-0.00%	-0.00%	-0.00%	-0.00%	-0.00%	-0.00%
CO_2-emission	6.020 Mton	21.244 Mton	20.767 Mton	0.665 Mton	18.391 Mton	0.00 Mton	27.857 Mton
CO_2 compared to 1990	-96.30%	-86.94%	-87.24%	-99.59%	-88.70%	-100.0%	-82.88%
Renewable electricity share	127.90%	125.11%	134.96%	218.97%	82.79%	268.10%	46.05%
Annual energy costs	€ 53.3 bln	€ 3.92 bln	€ 4.10 bln	€ 0.90 bln	€ 4.18 bln	€ 0.25 bln	€ 5.21 bln
Loss of Load Expectation (LOLE)	68.5 hr	0 hr	0 hr	0 hr	0 hr	0 hr	11 hr
Installed VRE capacity	29466.1 MW	23235.5 MW	25235.5 MW	27235.5 MW	11847.5 MW	16235.5 MW	7214.3 MW
Installed controllable capacity	5198.9 MW	20571.0 MW	22450.0 MW	33275.0 MW	23008.6 MW	46765.0 MW	19465.4 MW

Table 8.1: Resulting parameters of the simulations of the different mechanisms in the scenario without an energy demand trend.

8.2 Simulations with descending demand trend

Next up, all the capacity mechanisms were run with a descending energy demand trend. This trend is based on the international governance scenario and descends linearly towards -12.1% in 2050 in comparison to the load demand curve of 2020.

The following sections analyse the security of supply, the energy prices and the closeness to reality of the simulations.

8.2.1 Security of supply

To test the security of supply in this scenario that is closer to the expected scenario for the Netherlands in 2050, firstly the total installed capacity is analysed.

The total installed and operational capacity per capacity mechanisms can be seen in Figure 8.16.

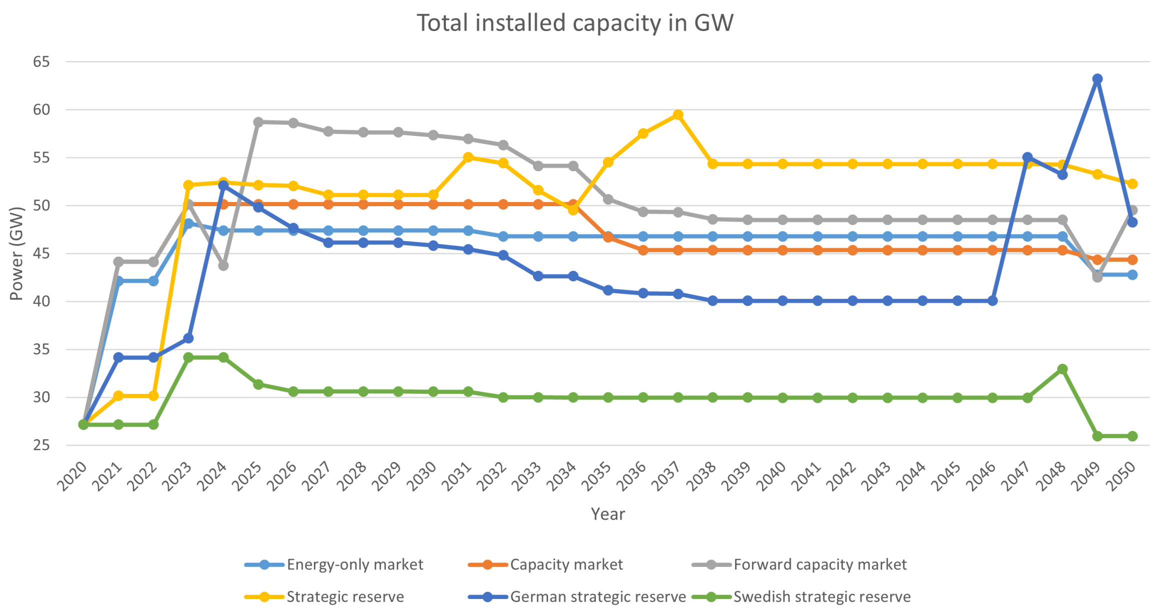

Figure 8.16: Total installed generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

As can be seen in Figure 8.16, there is not one mechanism with the highest installed capacity over all years. But the basic strategic reserve has the highest installed capacity for almost half the years of the simulation. Furthermore, the basic strategic reserve ends the simulation with the highest capacity and, more importantly, in the steady state period from 2038 to 2046 it has the highest capacity.

The Swedish strategic reserve clearly has the lowest installed capacity through the course of the simulation.

The installed capacity versus the energy demand is displayed as the supply ratio in Figure 8.17.

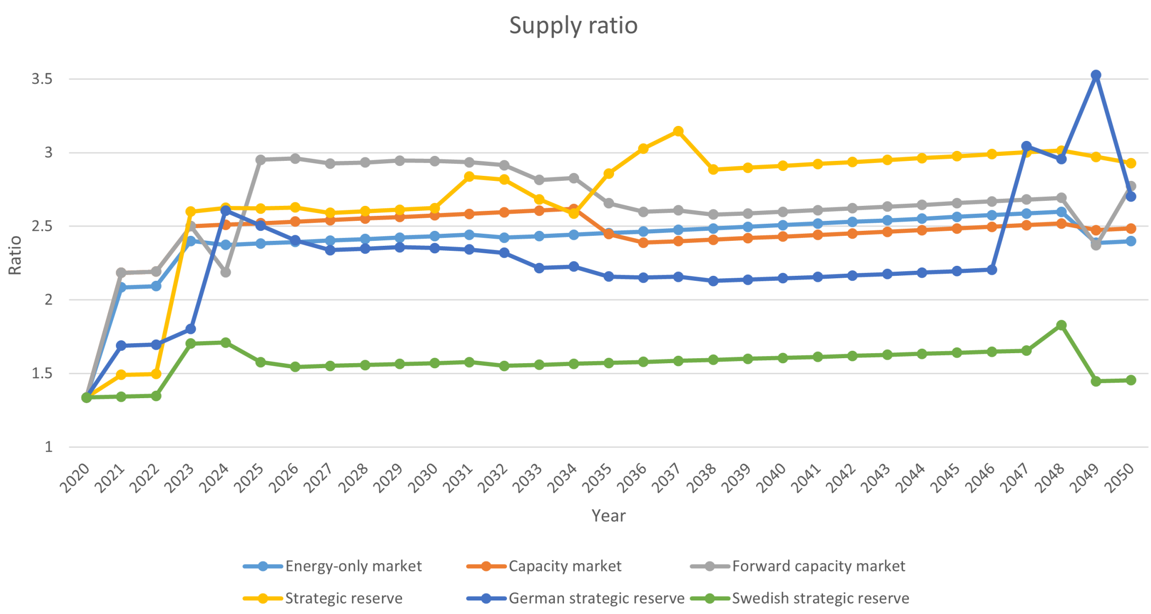

Figure 8.17: Supply ratio per capacity mechanism, calculated by dividing the total installed capacity by the peak energy demand. The represented data are yearly data points extracted from the simulation results.

Since the installed capacity stays roughly the same for multiple years in all the capacity mechanisms, while the demand linearly descends, the supply ratio grows steadily in all the mechanisms, as can be seen in Figure 8.17. Furthermore, the graph of the supply ratio shows the same results as the graph of the installed capacity. Namely, that the basic strategic has the highest supply ratio during the steady state years, while the Swedish strategic reserve has by far the lowest.

The second research question is focused on determining if there would be any energy shortage at peak times when there is only an energy-only market active. To evaluate the adequacy of the installed capacity, the different installed energy sources need to be examined.

Variable renewable energy sources

The energy sources that count as variable renewable energy sources are on- and offshore wind farms, PV installations and run-of-river hydroelectricity. The installed variable renewable energy capacity per capacity mechanism can be seen in Figure 8.18. In this figure the capacity of the yearly capacity market and forward capacity market are overlapping.

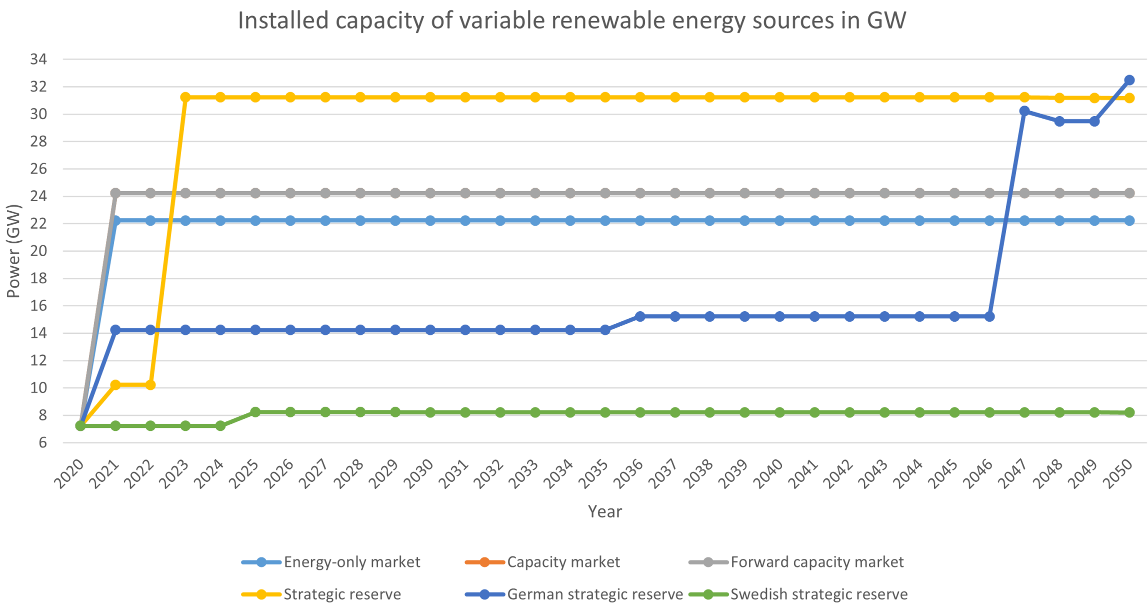

Figure 8.18: Operational variable renewable generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

In Figure 8.18 can be seen that the Swedish strategic reserve has continuously the lowest installed VRE capacity. Although this mechanism should promote investments in renewable energy sources, it clearly has a negative influence on the investments in VRE. The basic strategic reserve has the highest VRE capacity in most years of the simulation, however, just in the last year it is passed by the German strategic reserve.

Having a high capacity of variable renewable energy sources, however, does not mean the system has a high security of supply. This is because these sources do not insure energy production during a ”dunkelflaute” scenario. But it does mean the basic strategic reserve is the greenest of the mechanisms in most years, which is supported by the production of the variable renewable energy sources, as can be seen in Figure 8.19.

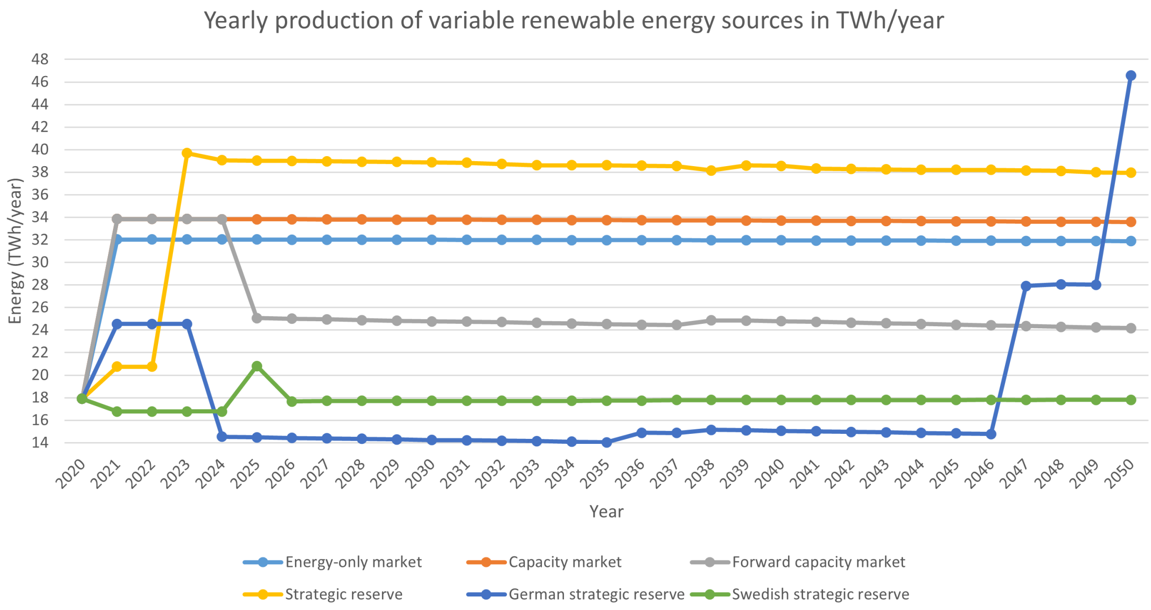

Figure 8.19: Yearly variable renewable energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

From Figure 8.19 can be learned that the share of variable renewable energy grows through the years for all mechanisms. Since the total production of energy decreases, evenly with the demand, while the production of renewable energy stays roughly the same.

Although the yearly and forward capacity market have the same installed VRE capacity, in the yearly capacity market the energy production is higher from 2025 onward. So the yearly capacity market is more favourable of VRE. Furthermore, the German strategic reserve has the lowest use of VRE through the years, but has a massive rise in their usage in the last few years. So when the mechanism is given time to exercise its influence, it will be very favourable for VRE in the future.

Controllable renewable energy sources

Biomass and hydro storage energy are the sources that are counted as controllable renewable energy sources. The installed capacity of controllable renewable energy sources can be seen in Figure 8.20. The capacities of the energy-only market, yearly capacity market and the Swedish strategic reserve are overlapping.

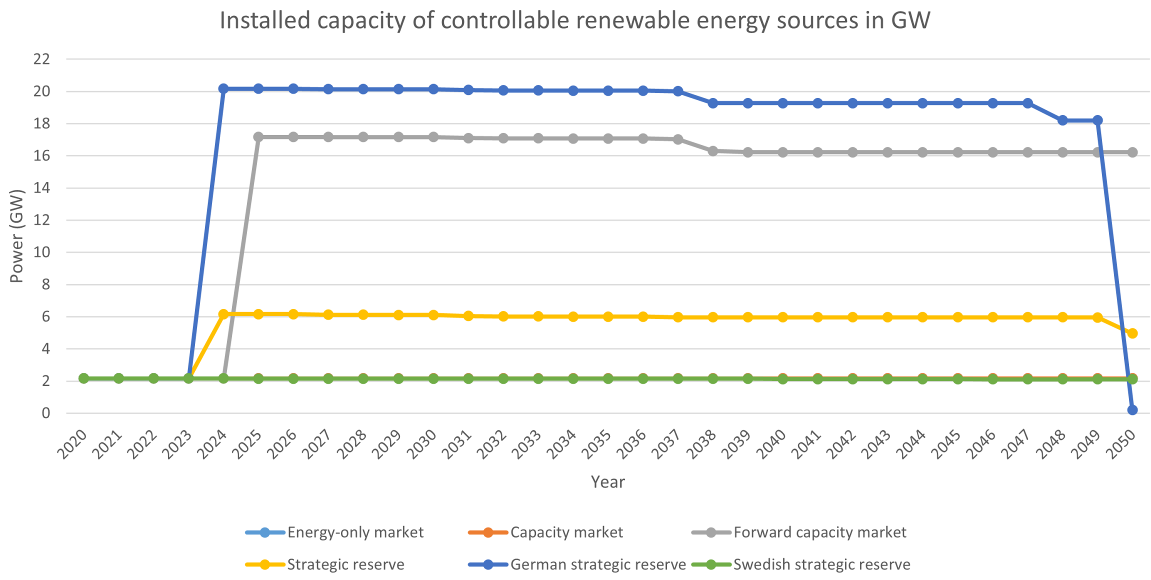

Figure 8.20: Operational controllable renewable generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

As can be seen in Figure 8.20, the installed capacity of controllable renewable energy sources in the energy-only market, yearly capacity market and the Swedish strategic reserve are constant through the years. So in these mechanisms CRE is profitable enough to not decommission the plants, but not profitable enough to invest more in it.

In the German strategic reserve the installed capacity of CRE is highest through the years. This is because in this mechanism a part of the conventional capacity is taken off the market and put in the reserve, so another form of controllable energy is needed. Since the capacity of CRE is so high in the German strategic reserve, there is also less energy needed from VRE sources, therefore, the generation of VRE was low. However, this installed capacity of CRE consists for 99.8% of biomass energy, which is not very realistic for the Netherlands. At the end of the simulation almost all biomass plants get decommissioned in the German strategic reserve, but a drop in production of CRE goes prior to this event. This can be seen in Figure 8.21. The decommissioning of the biomass power plants was compensated by investments in VRE capacity, as can be seen in Figure 8.18.

Furthermore, the generation of CRE in the different mechanisms corresponds closely to their installed capacity levels.

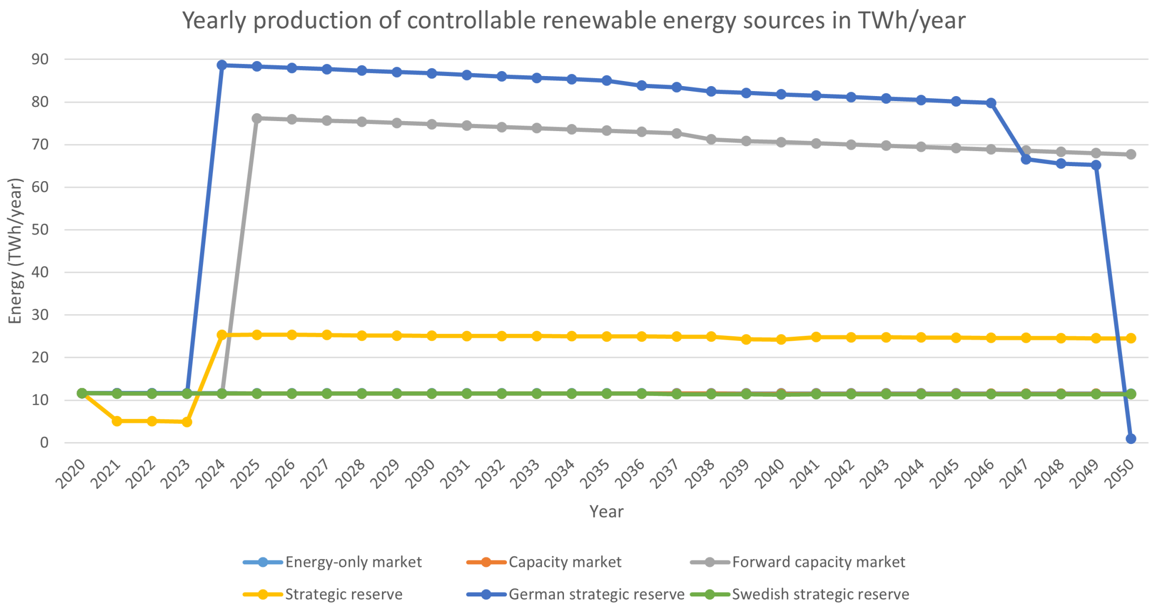

Figure 8.21: Yearly variable controllable energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

Conventional energy sources

The remaining power plants are the conventional energy sources, these are coal, CCGT, OCGT, nuclear, lignite, fuel oil and lithium battery energy sources. Figure 8.22 shows the installed capacity of the conventional energy sources for all mechanisms.

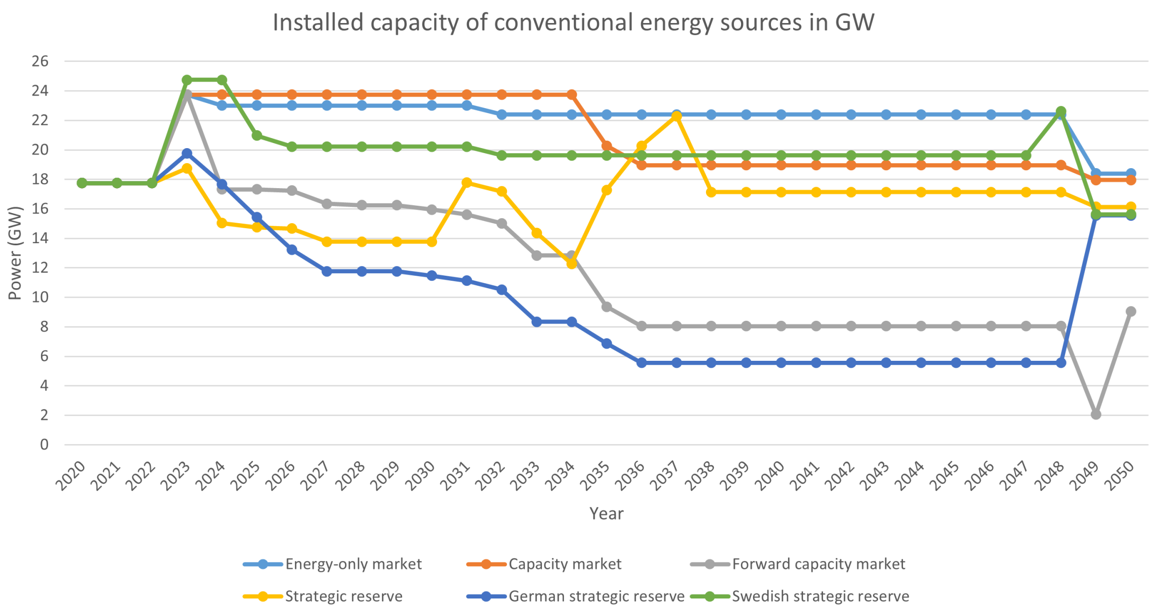

Figure 8.22: Operational conventional generation capacity per capacity mechanism in GW. The represented data are yearly data points extracted from the simulation results.

Figure 8.22 shows that actually the energy-only market has the highest installed capacity of conventional energy sources during the steady state years and at the end of the simulation. Since most capacity mechanisms have higher levels of installed VRE and CRE, this means most capacity mechanisms offer a higher incentive for investments in renewable energy than the energy-only market will.

The Swedish strategic reserve has a relatively high installed capacity of conventional plants. So, although this mechanism should promote investments in renewable energy sources, it actually promotes investment in conventional power plants.

The German strategic reserve has the highest decommissioning of conventional power plants, which means the mechanism functions and conventional plants do get contracted in the strategic reserve and, because of that, decommissioned sooner than they normally would. However, due to an energy shortage there is a large investment round in the last few years in conventional power. This results in an investment cycle and could delay a near zero-carbon energy system.

In Figure 8.23 the production of the conventional power plants can be seen.

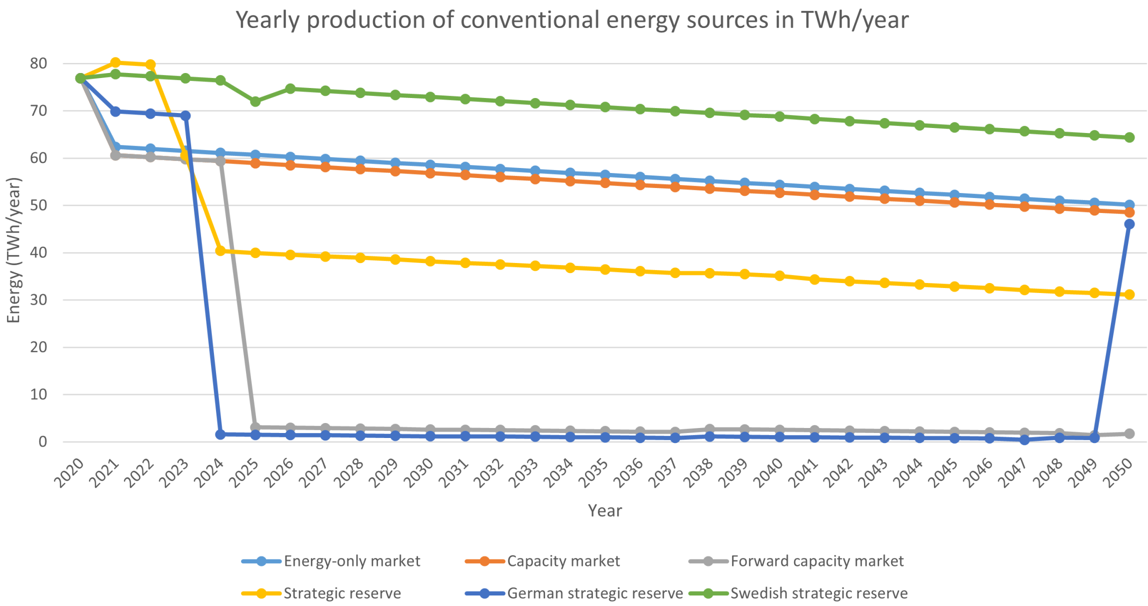

Figure 8.23: Yearly conventional energy production per capacity mechanism in TWh. The represented data are yearly data points extracted from the simulation results.

Figure 8.23 shows that in a scenario with a descending energy demand, the reduced demand is firstly chipped away from the production of conventional power plants.

The production of conventional power plants is the highest in the Swedish strategic reserve, which makes this mechanism the worst for reaching the climate policy goals.

Since a large part of the conventional power plants are contracted in the German strategic reserve, their dispatch is very low and so is the produced energy coming from conventional power plants. This only changed in the last year, due to the large investment in conventional power plants there is a lot of capacity which is not contracted in the reserve and that can freely participate in the spot market.

Contracted technologies

The differences in the results of the capacity mechanisms are caused by the money different generating technologies earn through the mechanisms. To see where the difference comes from, the average contracted capacities over the years can be seen in Figure 8.24 and 8.25.

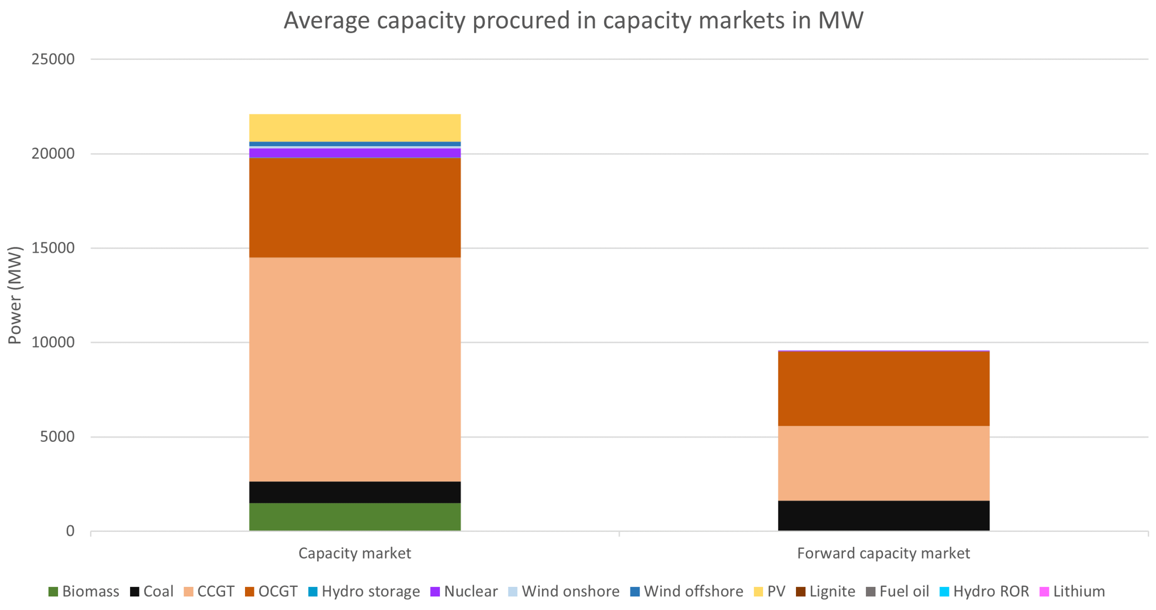

Figure 8.24: Average of the yearly procured capacity in capacity markets over the years 2020 to 2050 in MW.

As can be seen in Figure 8.24 the average total amount of capacity sold on the yearly capacity market is much higher than the average capacity sold on the forward capacity market. On the yearly capacity market all installed generation technologies are represented, while on the forward capacity market only conventional capacity is sold. This is due to the renewable power plants not being allowed to participate in the forward capacity market if they receive supportive subsidies.

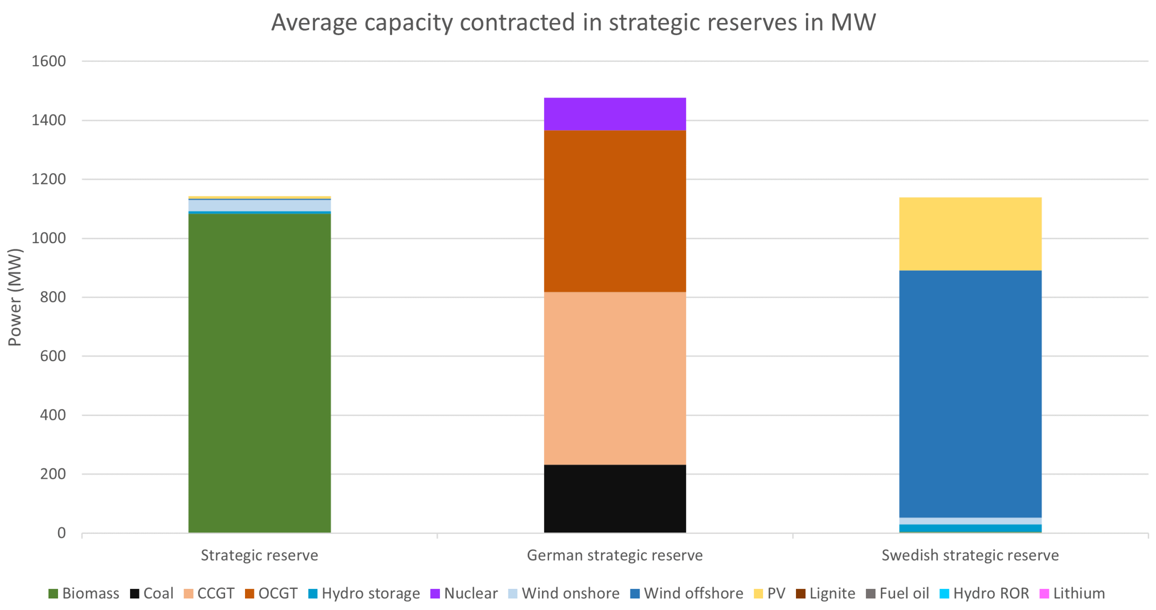

Figure 8.25: Average of the yearly contracted capacity in strategic reserves over the years 2020 to 2050 in MW.

Figure 8.25 shows that the amount of capacity contracted in the German strategic reserve is on average higher than in the other two strategic reserves. This is due to the long term contracts in the German strategic reserve, when a power plant is contracted it is in the strategic reserve until the end of its lifetime.

Although all power plants may participate in the basic strategic reserve, the average contracted capacity almost solely consists of biomass power plants. The basic strategic reserve contracts the power plants with the highest combined fixed and variable costs first, so this means the operating costs of biomass power plants are the highest.

In the scenario without a demand trend, the Swedish strategic reserve consisted mostly of PV capacity, however, in this scenario with a descending demand trend it consists mostly of offshore wind capacity.

Installed capacity in 2050

The resulting installed capacity at the end of the simulations can be seen in Figure 8.26.

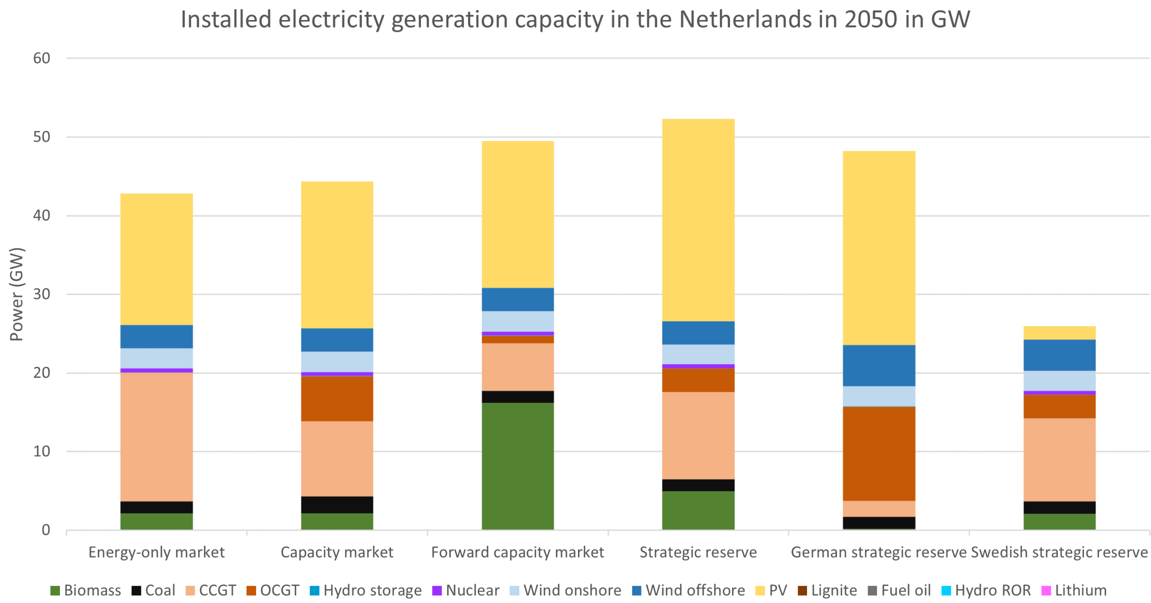

Figure 8.26: Installed and operational generation capacity in the Netherlands in 2050 in GW.

Figure 8.26 learns us that that the basic strategic reserve has the highest total installed capacity, due to a large amount of PV capacity. The forward capacity market has the highest installed capacity of controllable energy sources. However, this controllable capacity of the forward capacity market mostly consists of biomass, which is less realistic to actually be installed than the amounts of capacity the basic strategic reserve has of CCGT and OCGT power plants. Because a high level of biomass capacity means a large feedstock in the form of wood pellets is needed, which requires large areas of forest to be cut down. This could result in deforestation.

The German strategic reserve has the highest level of installed VRE capacity. This is due to the large amount of PV capacity, next to it being the mechanism with the highest investment in offshore wind capacity. However, the German strategic reserve has the lowest level of installed controllable capacity, which can cause shortage hours in a "dunkelflaute" scenario. Furthermore, the German strategic reserve is the only mechanism that decommissions the nuclear power plant that was already installed in 2020. This was done after the nuclear power plant was contracted in the reserve, because it was expensive to operate.

To get back to the second research question, is has to be determined whether there would be any shortage hours when the results of the energy only-market are run in a "dunkelflaute" scenario in 2050. In the ”dunkelflaute” scenario not only the demand is higher for longer periods of time, but there will be no wind or solar energy available during this period. Thus the energy-only market scenario was run for one year in 2050 with the installed capacity that resulted from the simulation and a so called ”dunkelflaute” scenario as input for the demand. When running the ”dunkelflaute” scenario there did not occur any shortage hours, as was the case during the normal simulation.

During the cold winter in January in the scenario the peak load volume is $V_{pl} = 18354.6\ MW$. The installed capacity in the energy-only market is $C_{total} = 42806.4\ MW$, of which the variable renewable energy capacity is $C_{vre} = 22235.5\ MW$, the controllable renewable energy capacity is $C_{cre} = 2168.9\ MW$ and the conventional energy capacity is $C_{con} = 18402.0\ MW$. So when there is no solar or wind energy available, C_{vre} becomes zero and there is still $C_{dunkelflaute} = C_{cre} + C_{con} = 20570.9\ MW$ available. This is still higher than the peak load volume of the harsh winter, thus there will be no shortage of energy, according to the energy-only market simulation. Furthermore, according to the simulations the energy-only market will even have a higher security of supply on the long-term than the German and the Swedish strategic reserve mechanisms. Since the energy-only market has a higher level of installed controllable capacity than the German and the Swedish strategic reserves.

Another way to define shortage hours is when the price of electricity on the spot market reaches the VoLL. However, in the energy-only market the electricity prices never reach the predefined VoLL of €3000 per MWh, at which the spot market prices are capped. This was tested for all mechanisms, but only in the German and the Swedish strategic reserves there were hours the prices reached the VoLL, this is due to these two mechanisms having the lowest level of installed controllable capacity. To be precise, in the ”dunkelflaute” scenario the German strategic reserve had 917 shortage hours and the Swedish strategic reserve had 238 shortage hours in 2050, in which the spot market prices reached the VoLL.

So according to this measurement, except for the German and Swedish strategic reserves, all other mechanisms offer an adequate security of supply, in which no shortage hours will occur during a ”dunkelflaute” scenario.

8.2.2 Energy prices

To test the costs to society of the mechanisms multiple aspects of the prices will be analysed. In Figure 8.27 the average electricity prices per year on the spot market can be seen.

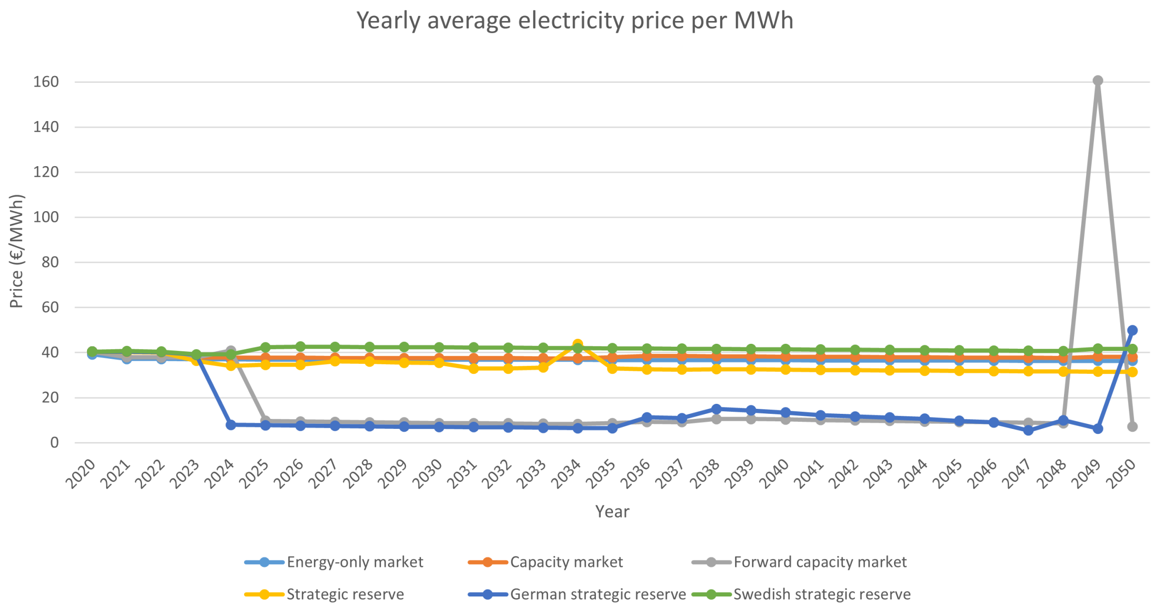

Figure 8.27: The yearly average electricity price on the spot market in Euro per MWh. The represented data are yearly data points extracted from the simulation results.

In Figure 8.27 the results of the large investments at the beginning of the simulations in biomass energy can be clearly seen in the price drops of the German strategic reserve and the forward capacity market. Therefore, these two mechanisms have much lower energy prices on the spot market, when compared to the other mechanisms. The energy-only market, yearly capacity market, basic strategic reserve and Swedish strategic reserve all have quite constant spot market prices of around €40 per MWh. Although the demand is descending, the price per MWh stays nearly constant for most mechanisms through the years.

Through the years the Swedish strategic reserve has persistently the highest spot market prices, due to a portion of renewable energy sources being taken off the market and contracted into the reserve. Furthermore, due to a high energy shortage of 345 hours in 2049 in the forward capacity market, there is a huge price spike on the spot market.

To determine which mechanisms has the lowest total costs to society, the costs of implementing the mechanism also has to be accounted for. In Figure 8.28 the total cumulative costs per mechanism can be seen. This includes the price of electricity on the spot market and the additional costs for the mechanism. In this figure the costs of the strategic reserve mechanisms are socialised, like they would in reality by the TSO by being passed on to network or system tariffs.

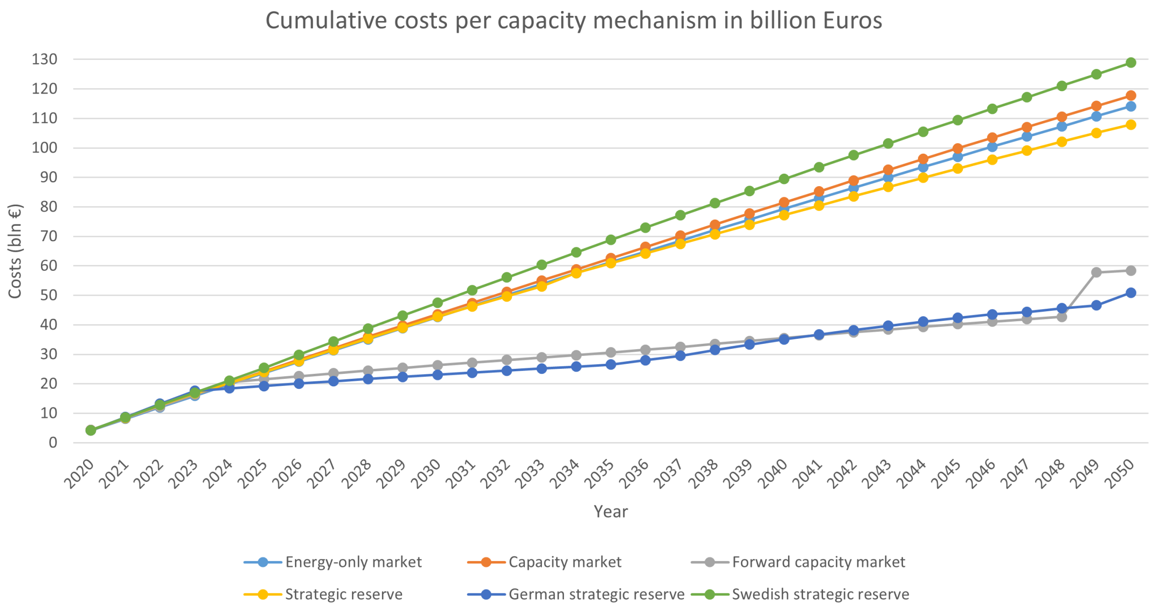

Figure 8.28: Cumulative costs per capacity mechanism in billion Euros. The represented data are yearly data points extracted from the simulation results.

As can be seen in Figure 8.28, the cumulative costs of the forward capacity market and the German strategic reserve are much lower compared to the other mechanisms. This is due to the forward capacity market and German strategic reserve having a much lower price per MWh on the spot market most of the years.

The Swedish strategic reserve is clearly the most expensive to society, while it is also the worst mechanism for the environment and for ensuring security of supply.

To further analyse where the price differences come from, the capacity mechanism specific additional costs should be examined.

Mechanism specific costs

The yearly additional costs of the mechanisms can be seen in Figure 8.29. When the costs are positive in the figure, it means that the mechanisms costs money, but when the costs are negative it means that the mechanism makes profit in that year. In this figure the yearly costs of the yearly and forward capacity markets are overlapping.

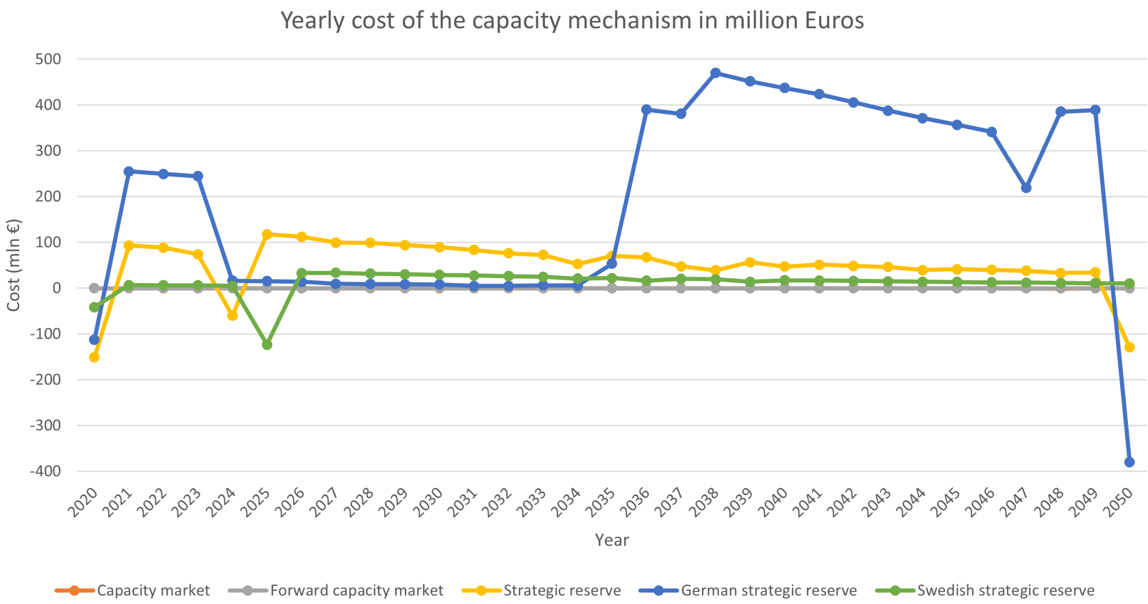

Figure 8.29: Yearly costs per capacity mechanism in million Euros. The represented data are yearly data points extracted from the simulation results.

Figure 8.29 shows that the yearly additional costs of the yearly and forward capacity market are very little in comparison to the costs or profits of the strategic reserves. When the contracted plants in the strategic reserves are not dispatched, or only very little, the reserves make losses, due to the strategic reserve operator always having to pay the fixed operating costs of the power plants. Since the German strategic reserve has a higher contracted capacity from 2035 onward, in comparison to the other strategic reserves, it also has much higher yearly costs. In 2050 the German strategic reserve is largely dispatched, therefore, it makes a lot of profit. This is due to the operator earning € 800 per MWh, while the marginal operating costs per MWh are much lower. These high profits are meant to cover the costs of the strategic reserves, but this is not the case, as can be seen in Figure 8.30.

Figure 8.30 shows the cumulative profits of the different capacity mechanisms. The profits in this figure only contain the mechanism specific profits, not the profits of electricity spot market. In this figure the profits of the yearly and forward capacity markets are overlapping again.

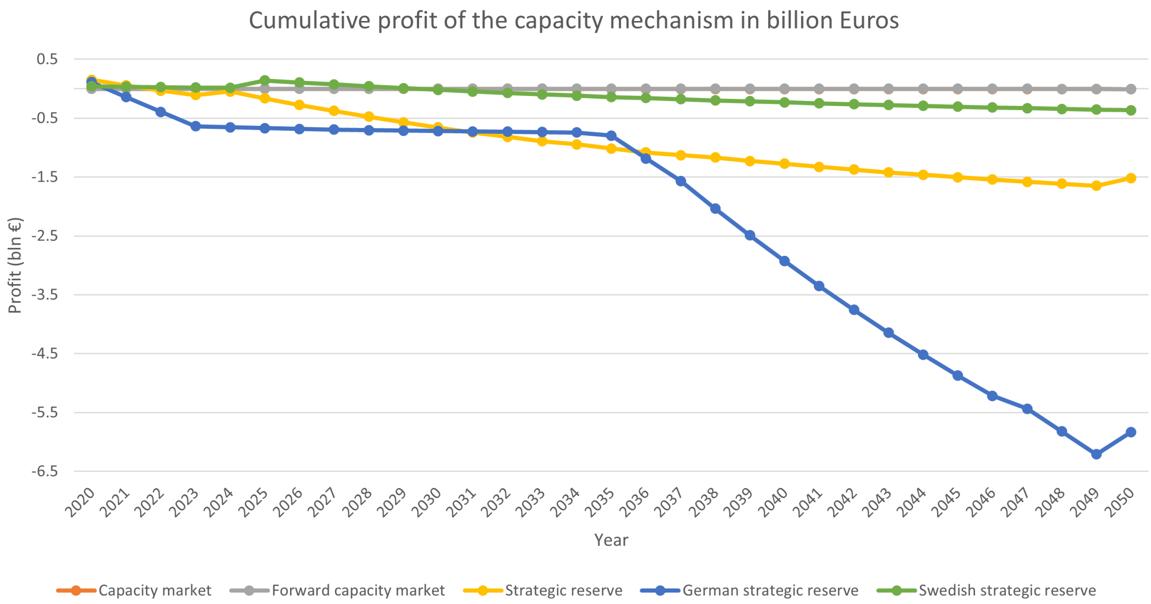

Figure 8.30: Cumulative profit per capacity mechanism in billion Euros. The represented data are yearly data points extracted from the simulation results.

As can be seen in Figure 8.30, the costs of the yearly and forward capacity markets are really small compared to the costs of the strategic reserves. The figure shows that the strategic reserves all make losses and, therefore, the network or system tariffs have to be increased to cover the costs of the reserves in a socialised way.

Although the German strategic reserve has very high costs of contracting the reserve, in combination with the very low spot market prices it is the cheapest mechanism to society in this scenario.

8.2.3 Closeness to reality

This time the scenario that was used as input for the demand is based on the expected future energy scenario for the Dutch energy system according to the international governance. The results of the simulations can be seen in Table 8.2. As can be seen in the table, all the scenarios have an energy demand in 2050 which is 12.1% lower than the demand was in 2020, same as in the international governance scenario.

Only the forward capacity market reaches the CO_2-emission goals, but the German strategic reserve comes very close to the goal. In the international governance scenario the CO_2-emissions have dropped with 95.2%, but in the simulations the forward capacity market reaches the highest level of CO_2-emission reduction of 99.7%.

Nonetheless, the simulations outperform the international governance scenario on the other metrics. Except for the Swedish strategic reserve, all the mechanisms have a higher share of renewable electricity, which is 80.7% in the international governance scenario. This means there is heavy over investment in renewables and especially in solar energy, which increases the installed capacity, but does not necessarily increase the security of supply.

The mechanisms in the simulations also have a much lower annual cost for energy, since the annual costs are € 56.4 bln in the international governance scenario. The forward capacity market has the lowest annual costs by far, at € 0.66 bln.

Furthermore, the LOLE of the international governance scenario is 128 hours, but in the simulations most mechanisms have a LOLE of zero hours, only the German and Swedish strategic reserve have a LOLE of 2 hours in 2050. The LOLE hours of these strategic reserves are caused by their low installed capacity of controllable energy sources.

2050	**International governance**	**Energy-only market**	**Capacity market**	**Forward capacity market**	**Strategic reserve**	**German strategic reserve**	**Swedish strategic reserve**
Energy usage compared to 2020	-12.10%	-12.10%	-12.10%	-12.10%	-12.10%	-12.10%	-12.10%
CO_2-emission	7.810 Mton	16.936 Mton	16.638 Mton	0.417 Mton	9.283 Mton	19.818 Mton	22.496 Mton
CO_2 compared to 1990	-95.20%	-89.59%	-89.77%	-99.74%	-94.74%	-87.82%	-86.17%
Renewable electricity share	80.70%	120.18%	130.03%	199.28%	178.00%	160.98%	50.85%
Annual energy costs	€ 56.4 bln	€ 3.40 bln	€ 3.56 bln	€ 0.66 bln	€ 2.82 bln	€ 4.30 bln	€ 3.91 bln
Loss of Load Expectation (LOLE)	128 hr	0 hr	0 hr	0 hr	0 hr	2 hr	2 hr
Installed VRE capacity	21131.0 MW	22235.5 MW	24235.5 MW	24235.5 MW	31181.9 MW	32483.5 MW	8214.3 MW
Installed controllable capacity	8678.0 MW	20571.0 MW	20130.0 MW	25275.0 MW	21104.4 MW	15765.0 MW	17737.4 MW

Table 8.2: Resulting parameters of the simulations of the different mechanisms in the scenario with a descending energy demand trend.

9 Conclusion

The goal of this dissertation was to evaluate the adequacy of the Dutch energy system during the transition to a zero-carbon energy system in a realistic scenario. The information needed to answer the three supportive research questions was gathered by doing an extensive literature study and by simulating models of the Dutch energy system until 2050. The findings for the supportive research questions will be merged into a recommendation for keeping sufficient incentive for investors to invest in controllable power generation during the energy transition.

The first research question was aimed at finding a realistic energy generation scenario for the Netherlands in 2050. However, since no one can predict the future it is nearly impossible to define one single scenario, but the vertices can be sketched in which the scenario will lie with a high probability. The vertices are the four so called scenarios, regional governance, national governance, European CO_2-governance and international governance. The regional governance scenario focuses on delivering heat through heat networks and a heavy electrification in all sectors. The national governance focuses on heavy electrification in all consumption sectors, together with a big growth in wind and solar energy generation. In the European CO_2-governance there is an increase in the use of green gas in multiple sectors, with no CO_2-emission due to a combination of hybrid electrification and carbon capture and storage. The international governance scenario lets the market control the energy generation mix and the internationally cheapest option will prevail. While the first three scenarios are more heavily influenced by the government on, respectively, regional, national and European level, the international governance scenario is very little influenced by any government.

These scenarios were investigated to use as reference and to validate the simulation results. Since the investment decisions in the simulations are purely profit driven and the cheapest options prevail, the simulations have the most in common with the international governance scenario. Therefore, all capacity mechanisms were also simulated in a scenario replicating the international governance scenario.

However, the energy-only market will not converge towards a zero-carbon energy system, as the mentioned scenarios do, this can be seen in the results in Table 8.2. The energy-only market even ends the simulation in 2050 with the highest level of installed conventional power plant capacity of all the simulated mechanisms. So the simulations prove that without any governmental interference a (near) zero-carbon energy system will not be achieved, since most investments in energy generation sources are profit driven.

Secondly, the question whether there will be an energy shortage at peak times when there is no capacity mechanism in place can be answered. This was done by simulating a so called

”dunkelflaute” scenario for the Netherlands in 2050. As input the resulting installed power plants of the simulation of the energy-only market at the end of the descending energy demand trend scenario, replicating the international governance scenario, were used. Through the course of the simulations no shortage hours occurred. The energy-only market created enough investment incentive to keep sufficient generation capacity for supplying the demand. When the ”dunkelflaute” scenario was run, again no shortage hours did occur. The installed controllable renewable and conventional energy sources had enough capacity to generate the energy needed in the harsh winter.

Even the VoLL was never reached in the electricity spot market prices of the energy-only market in a ”dunkelflaute” scenario. However, the German and Swedish strategic reserves did have energy shortage hours in which the VoLL was reached in the electricity spot market in the ”dunkelflaute” scenario. In the German strategic reserve there were 917 hours in which the spot market price had capped at the VoLL and in the Swedish strategic reserve there were 238 hours.

Nevertheless, in the simulations there were still heavy investments in gas-fired power plants, so in a scenario which is going to a near zero-carbon energy system it might be the case that there are more energy shortages at peak times. To prevent shortages in ”dunkelflaute” scenarios in the future, heavy investment is needed in controllable renewable energy sources, like biomass power plants and hydro or lithium storage energy. Another possibility is to invest in technologies that have a lower CO_2-emission, like nuclear energy.

Thirdly, the simulation results provided an answer to the question what the least costly capacity mechanism for the entire society for providing sufficient security of supply would be. The security of supply of a capacity mechanism is sufficient when no periods of energy shortage occurred through the course of the simulation.

The yearly capacity market scored very average in all measured metrics and it excels nowhere, only the costs are on the high side. However, no shortage hours occurred in any of the simulated scenarios.

The forward capacity market is the second cheapest in cumulative costs over the course of the simulation with a descending demand trend and also has the second highest level of total installed capacity, with even the highest level of controllable capacity. Nonetheless, in 2049 a total amount of 345 shortage hours did occur.

The basic strategic has the highest level of total installed capacity in 2050 in the descending demand trend scenario. From the literature it was expected that a strategic reserve mechanism would offer a high level of security of supply, but will not provide the highest level of economic efficiency. However, the cumulative cost price is the third lowest, which means it is definitely not the most expensive mechanism. Nevertheless, in the scenario without a demand trend the basic strategic reserve had 443 energy shortage hours over the course of three years and it ended up in 2050 with the second lowest total installed capacity.

The German strategic reserve had a high level of installed capacity at a very low cost price to society for both the scenarios. However, in the descending demand trend scenario it had two shortage hours in 2050 and even worse, in the ”dunkelflaute” scenario it had 917 shortage hours.

The Swedish strategic reserve scored the worst overall, in both scenarios it always had the lowest level of installed capacity and the highest or second highest cumulative costs. Furthermore, in 2050 in the scenario without a demand trend it had 11 shortage hours and in the scenario with a descending demand trend 2 shortage hours. In addition, in the ”dunkelflaute” scenario it had 238 shortage hours.

So, according to the simulations in the realistic scenario for the Netherlands with a descending demand trend, the basic strategic reserve is the cheapest option while providing sufficient security of supply. The basic strategic reserve resulted in the highest level of installed capacity, which was sufficient to prevent significant shortage hours in the descending demand trend scenario and the ”dunkelflaute” scenario.

Finally, the main research question still lingers, how to maintain security of supply in the Netherlands during the transition to a zero-carbon energy system? The simulations showed that the security of supply in the energy system can be improved by the implementation of a capacity mechanism, although it could also be worsened by the implementation of the Swedish strategic reserve. By implementing a yearly capacity market the improvements of security of supply seem the most promising. The yearly capacity market did not result in the highest installed capacity, but it was sufficient to prevent shortage hours in all scenarios. Even though it was not the cheapest option to society, the higher prices offer the financial incentive needed for investors to keep investing in controllable energy sources.

10

Discussion

The findings can of course not be an exact representation of the future reality, since the model is a simplified version of the electricity sector. One such simplification is, for example, the fact that the model can only either decommission existing or build new power plants, but the model is not able to refurbish existing power plants. This makes the investment decisions quite divergent from real life scenarios. In many cases a power plant would get refurbished, instead of decommissioned, in a real scenario. Since refurbishing a power plant is much cheaper than decommissioning one and building a new one, this could make it cheaper to have a larger installed capacity of controllable power plants, which results in an improved security of supply.

Furthermore, in the defined future scenarios there is also a lot of installed hydrogen power plant capacity. In reality it is investigated if some gas-fired power plants can be refurbished to operate as hydrogen fired power plants. However, in the models it is not possible to either invest in new hydrogen power plants or to refurbish gas-fired power plants to hydrogen fired power plants. If this would be an option in the models, they could better match with the defined future scenarios for the Netherlands.

Next up, the model simulates investments in the energy system based on profits. Therefore, it keeps investing heavily in conventional power plants, and to be specific, mostly in gas-fired CCGT power plants. To simulate a more accurate energy system that is converging more towards a zero-carbon energy system, there needs to be more governmental intervention implemented in the model. This intervention needs to make sure that the investors are not allowed to keep investing in conventional power plants in the amount that was currently happening in the simulations. When all the simulations have an energy system that is converging towards a zero-carbon energy system, the results of the capacity mechanisms might be different. Furthermore, the main research question of how to maintain security of supply in the Netherlands during the transition to a zero-carbon energy system could be answered more accurately. However, I expect the results stay approximately the same and the yearly capacity market will again end up as the best option for creating an energy system sufficiently able to prevent shortage hours in all scenarios.

And lastly, as input for the simulations certain start values of fuel and energy prices were chosen and to determine the prices in the future years of the simulated periods price trends were assumed based on historical values. However, how the price of fuels will fluctuate in the future cannot be predicted. Since the war in Ukraine has started in the beginning of 2022, the prices of gas and oil haven risen extremely fast. Although these kind of extraordinary worldly events have a very small chance of really happening, only one man in the right (or wrong) position can have the power to influence the whole energy sector. Therefore, the model will never be super accurate and it has to be accounted for that one event could render all results unusable. The current gas prices could also render the gas-fired power plants, which are invested in by the simulations, not profitable anymore. So, with very high prices for fossil fuels the model could steer its investments automatically more towards renewable energy sources.

10.1 Future work

As discussed, there are some things that could be improved in the model and added to have simulations that result in more accurate outputs.

Firstly, the possibility to refurbish older power plants could be added. This could extent the lifetime of a power plant and make it economically viable again to keep it alive. By refurbishing a plant its efficiency could be increased, which would result in lower variable costs. The refurbishment will be a large investment, but will also result in lower fixed operating costs. This large investment will also be much lower than building a new power plant. Furthermore, the possibility to invest in hydrogen fired power plants could be added.

Secondly, a more influential government policy could be implemented. If the investments could be steered more towards renewable energy sources by some sort of governmental policy, the resulting simulations would depict a more accurate picture of the reality. Since in reality the government interferes heavily in the energy sector, which forces investors to invest mostly in renewable energy nowadays.

Thirdly, the consumers could be modelled as an agent that could participate in the market and create more interaction between supply and demand. When the consumers are modelled as agents, it would also be possible to implement the mechanism for the capacity subscription model. Since this model would convert a public problem into a private problem, it would be very interesting to see what kind of results this model will have on the market and on the investments.

Fourthly, the modelled forward capacity market is a simple version, in reality when decisions are made for future years the risks are incorporated in the decision making, which is not the case in the current model. To increase the accuracy of the capacity that is procured in four years in the future, a certain risk element should be added to the decision making of the agents. Because currently the agents have perfect insight on the energy demand in the future and act on it without hesitation.

Finally, a study could be done on new prices of fossil fuels, which more accurately represent the current situation. The results of the simulations will probably be very different if the current fuel prices would be used as input for the simulations. However, the prices are still very volatile, so an extensive study is needed to come up with an accurate representation of the price trends.

A

Simulation Results

A.1 Simulations without demand trend

A.1.1 Energy-only market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio
2020	106493608	4172638395	39.1821	75	27155.42	2	1.337293
2021	106494503	3942427268	37.0200	97	43155.42	0	2.125227
2022	106494503	3942427268	37.0200	97	43155.42	0	2.125227
2023	106494503	3924410439	36.8508	97	49155.42	0	2.420703
2024	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2025	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2026	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2027	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2028	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2029	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2030	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2031	106494503	3924410439	36.8508	94	48406.42	0	2.383817
2032	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2033	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2034	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2035	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2036	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2037	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2038	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2039	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2040	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2041	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2042	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2043	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2044	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2045	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2046	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2047	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2048	106494503	3924410439	36.8508	93	47806.42	0	2.354270
2049	106494503	3924584483	36.8525	89	43806.42	0	2.157286
2050	106494503	3924584483	36.8525	89	43806.42	0	2.157286

Table A.1: Overview of the simulation results of the energy-only market.

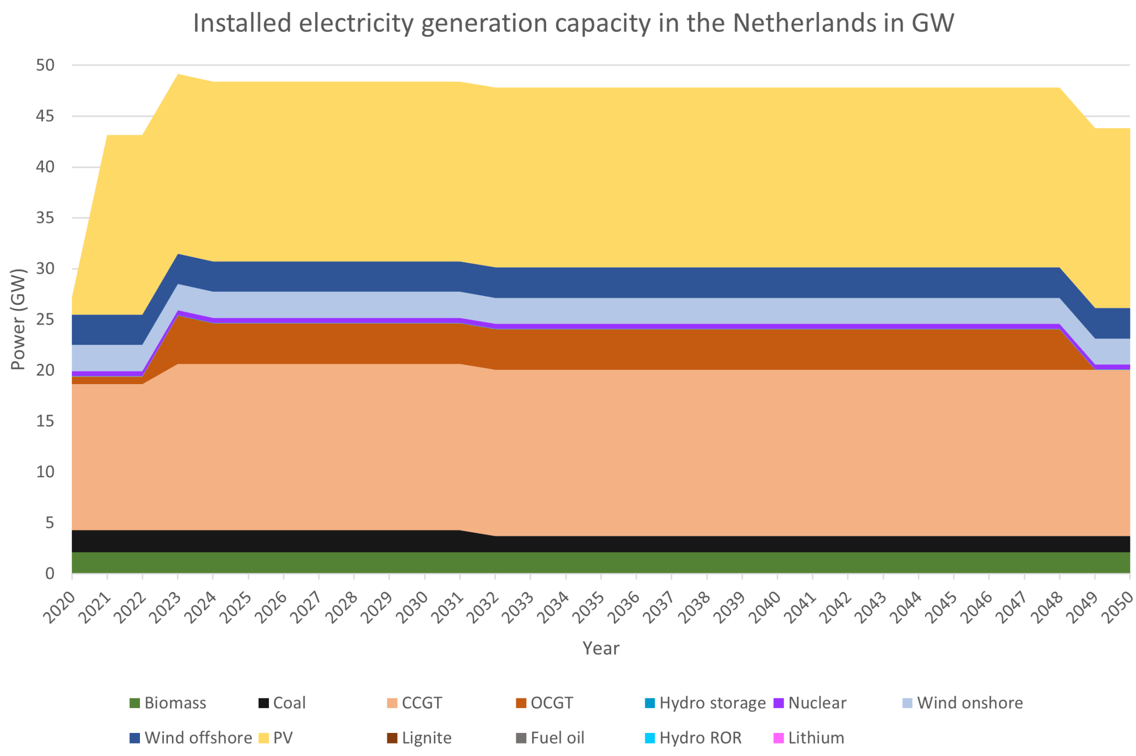

Figure A.1: Installed generation capacity per year in the energy-only market.

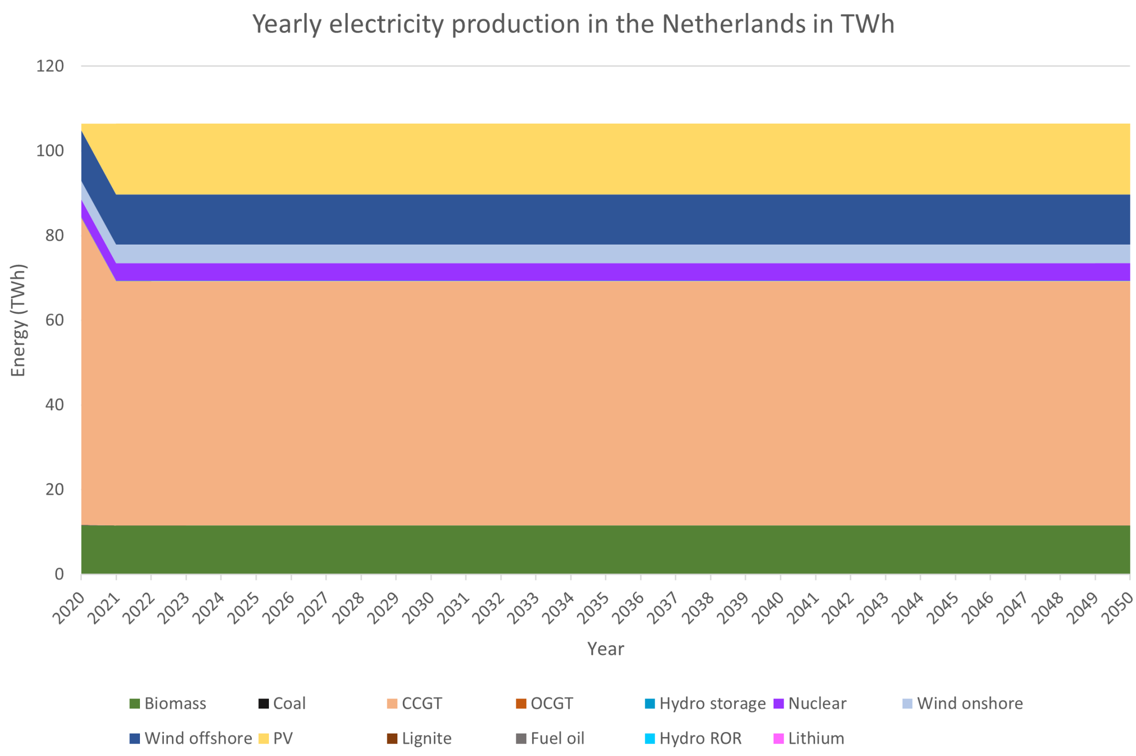

Figure A.2: Electricity production per year in the energy-only market.

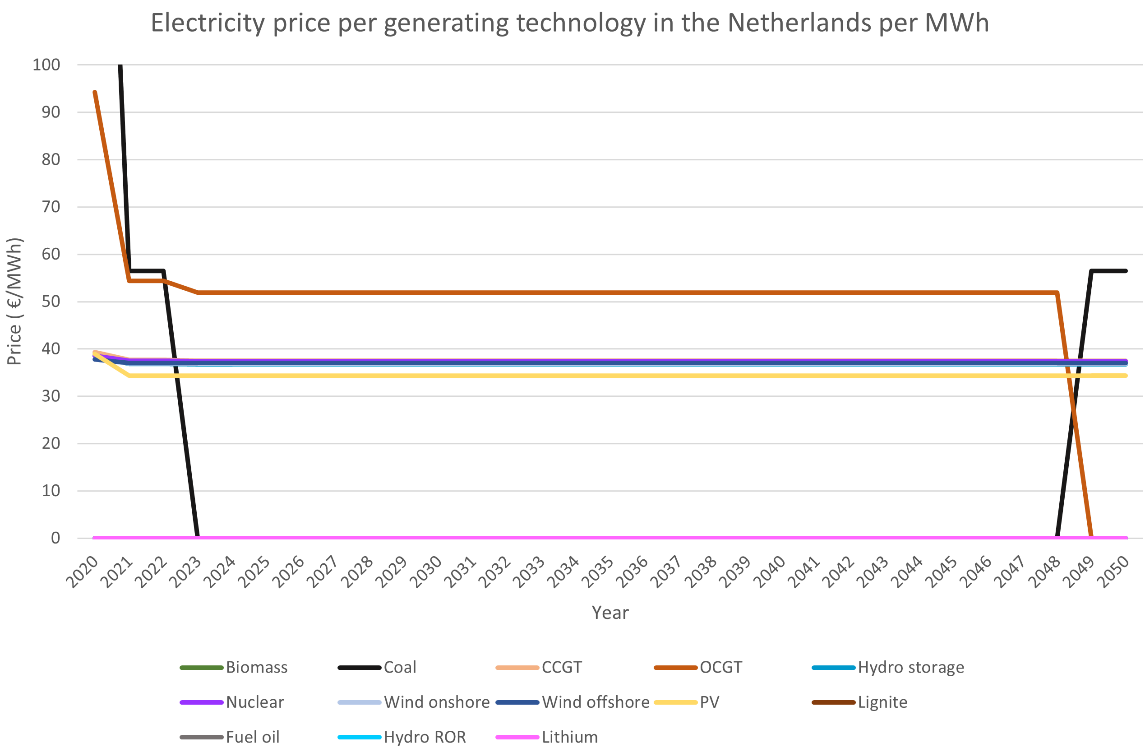

Figure A.3: Electricity price per MWh per year in the energy-only market.

A.1.2 Yearly capacity market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	CM volume (MW)	CM price (€)	CM price per MW (€/MWh)
2020	106493608	4300703079	40.3846	75	27155.42	2	1.337293	19763.37	74464.0	3.768
2021	106494503	4020966367	37.7575	99	45155.42	0	2.223719	21203.37	205281.1	9.682
2022	106494503	4020966367	37.7575	99	45155.42	0	2.223719	21203.37	194573.3	9.177
2023	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22785.13	188134.2	8.257
2024	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22797.80	178992.9	7.851
2025	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22809.87	170287.0	7.465
2026	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22821.36	161995.6	7.098
2027	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22832.31	154099.1	6.749
2028	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22842.73	146578.5	6.417
2029	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22852.66	139416.1	6.101
2030	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22862.12	132594.8	5.800
2031	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22871.12	126098.3	5.513
2032	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22879.70	119911.2	5.241
2033	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22887.87	114018.6	4.982
2034	106494503	4007635389	37.6323	99	51155.42	0	2.519194	22895.65	108406.7	4.735
2035	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22667.95	64624.7	2.851
2036	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22686.03	60215.8	2.654
2037	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22703.25	56298.3	2.480
2038	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22719.65	52773.2	2.323
2039	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22735.26	49491.5	2.177
2040	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22750.14	46571.9	2.047
2041	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22764.30	43791.4	1.924
2042	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22777.79	41218.8	1.810
2043	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22790.64	38974.6	1.710
2044	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22802.88	36837.2	1.615
2045	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22814.53	34801.7	1.525
2046	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22825.63	32863.0	1.440
2047	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22836.20	31016.7	1.358
2048	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22846.27	29258.3	1.281
2049	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22855.85	27583.6	1.207
2050	106494503	4104823984	38.5449	98	47685.42	0	2.348311	22864.99	25988.7	1.137

Table A.2: Overview of the simulation results of the yearly capacity market.

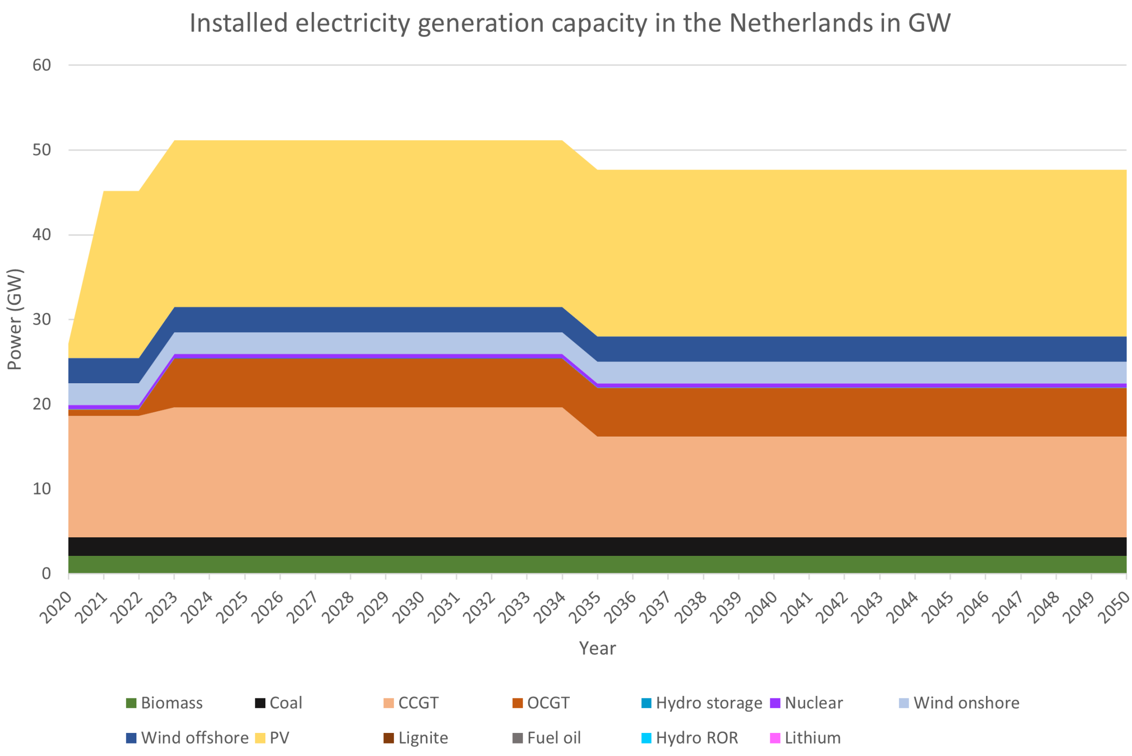

Figure A.4: Installed generation capacity per year in the yearly capacity market.

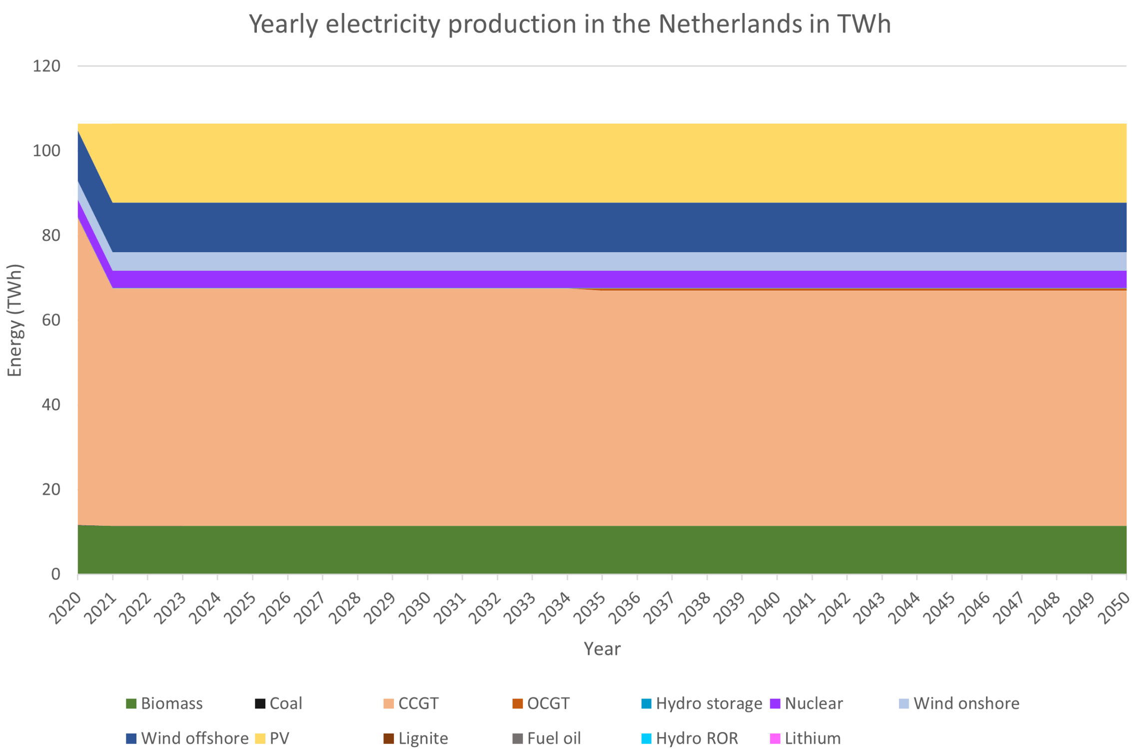

Figure A.5: Electricity production per year in the yearly capacity market.

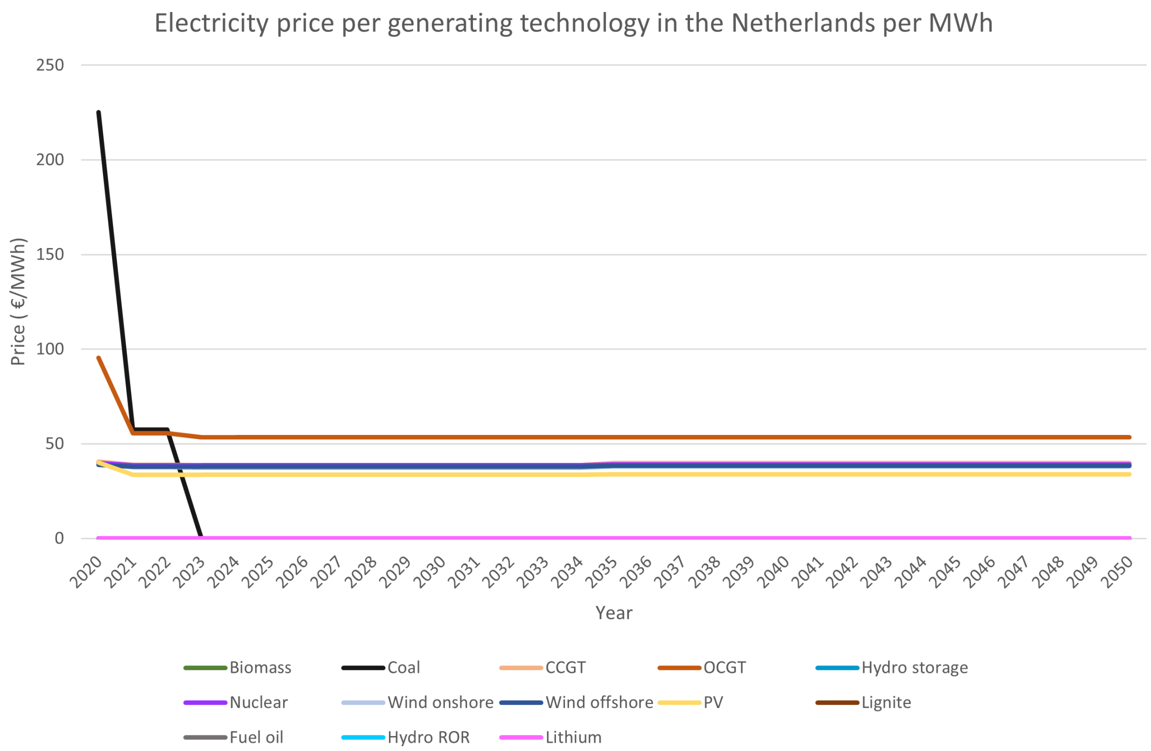

Figure A.6: Electricity price per MWh per year in the yearly capacity market.

A.1.3 Forward capacity market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	CM volume (MW)	CM price (€)	CM price per MW (€/MWh)
2020	106493608	4300703079	40.3846	75	27155.42	2	1.337293	11222	74463.98	6.636
2021	106494503	4020966367	37.7575	99	45155.42	0	2.223719	17222	211890.66	12.303
2022	106494503	4020966367	37.7575	115	45155.42	0	2.223719	17142	192911.18	11.254
2023	106494503	3996836588	37.5309	115	52155.42	0	2.568440	15766	178422.99	11.317
2024	106494042	4375466283	41.0865	98	45723.42	2	2.251691	15766	45159.92	2.864
2025	106494503	1039603862	9.7620	98	60723.42	0	2.990379	15766	162797.39	10.326
2026	106494503	1039603862	9.7620	97	60643.42	0	2.986440	15466	145541.71	9.410
2027	106494503	1039603862	9.7620	96	59752.42	0	2.942561	15127	129107.72	8.535
2028	106494503	1039603862	9.7620	94	59654.22	0	2.937725	14527	112842.31	7.768
2029	106494503	1040107079	9.7668	93	59652.47	0	2.937639	12350	97965.44	7.932
2030	106494503	1040107079	9.7668	92	59352.47	0	2.922866	12350	93300.42	7.555
2031	106494503	1054056800	9.8978	91	58958.47	0	2.903463	8880	79354.12	8.936
2032	106494503	1060147442	9.9549	89	58333.47	0	2.872684	7560	66071.92	8.740
2033	106494503	931097693	8.7432	88	57156.47	0	2.814722	7560	62704.57	8.294
2034	106494503	931138492	8.7435	87	57154.07	0	2.814603	7560	59708.12	7.898
2035	106494503	1016144683	9.5418	87	53684.07	0	2.643720	7560	51765.45	6.847
2036	106494083	1209017996	11.3529	87	52364.07	2	2.578715	7560	13192.85	1.745
2037	106494021	1223142181	11.4855	86	52314.07	2	2.576253	7560	12284.38	1.625
2038	106494503	885245050	8.3126	86	53314.07	0	2.625499	7560	41327.25	5.467
2039	106494503	901271093	8.4631	85	53242.47	0	2.621973	7560	38807.80	5.133
2040	106494265	1174469117	11.0285	83	52510.47	2	2.585925	7560	9810.39	1.298
2041	106494265	1174469117	11.0285	83	52510.47	2	2.585925	7560	9062.99	1.199
2042	106494265	1174469117	11.0285	83	52510.47	2	2.585925	7560	8351.18	1.105
2043	106494265	1174469117	11.0285	83	52510.47	2	2.585925	7560	7673.26	1.015
2044	106494265	1174469117	11.0285	83	52510.47	2	2.585925	7560	7027.63	0.930
2045	106494265	1174469117	11.0285	83	52510.47	2	2.585925	1560	6412.74	4.111
2046	106494265	1174469117	11.0285	83	52510.47	2	2.585925	1560	5827.13	3.735
2047	106494265	1174469117	11.0285	83	52510.47	2	2.585925	1560	5269.40	3.378
2048	106494265	1174469117	11.0285	91	52510.47	2	2.585925	9560	205712.96	21.518
2049	106494265	1174469117	11.0285	106	52510.47	2	2.585925	8000	191404.50	23.926
2050	106494503	898899122	8.4408	106	60510.47	0	2.979892	8000	182113.15	22.764

Table A.3: Overview of the simulation results of the forward capacity market.

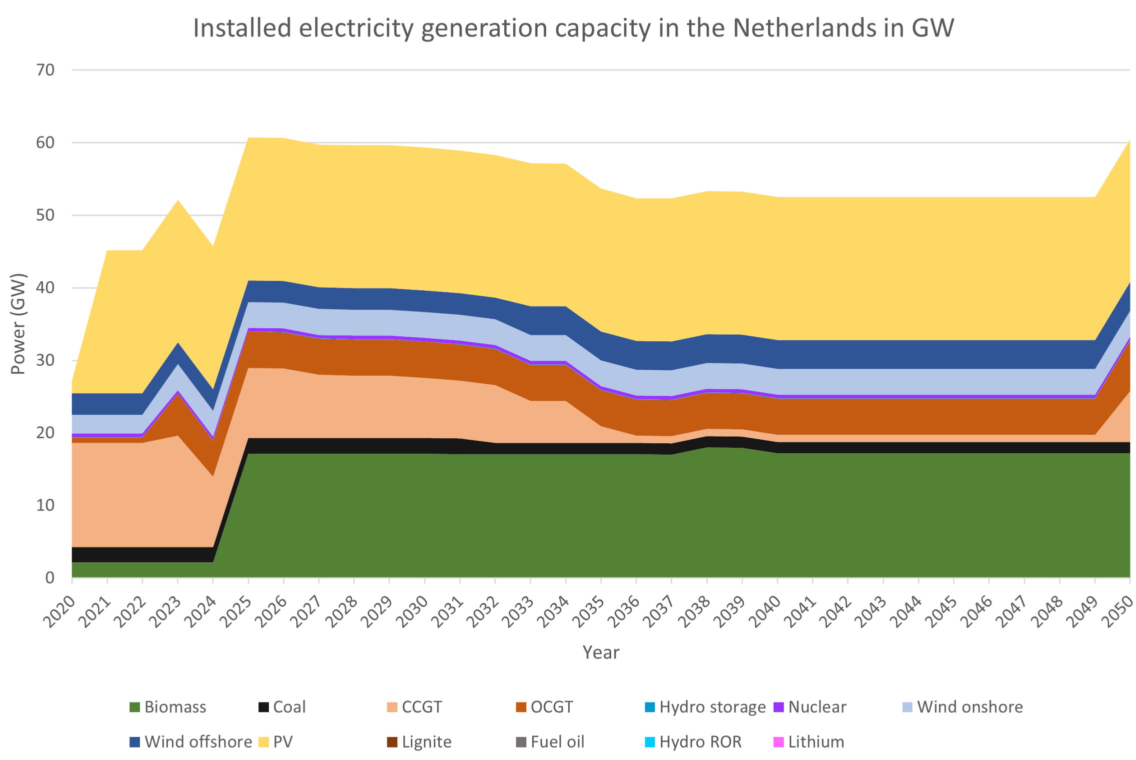

Figure A.7: Installed generation capacity per year in the forward capacity market.

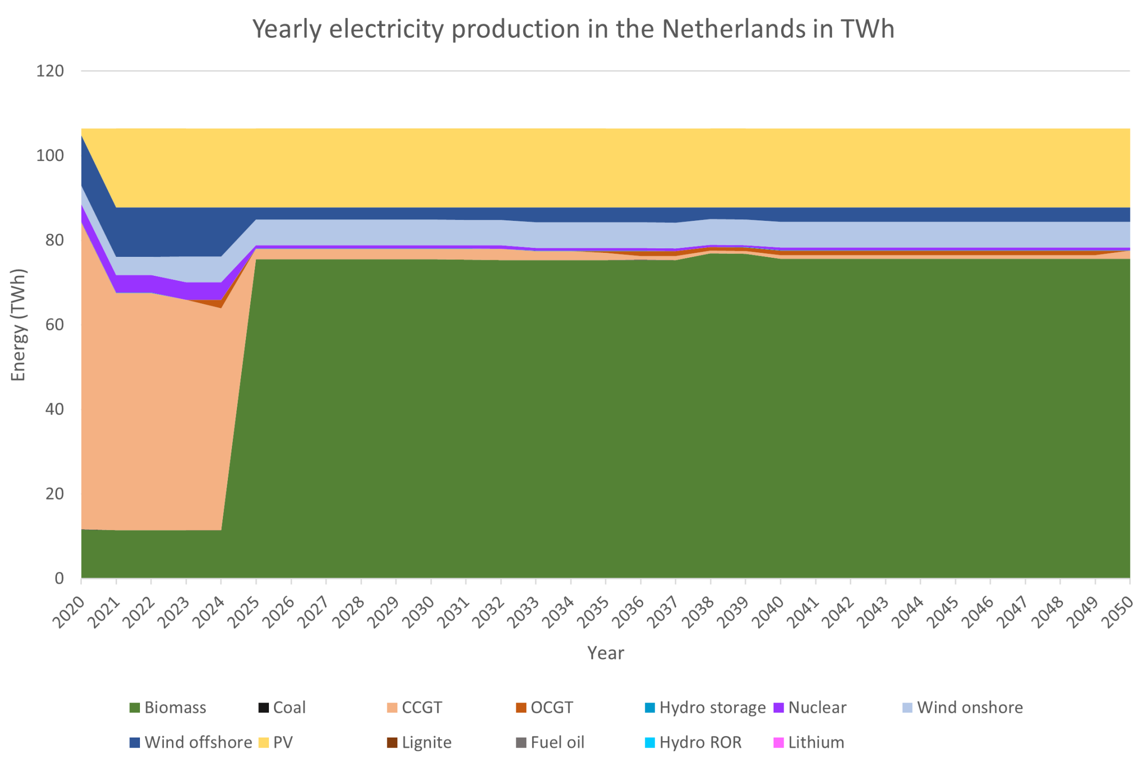

Figure A.8: Electricity production per year in the forward capacity market.

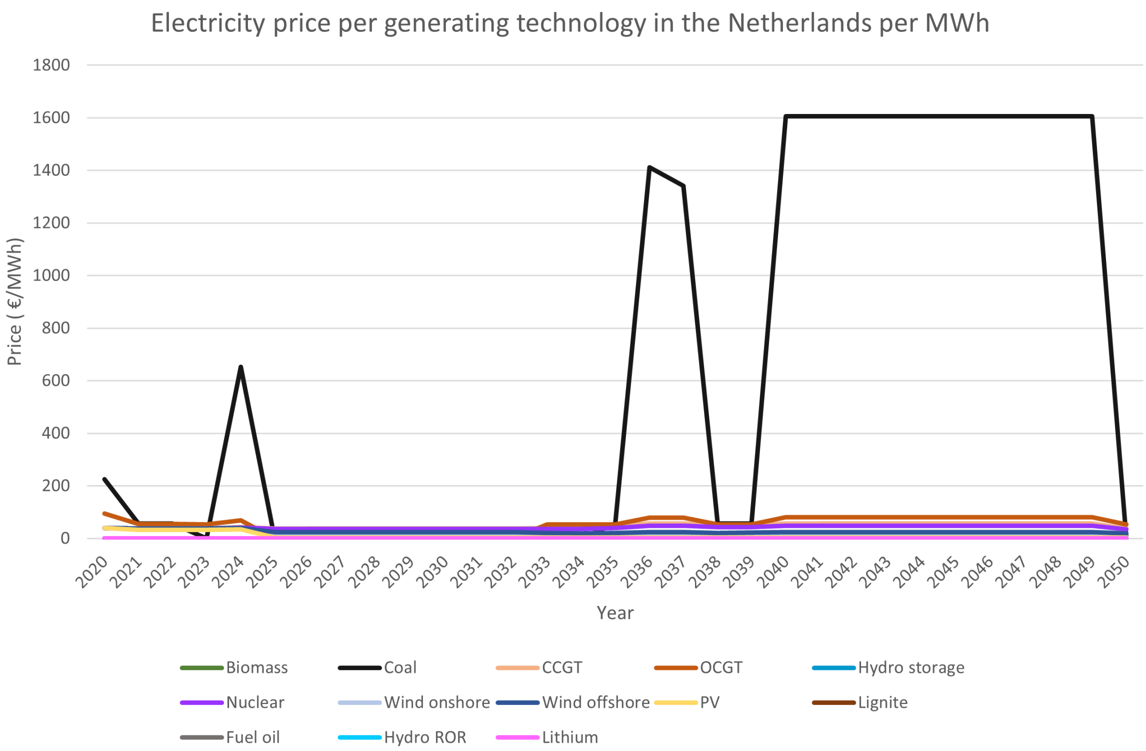

Figure A.9: Electricity price per MWh per year in the forward capacity market.

A.1.4 Strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	2	1.337293	14	1217.89	151054893	2
2021	106494503	4283777379	40.225	84	31155.417	0	1.534276	14	1217.89	57825298	6
2022	106494503	4283777379	40.225	84	31155.417	0	1.534276	14	1217.89	-30964792	6
2023	106494503	4183454986	39.283	85	33155.417	0	1.632768	14	1217.89	-115526783	0
2024	106494503	4157395817	39.039	82	35132.417	0	1.730127	14	1217.99	-25809269	0
2025	106494032	4590356191	43.104	77	33354.417	4	1.642568	14	1217.99	-138963533	11
2026	106494032	4590356191	43.104	77	33354.417	4	1.642568	14	1217.99	-246415126	11
2027	106494032	4590356191	43.104	77	33354.417	4	1.642568	14	1217.99	-348435605	11
2028	106493858	4589833903	43.100	73	33284.217	4	1.639111	10	1217.79	-442926121	11
2029	106493854	4666587698	43.820	75	33282.467	4	1.639025	11	1218.34	-632271413	16
2030	106493534	4665627698	43.811	74	33202.467	4	1.635085	15	1216.33	-714157704	16
2031	106494503	4128432459	38.767	73	36147.467	0	1.780114	12	1217.34	-783887980	0
2032	106494503	4129284748	38.775	73	36122.467	0	1.778883	12	1217.34	-845952467	0
2033	106494503	4129495571	38.777	72	35522.467	0	1.749336	12	1217.34	-925519774	0
2034	106319429	15806705538	148.672	59	30182.067	186	1.486343	11	1214.94	-718073801	316
2035	106319429	15806705538	148.672	70	30182.067	186	1.486343	11	1214.94	-507023095	316
2036	106438570	9341462441	87.764	70	31182.067	71	1.535589	11	1214.94	-469310611	143
2037	106494503	4115848930	38.648	70	42182.067	0	2.077294	11	1214.94	-534702612	0
2038	106494503	4115848930	38.648	70	42182.067	0	2.077294	11	1214.94	-596980708	0
2039	106494503	4115848930	38.648	69	42132.067	0	2.074831	11	1215.34	-651811567	0
2040	106494503	4172344951	39.179	65	37244.067	0	1.834118	10	1214.34	-707033024	0
2041	106494503	4172344951	39.179	65	37244.067	0	1.834118	10	1214.34	-759624887	0
2042	106494503	4172344951	39.179	64	37243.367	0	1.834083	9	1213.64	-809711690	0
2043	106494503	4172344951	39.179	64	37243.367	0	1.834083	9	1213.64	-857413407	0
2044	106494503	4172344951	39.179	63	37099.367	0	1.826992	10	1211.23	-883621294	0
2045	106494503	4175603465	39.210	63	37099.367	0	1.826992	10	1211.23	-926747340	0
2046	106494503	4175603465	39.210	62	37048.967	0	1.824510	7	1217.23	-963810913	0
2047	106494503	4176092231	39.214	62	37048.967	0	1.824510	7	1217.23	-1002930554	0
2048	106494503	4176092231	39.214	61	36919.967	0	1.818157	10	1217.83	-1014800163	0
2049	106494503	4180784508	39.258	60	35919.967	0	1.768911	10	1217.83	-1049997928	0
2050	106494503	4180784508	39.258	57	34856.127	0	1.716521	10	1213.99	-877913518	0

Table A.4: Overview of the simulation results of the strategic reserve.

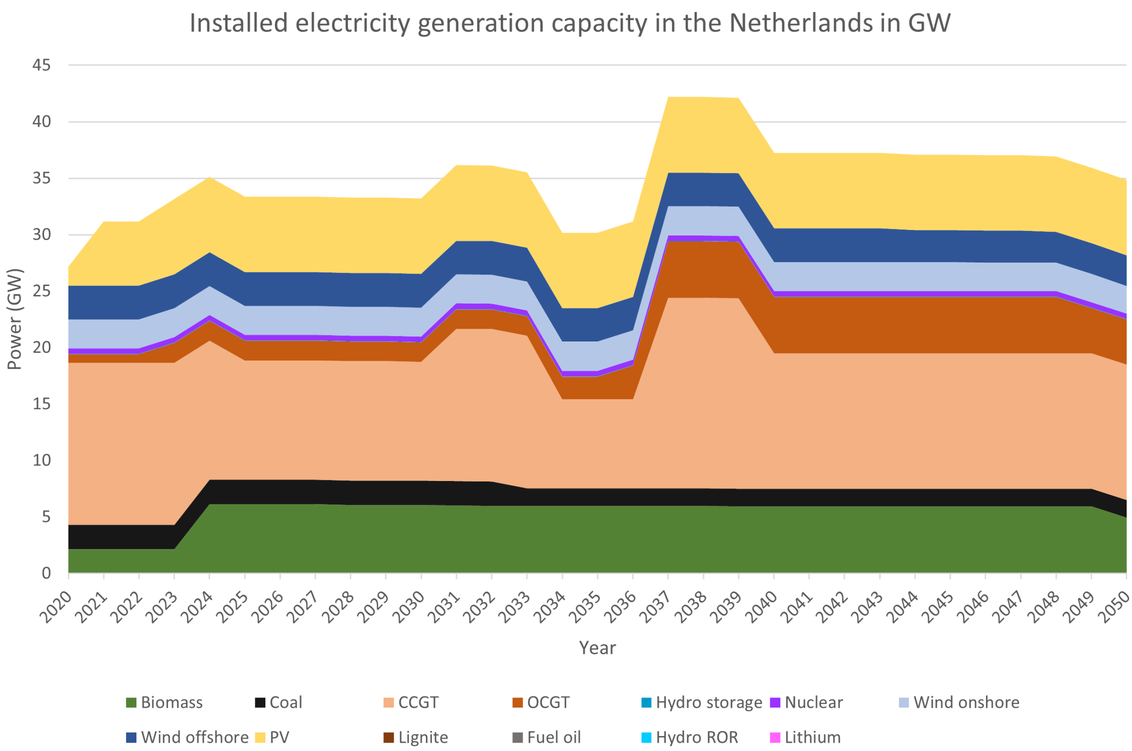

Figure A.10: Installed generation capacity per year in the strategic reserve.

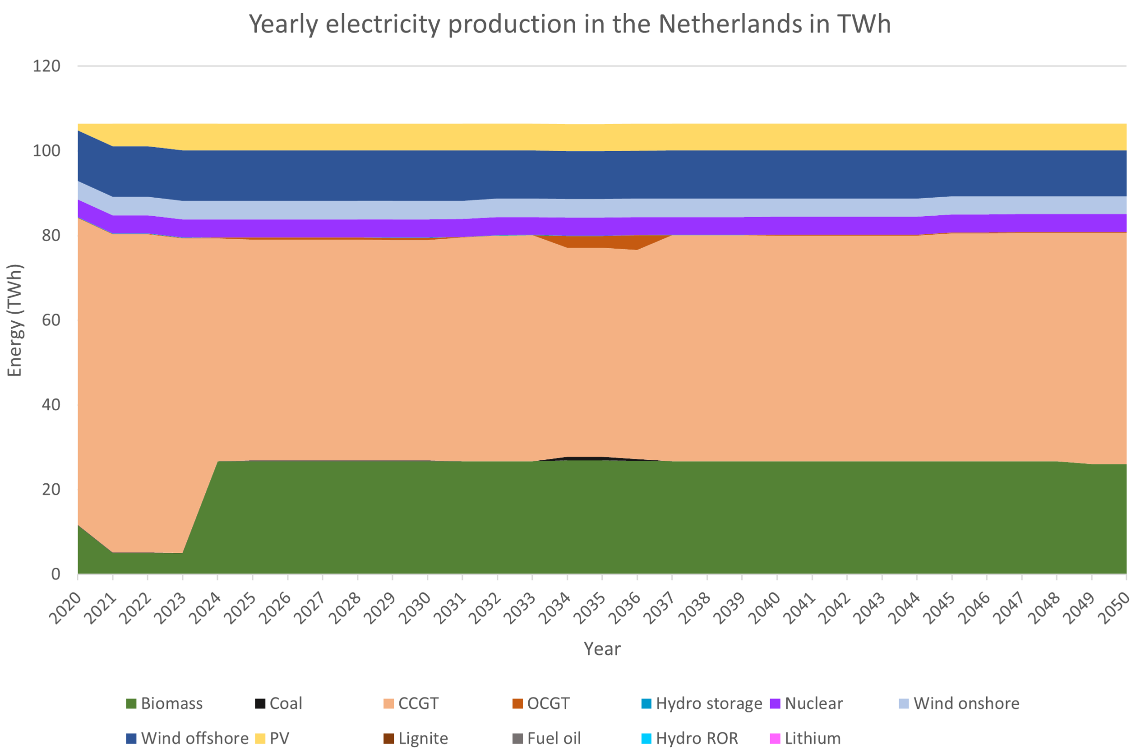

Figure A.11: Electricity production per year in the strategic reserve.

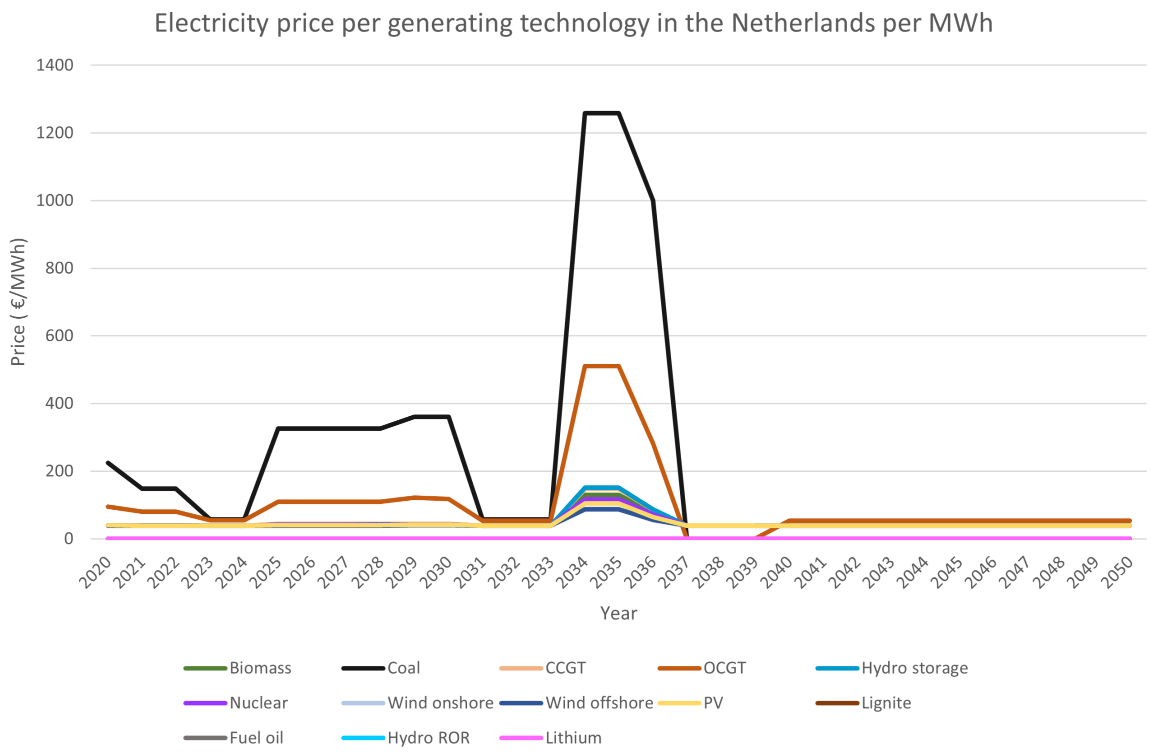

Figure A.12: Electricity price per MWh per year in the strategic reserve.

A.1.5 German strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	2	1.337293	4	1215	112824043	2
2021	106494503	4301402185	40.391	103	35155.417	0	1.731260	4	1215	-136625667	9
2022	106494503	4301402185	40.391	103	35155.417	0	1.731260	4	1215	-385156213	9
2023	106494503	4162100967	39.083	103	37155.417	0	1.829752	4	1215	-633823707	0
2024	106494503	889019301	8.348	100	54146.417	0	2.666489	4	1189	-650378461	0
2025	106494503	889019301	8.348	93	50934.417	0	2.508311	4	1189	-666144893	0
2026	106494503	889019301	8.348	85	48643.417	0	2.395489	3	1182	-680501285	0
2027	106494503	894521228	8.400	81	47145.417	0	2.321718	2	939	-690096922	0
2028	106494503	895089560	8.405	80	47144.217	0	2.321659	2	939	-699235624	0
2029	106494503	895089560	8.405	79	47142.467	0	2.321573	2	939	-707939150	0
2030	106494503	895089560	8.405	78	46842.467	0	2.306799	2	939	-716228223	0
2031	106494503	905038265	8.498	76	46448.467	0	2.287396	1	600	-721472108	0
2032	106494503	907205370	8.519	75	45823.467	0	2.256618	1	1000	-726464605	0
2033	106494503	915972725	8.601	77	43646.467	0	2.149409	1	1000	-742721476	0
2034	106494503	917290616	8.614	76	44644.067	0	2.198537	2	2000	-766546748	0
2035	106494503	924852966	8.685	75	44174.067	0	2.175392	3	3000	-829089700	0
2036	106494503	1509827065	14.178	77	43854.067	0	2.159633	3	3000	-1520877419	36
2037	106494503	1577713230	14.815	76	43804.067	0	2.157171	3	3000	-2218703765	40
2038	106494503	1577713230	14.815	76	43804.067	0	2.157171	3	3000	-2914824510	40
2039	106494503	690976147	6.488	76	45804.067	0	2.255662	3	3000	-3276300669	5
2040	106494503	690976147	6.488	76	45804.067	0	2.255662	3	3000	-3636229799	5
2041	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-4291609212	32
2042	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-4945585423	32
2043	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-5598225253	32
2044	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-6249592337	32
2045	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-6899747284	32
2046	106494503	1413662303	13.275	73	44000.467	0	2.166843	3	3000	-7548747814	32
2047	106494503	1413662303	13.275	94	44000.467	0	2.166843	3	3000	-8196648900	32
2048	106494503	1413662303	13.275	94	44000.467	0	2.166843	3	3000	-8843502895	32
2049	106494503	852921895	8.009	92	45000.467	0	2.216088	3	3000	-9544606378	0
2050	106494503	202339555	1.900	92	63000.467	0	3.102515	3	3000	-9588002918	0

Table A.5: Overview of the simulation results of the German strategic reserve.

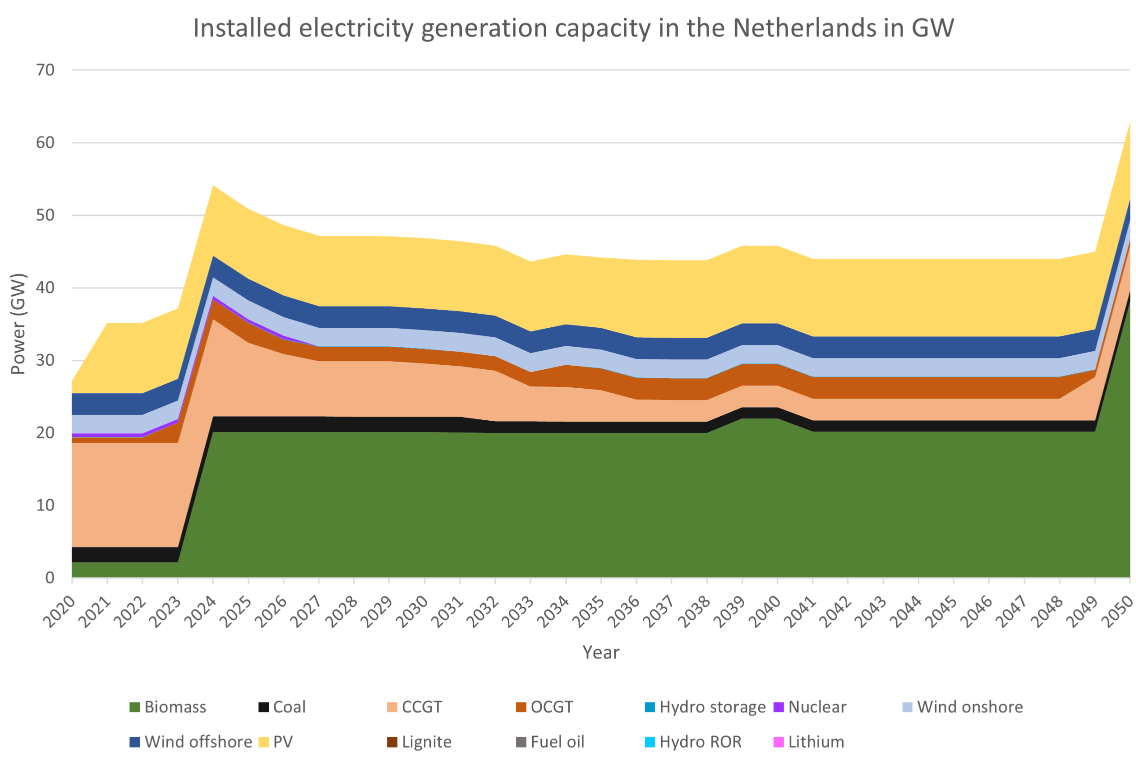

Figure A.13: Installed generation capacity per year in the German strategic reserve.

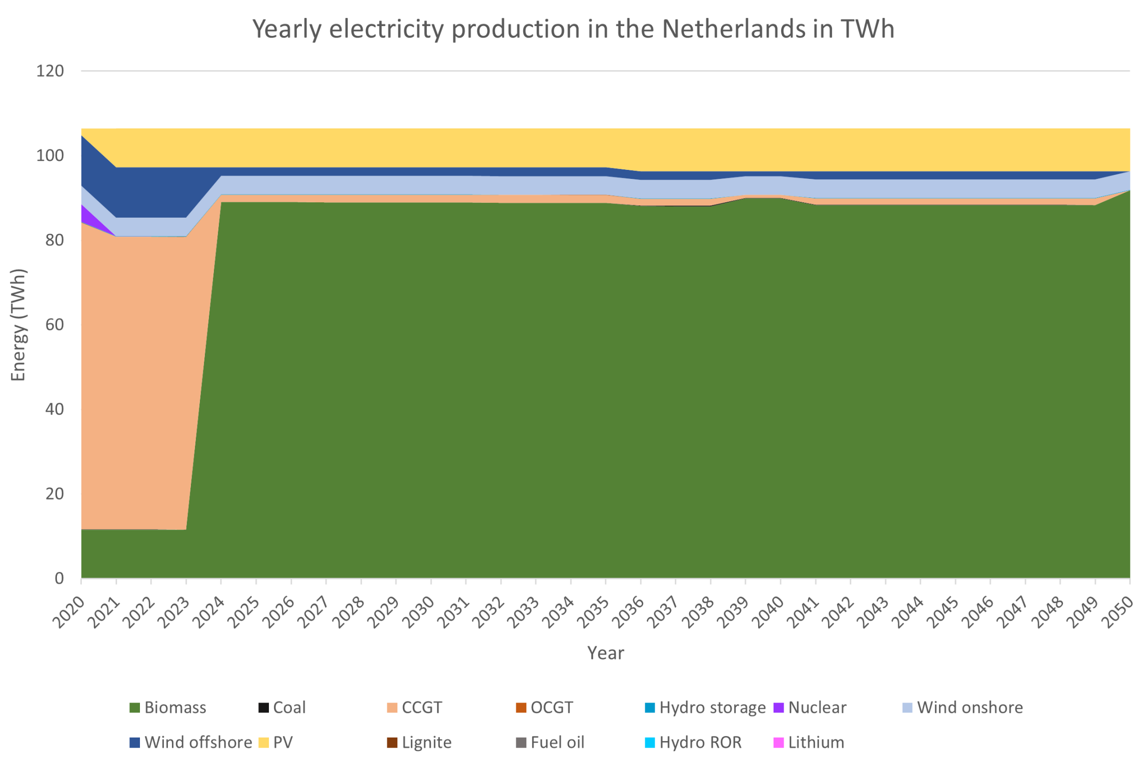

Figure A.14: Electricity production per year in the German strategic reserve.

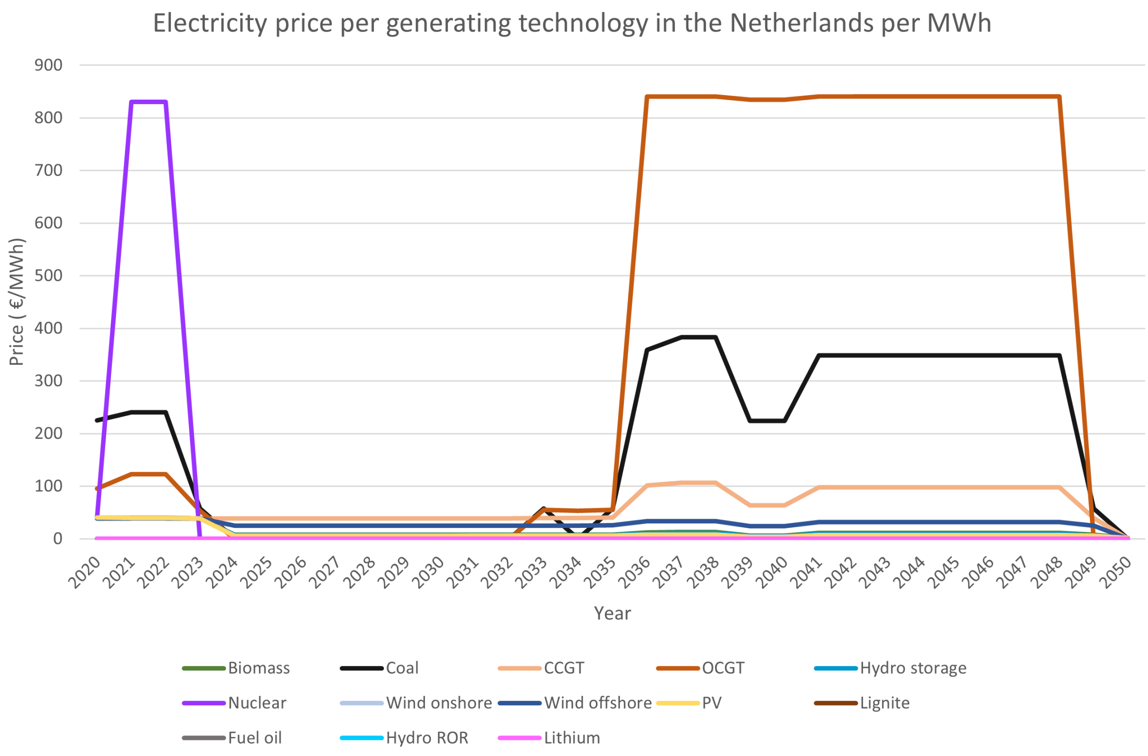

Figure A.15: Electricity price per MWh per year in the German strategic reserve.

A.1.6 Swedish strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	2	1.337293	19	1209.81	41487276	2
2021	106493608	4339132606	40.745	82	27155.417	2	1.337293	19	1209.81	34737301	4
2022	106493608	4339132606	40.745	82	27155.417	2	1.337293	19	1209.81	28344829	4
2023	106494503	4185751079	39.305	82	34155.417	0	1.682014	19	1209.81	21535225	0
2024	106494503	4185751079	39.305	82	34155.417	0	1.682014	19	1209.81	15049888	0
2025	106494503	4519595114	42.440	77	31068.417	0	1.529992	15	1217.85	11312613	0
2026	106494503	4519622186	42.440	73	30301.417	0	1.492220	15	1217.85	5488613	0
2027	106494503	4519622186	42.440	73	30301.417	0	1.492220	15	1217.85	-58054	0
2028	106494503	4519622186	42.440	72	30300.217	0	1.492161	14	1216.65	-5301108	0
2029	106494503	4519622186	42.440	72	30300.217	0	1.492161	14	1216.65	-10294492	0
2030	106494503	4519622186	42.440	72	30300.217	0	1.492161	14	1216.65	-15050096	0
2031	106494503	4519622186	42.440	72	30300.217	0	1.492161	14	1216.65	-19579243	0
2032	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-23892716	0
2033	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-28000786	0
2034	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-31913233	0
2035	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-35639374	0
2036	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-39188079	0
2037	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-42567798	0
2038	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-45786578	0
2039	106494503	4519622186	42.440	71	29700.217	0	1.462614	14	1216.65	-48852083	0
2040	106494503	4519622186	42.440	70	29699.217	0	1.462565	14	1218.05	-51281673	0
2041	106494503	4519877303	42.442	70	29699.217	0	1.462565	14	1218.05	-54086963	0
2042	106494503	4519877303	42.442	69	29698.517	0	1.462530	13	1217.35	-56757980	0
2043	106494503	4519877303	42.442	69	29698.517	0	1.462530	13	1217.35	-59301806	0
2044	106494503	4519877303	42.442	68	29696.117	0	1.462412	13	1216.70	-61327475	0
2045	106494503	4520072200	42.444	68	29696.117	0	1.462412	13	1216.70	-63615007	0
2046	106494503	4520072200	42.444	71	29685.117	0	1.461870	13	1218.29	-65276905	0
2047	106494503	4520072200	42.444	71	29685.117	0	1.461870	13	1218.29	-67361955	0
2048	106494503	4520072200	42.444	69	33682.167	0	1.658709	11	1215.34	-69324106	0
2049	106491081	5206718944	48.893	61	26680.567	11	1.313908	10	1213.74	-67611698	15
2050	106491079	5206715598	48.893	62	26679.727	11	1.313867	9	1212.90	-65812009	15

Table A.6: Overview of the simulation results of the Swedish strategic reserve.

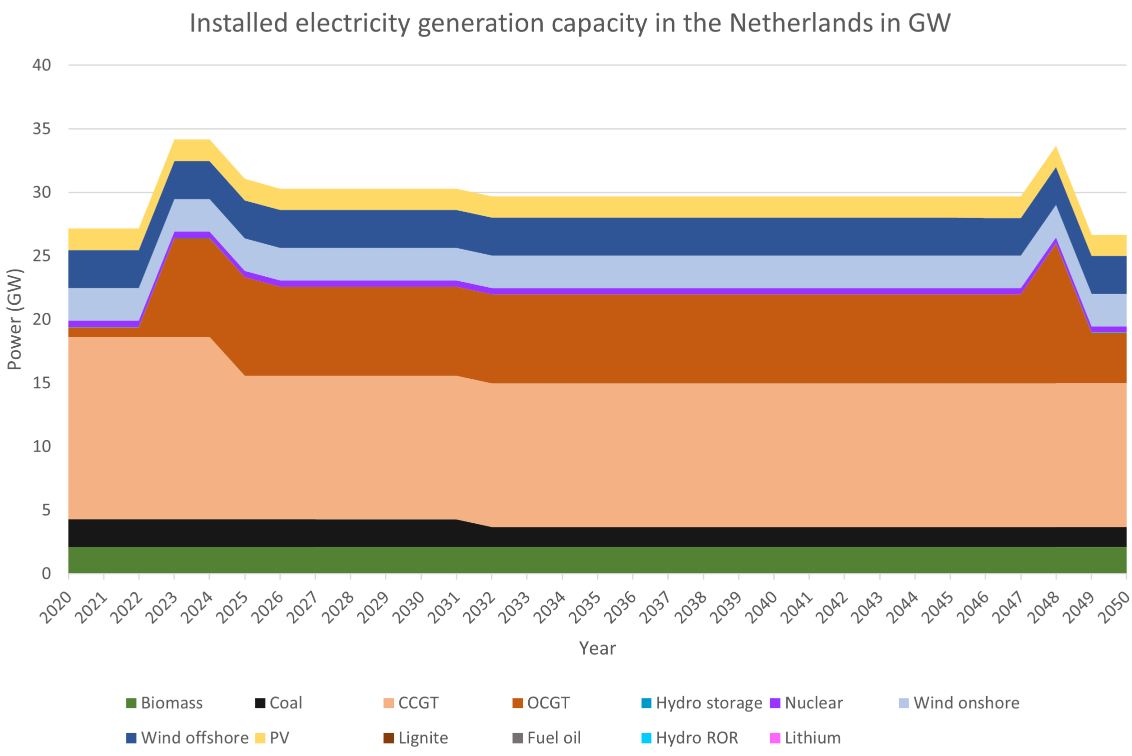

Figure A.16: Installed generation capacity per year in the Swedish strategic reserve.

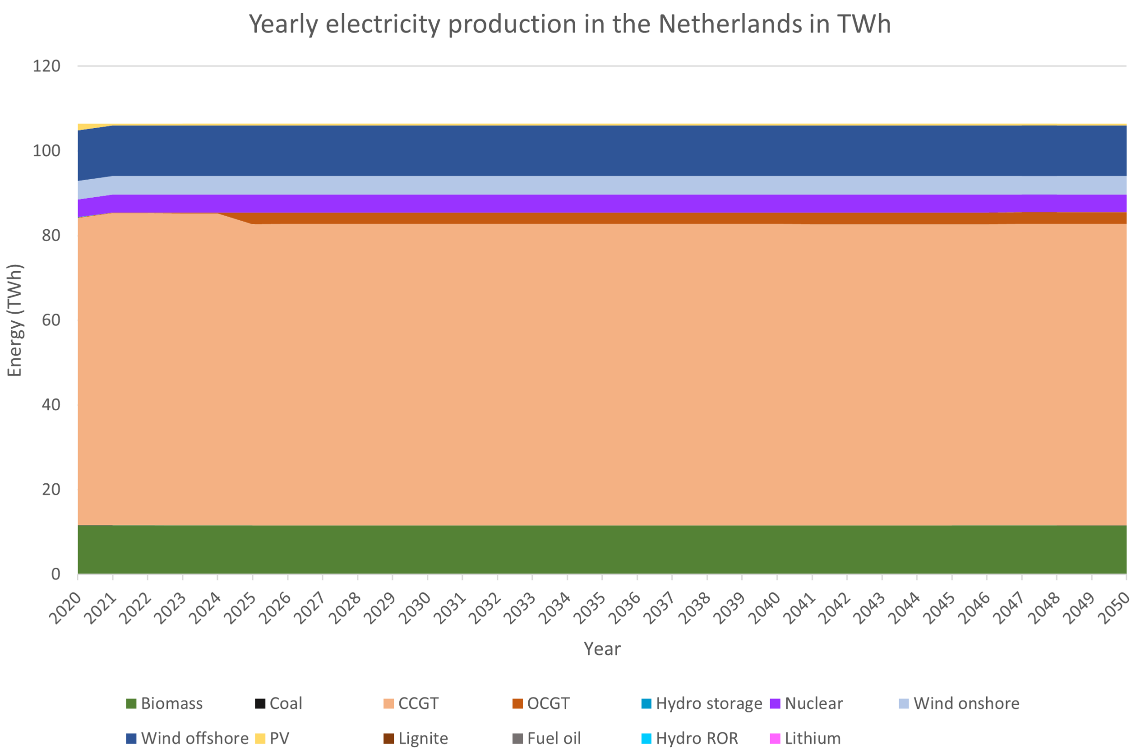

Figure A.17: Electricity production per year in the Swedish strategic reserve.

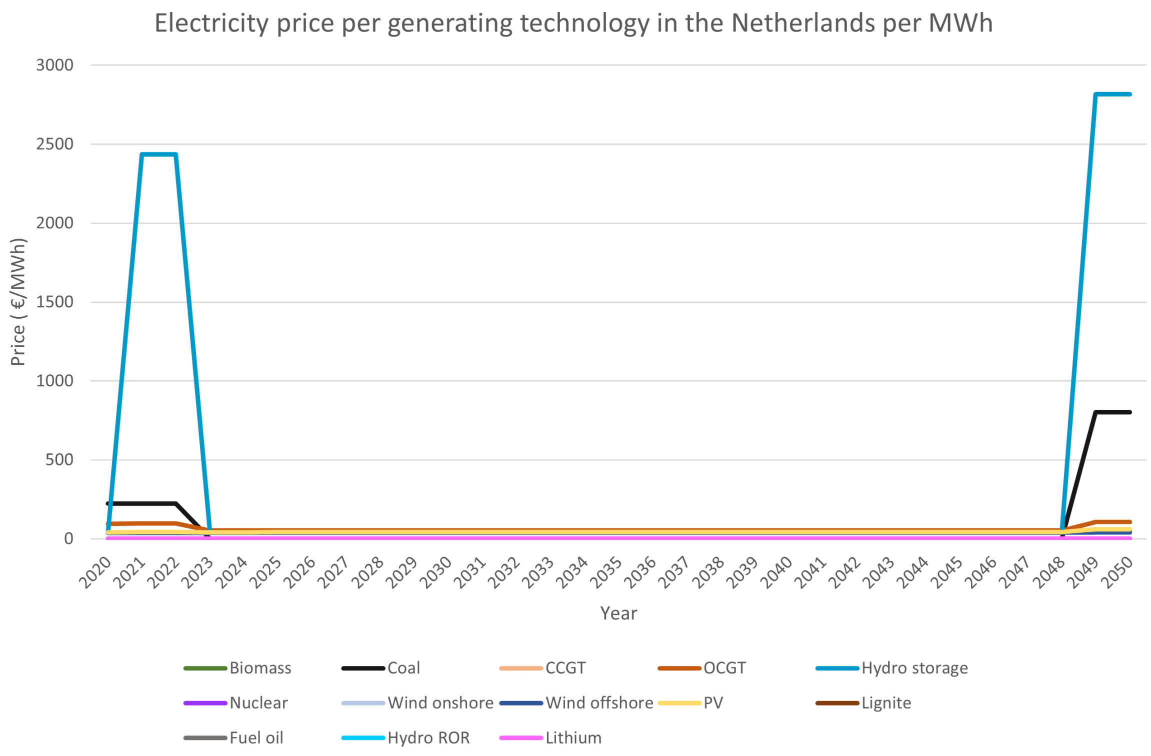

Figure A.18: Electricity price per MWh per year in the Swedish strategic reserve.

A.2 Simulations with descending demand trend

A.2.1 Energy-only market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio
2020	106493608	4172638395	39.1821	75	27155.42	2	1.337293
2021	106064975	3941829317	37.1643	96	42155.42	0	2.084388
2022	105635447	3923298568	37.1400	96	42155.42	0	2.092864
2023	105205919	3889106785	36.9666	96	48155.42	0	2.400503
2024	104776391	3872422612	36.9589	93	47406.42	0	2.372854
2025	104346863	3854287366	36.9373	93	47406.42	0	2.382621
2026	103917336	3837178475	36.9253	93	47406.42	0	2.392469
2027	103487808	3819203063	36.9049	93	47406.42	0	2.402399
2028	103058280	3799865426	36.8710	93	47406.42	0	2.412412
2029	102628752	3782414866	36.8553	93	47406.42	0	2.422509
2030	102199224	3764094421	36.8309	93	47406.42	0	2.432690
2031	101769696	3746804471	36.8165	93	47406.42	0	2.442957
2032	101340169	3729782828	36.8046	92	46806.42	0	2.422261
2033	100910641	3712388977	36.7889	92	46806.42	0	2.432572
2034	100481113	3693667435	36.7598	92	46806.42	0	2.442970
2035	100051585	3676382496	36.7449	92	46806.42	0	2.453458
2036	99622057	3656413532	36.7029	92	46806.42	0	2.464037
2037	99192529	3639072814	36.6870	92	46806.42	0	2.474706
2038	98763002	3619471944	36.6481	92	46806.42	0	2.485469
2039	98333474	3600203440	36.6122	92	46806.42	0	2.496326
2040	97903946	3581069272	36.5774	92	46806.42	0	2.507278
2041	97474418	3562198843	36.5450	92	46806.42	0	2.518326
2042	97044890	3543747240	36.5166	92	46806.42	0	2.529473
2043	96615363	3525244121	36.4874	92	46806.42	0	2.540718
2044	96185835	3506606170	36.4566	92	46806.42	0	2.552064
2045	95756307	3487346323	36.4190	92	46806.42	0	2.563511
2046	95326779	3470205390	36.4033	92	46806.42	0	2.575062
2047	94897251	3452777595	36.3844	92	46806.42	0	2.586718
2048	94467723	3435248066	36.3643	92	46806.42	0	2.598479
2049	94038196	3416717612	36.3333	88	42806.42	0	2.387272
2050	93608668	3399127279	36.3121	88	42806.42	0	2.398226

Table A.7: Overview of the simulation results of the energy-only market.

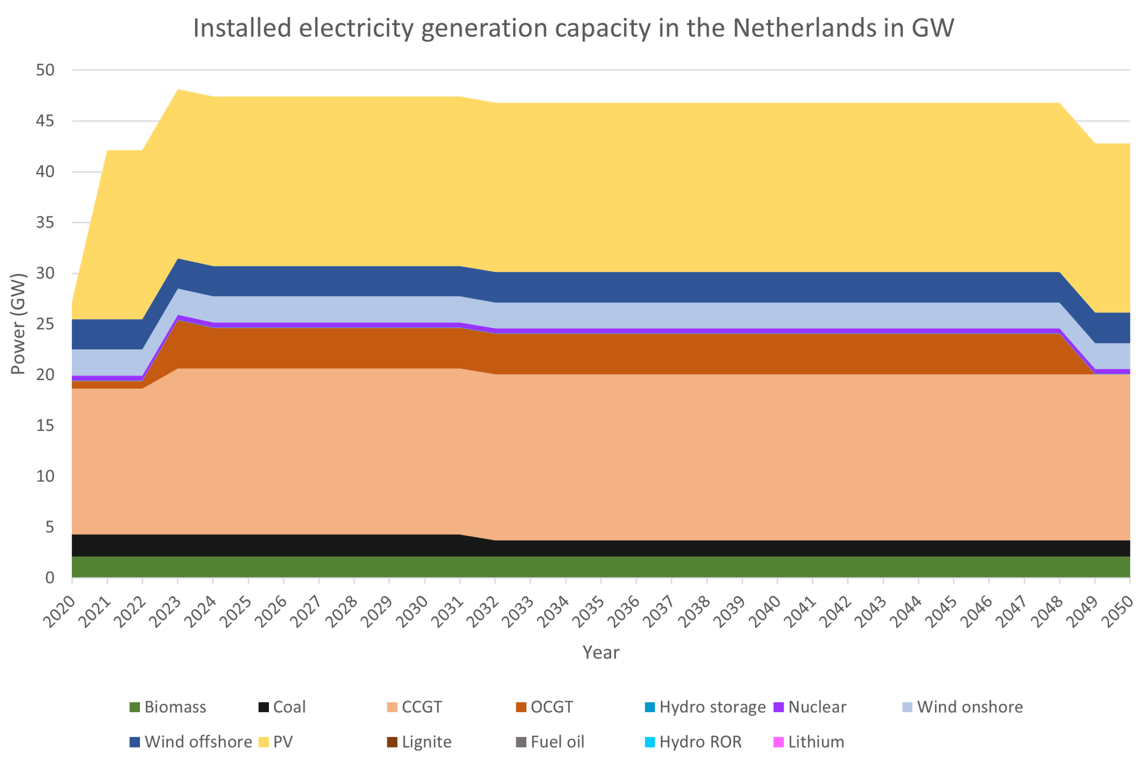

Figure A.19: Installed generation capacity per year in the energy-only market.

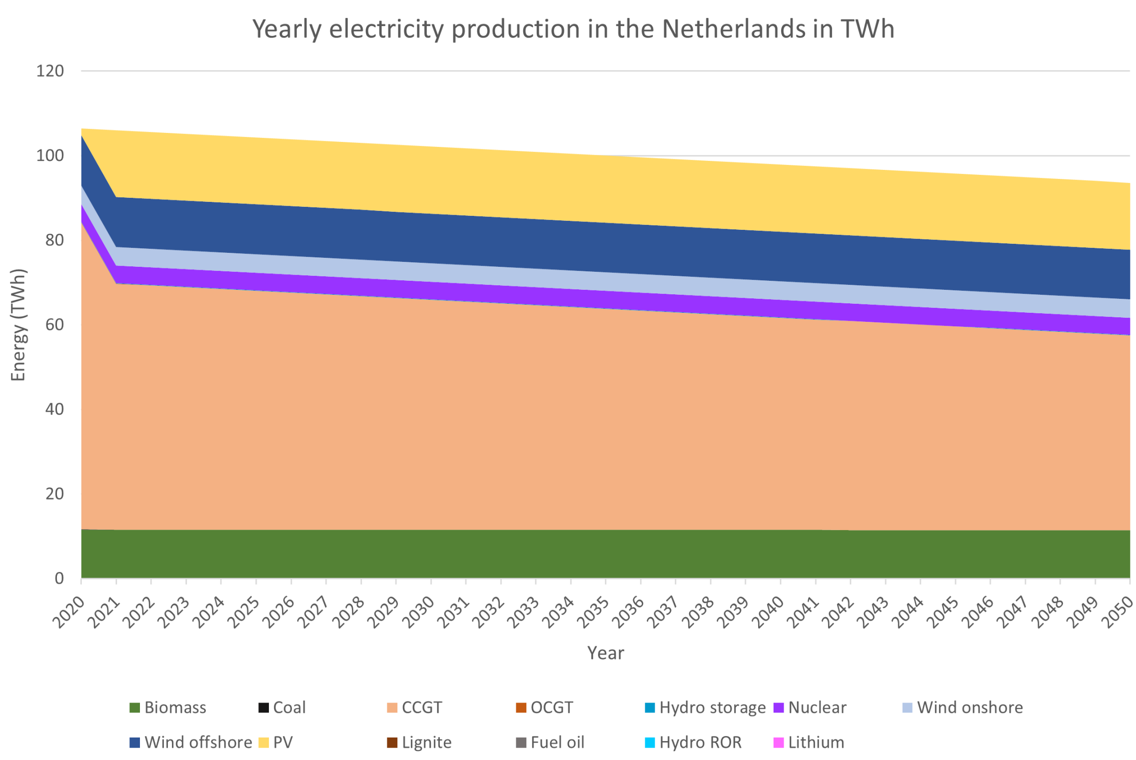

Figure A.20: Electricity production per year in the energy-only market.

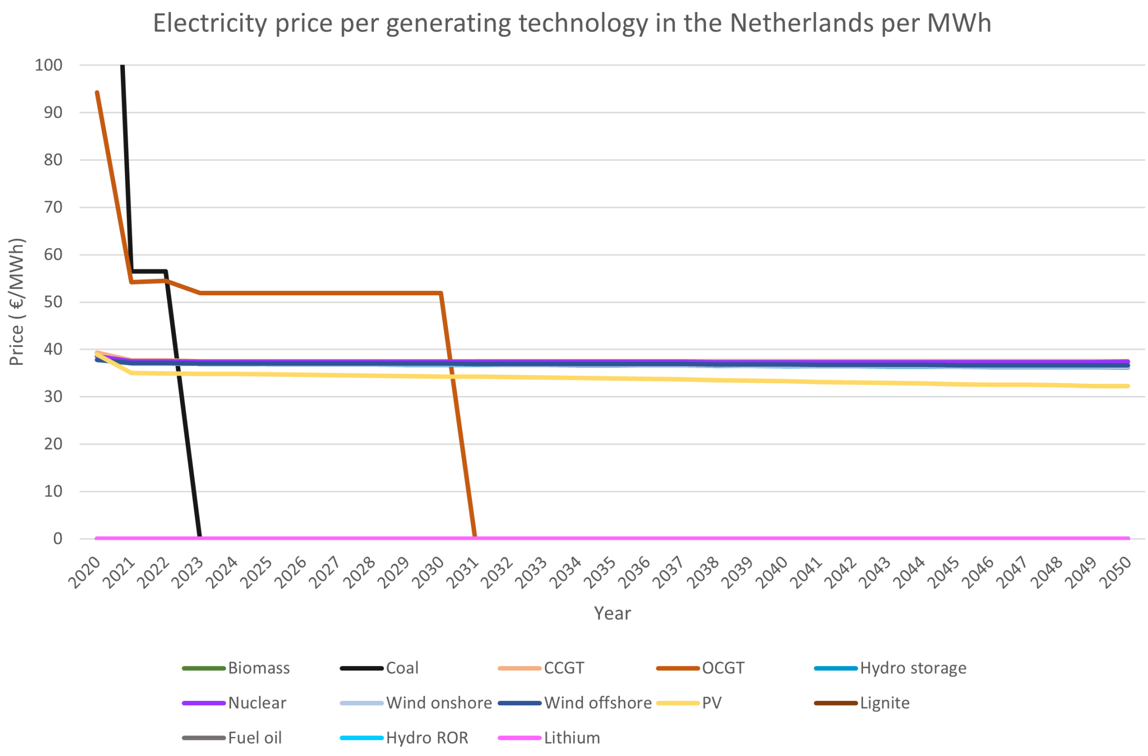

Figure A.21: Electricity price per MWh per year in the energy-only market.

A.2.2 Yearly capacity market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	CM volume (MW)	CM price (€)	CM price per MW (€/MWh)
2020	106493608	4300703079	40.3846	75	27155.42	2	1.337293	19763.37	74464.0	3.768
2021	106064975	4028606105	37.9824	98	44155.42	0	2.183279	21123.37	205378.2	9.723
2022	105635447	4008166704	37.9434	98	44155.42	0	2.192157	21123.37	196412.0	9.298
2023	105205919	3974683398	37.7800	98	50155.42	0	2.500201	22508.60	189018.4	8.398
2024	104776391	3955140175	37.7484	98	50155.42	0	2.510450	22428.62	180466.7	8.046
2025	104346863	3936809975	37.7281	98	50155.42	0	2.520784	22347.95	172350.3	7.712
2026	103917336	3917133222	37.6947	98	50155.42	0	2.531204	22267.18	164058.9	7.368
2027	103487808	3897186822	37.6584	98	50155.42	0	2.541709	22185.77	156162.4	7.039
2028	103058280	3877514422	37.6245	98	50155.42	0	2.552303	22103.78	148641.8	6.725
2029	102628752	3857912059	37.5909	98	50155.42	0	2.562985	22020.69	142069.0	6.452
2030	102199224	3838708685	37.5610	98	50155.42	0	2.573757	21937.60	135247.6	6.165
2031	101769696	3819476419	37.5306	98	50155.42	0	2.584619	21853.74	129045.9	5.905
2032	101340169	3800483170	37.5022	98	50155.42	0	2.595574	21769.66	122858.7	5.644
2033	100910641	3782158246	37.4803	98	50155.42	0	2.606622	21684.87	117269.8	5.408
2034	100481113	3762039199	37.4403	98	50155.42	0	2.617765	21599.91	111656.1	5.169
2035	100051585	3792737827	37.9078	97	46685.42	0	2.447116	21430.86	67780.7	3.163
2036	99622057	3836667301	38.5122	96	45365.42	0	2.388178	21222.03	56009.1	2.639
2037	99192529	3814253867	38.4530	96	45365.42	0	2.398519	21146.56	53208.0	2.516
2038	98763002	3791406917	38.3889	96	45365.42	0	2.408950	21070.20	50535.3	2.398
2039	98333474	3766800864	38.3064	96	45365.42	0	2.419473	20992.98	48146.4	2.293
2040	97903946	3743136285	38.2327	96	45365.42	0	2.430088	20914.96	45784.2	2.189
2041	97474418	3720448480	38.1685	96	45365.42	0	2.440796	20836.17	43545.8	2.090
2042	97044890	3696174315	38.0873	96	45365.42	0	2.451599	20773.37	27218.4	1.310
2043	96615363	3672636472	38.0130	96	45365.42	0	2.462498	20773.37	25858.4	1.245
2044	96185835	3649379355	37.9409	96	45365.42	0	2.473495	20735.60	24587.8	1.186
2045	95756307	3624969935	37.8562	96	45365.42	0	2.484590	20645.82	23476.6	1.137
2046	95326779	3603304837	37.7995	96	45365.42	0	2.495785	20559.14	22226.7	1.081
2047	94897251	3580066838	37.7257	96	45365.42	0	2.507082	20469.80	21173.9	1.034
2048	94467723	3555517169	37.6374	96	45365.42	0	2.518481	20379.34	20226.7	0.993
2049	94038196	3588093775	38.1557	95	44365.42	0	2.474216	20182.48	25675.0	1.272
2050	93608668	3562577679	38.0582	95	44365.42	0	2.485569	20098.32	24452.4	1.217

Table A.8: Overview of the simulation results of the yearly capacity market.

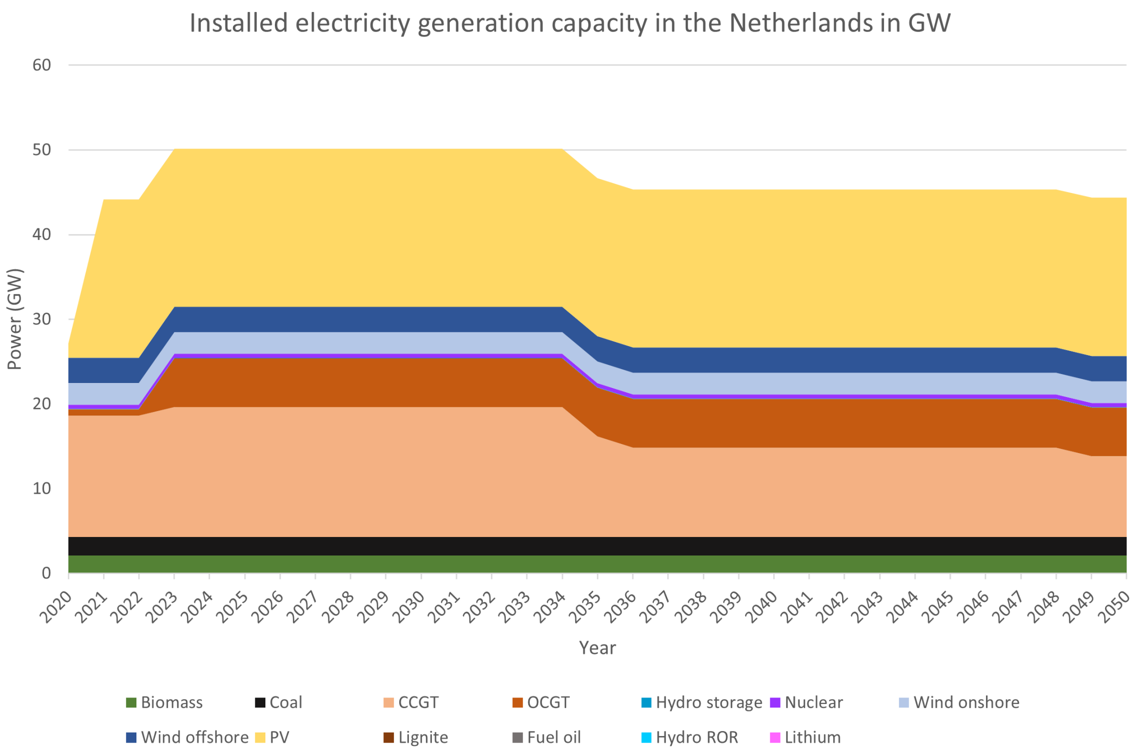

Figure A.22: Installed generation capacity per year in the yearly capacity market.

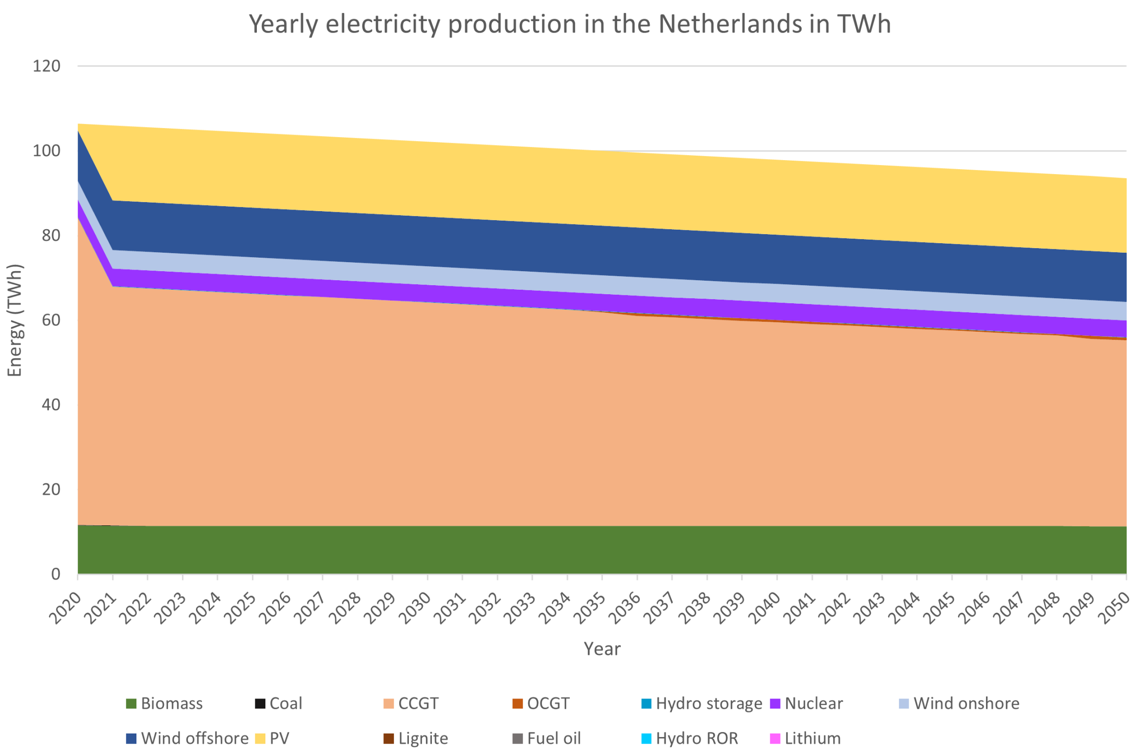

Figure A.23: Electricity production per year in the yearly capacity market.

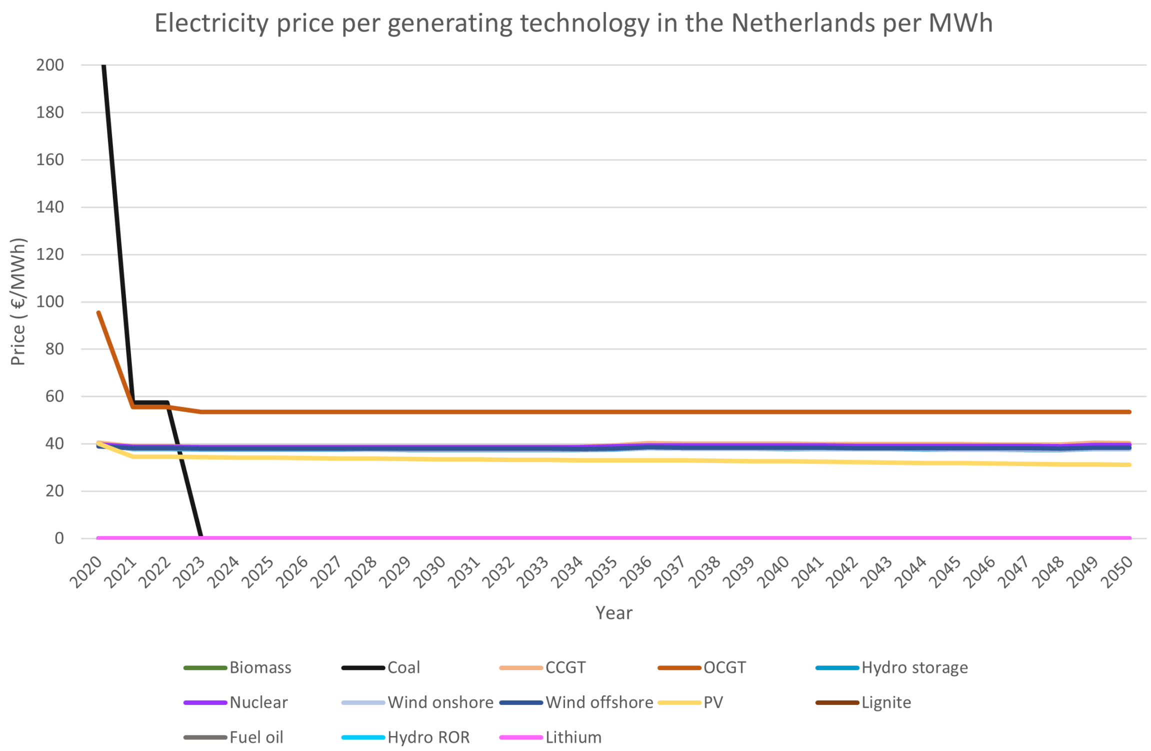

Figure A.24: Electricity price per MWh per year in the yearly capacity market.

A.2.3 Forward capacity market

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	CM volume (MW)	CM price (€)	CM price per MW (€/MWh)
2020	106493608	4300703079	40.3846	75	27155.42	2	1.337293	11222	74463.98	6.636
2021	106064975	4028606105	37.9824	98	44155.42	0	2.183279	17222	211918.98	12.305
2022	105635447	4008166704	37.9434	113	44155.42	0	2.192157	17142	193426.12	11.284
2023	105205919	3974683398	37.7800	113	50155.42	0	2.500201	15766	178599.85	11.328
2024	104776334	4278025545	40.8301	96	43723.42	1	2.188507	15766	68746.91	4.360
2025	104346863	1009466956	9.6741	96	58723.42	0	2.951407	15766	162797.39	10.326
2026	103917336	982804142	9.4576	95	58643.42	0	2.959569	15466	145541.71	9.410
2027	103487808	961288124	9.2889	94	57752.42	0	2.926700	15127	129107.72	8.535
2028	103058280	936605618	9.0881	92	57654.22	0	2.933901	14527	112842.31	7.768
2029	102628752	917492229	8.9399	91	57652.47	0	2.946091	12350	97965.44	7.932
2030	102199224	893082849	8.7386	90	57352.47	0	2.943078	12350	93300.42	7.555
2031	101769696	883629688	8.6826	88	56958.47	0	2.935196	8880	79354.12	8.936
2032	101340169	869739518	8.5824	86	56333.47	0	2.915292	7560	66071.92	8.740
2033	100910641	852660264	8.4497	85	54156.47	0	2.814561	7560	62866.69	8.316
2034	100481113	832009515	8.2803	84	54154.07	0	2.826467	7560	59870.23	7.919
2035	100051585	870893655	8.7044	83	50684.07	0	2.656714	7560	53199.35	7.037
2036	99622057	924420242	9.2793	83	49364.07	0	2.598679	7560	45569.43	6.028
2037	99192529	912663274	9.2009	82	49314.07	0	2.607289	7560	43113.62	5.703
2038	98763002	1045829861	10.5893	81	48583.07	0	2.579811	7560	38433.42	5.084
2039	98333474	1035760848	10.5331	80	48511.47	0	2.587261	7560	36203.52	4.789
2040	97903946	1010906220	10.3255	79	48510.47	0	2.598559	7560	34345.49	4.543
2041	97474418	982819570	10.0828	79	48510.47	0	2.610009	7560	32770.80	4.335
2042	97044890	960787709	9.9004	79	48510.47	0	2.621561	7560	31007.96	4.102
2043	96615363	934794751	9.6754	79	48510.47	0	2.633216	7560	29444.86	3.895
2044	96185835	910190854	9.4628	79	48510.47	0	2.644975	7560	27885.32	3.689
2045	95756307	885115214	9.2434	79	48510.47	0	2.656839	1560	12297.79	7.883
2046	95326779	861605332	9.0384	79	48510.47	0	2.668811	1560	11712.18	7.508
2047	94897251	838820204	8.8392	79	48510.47	0	2.680890	1560	11154.46	7.150
2048	94467723	811789079	8.5933	86	48510.47	0	2.693080	8560	203059.16	23.722
2049	93651699	15044589352	160.6441	94	42510.47	345	2.370767	7000	183272.25	26.182
2050	93608668	664001763	7.0934	94	49510.47	0	2.773820	7000	174456.57	24.922

Table A.9: Overview of the simulation results of the forward capacity market.

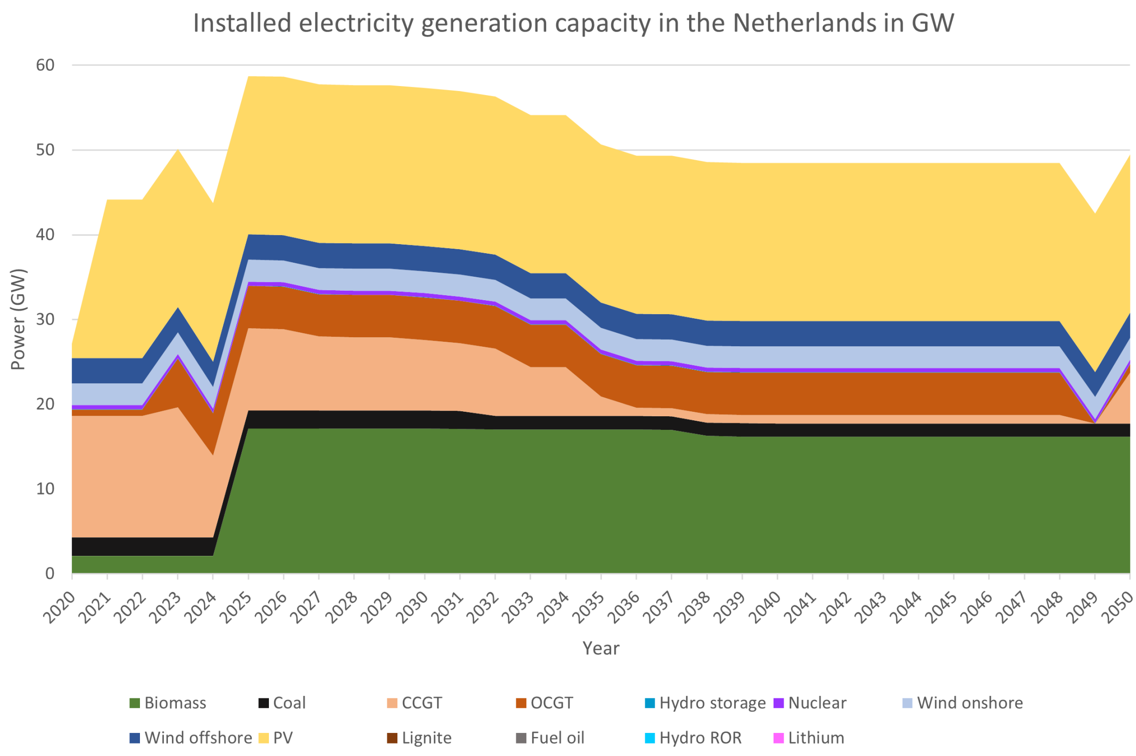

Figure A.25: Installed generation capacity per year in the forward capacity market.

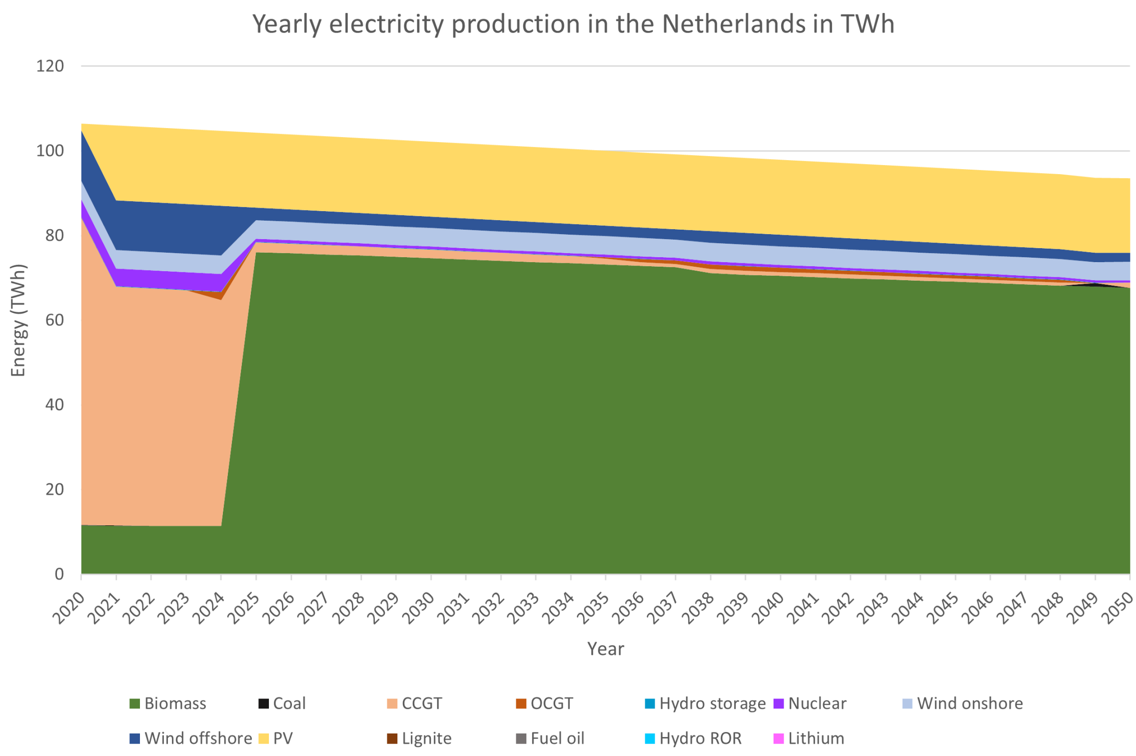

Figure A.26: Electricity production per year in the forward capacity market.

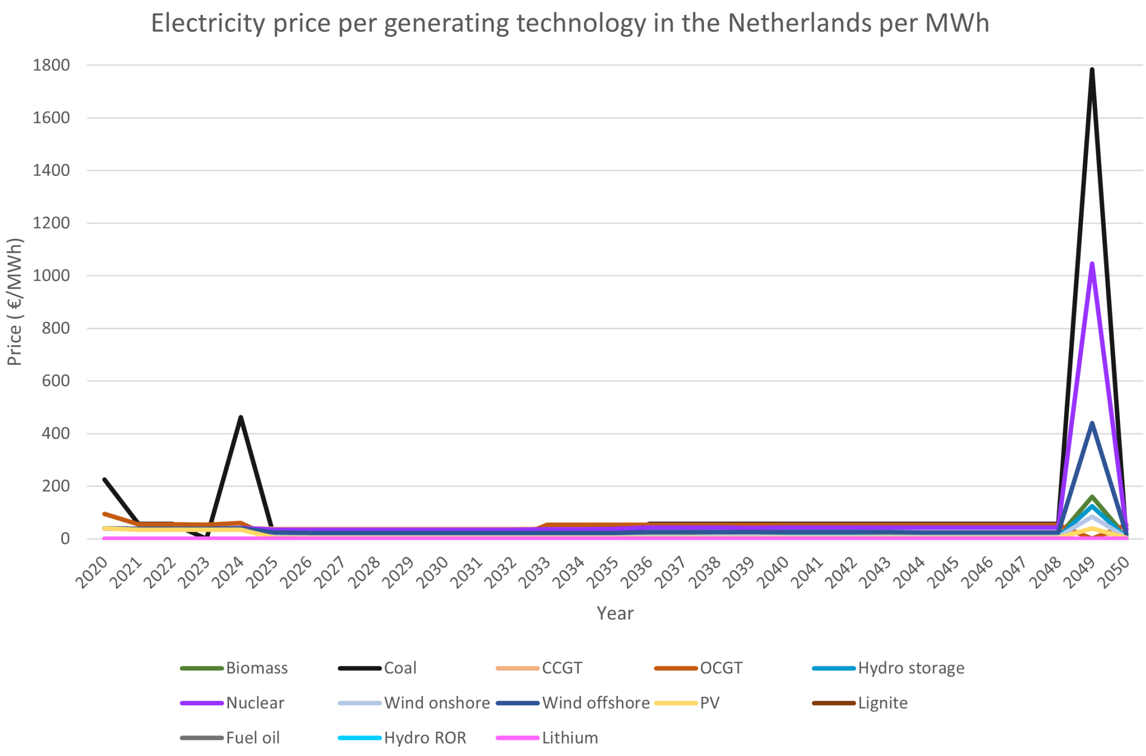

Figure A.27: Electricity price per MWh per year in the forward capacity market.

A.2.4 Strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of elec- tricity (€/MWh)	Number of power plants	Total in- stalled capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	0	1.337293	2	1217.89	151054893	2
2021	106064975	4269773125	40.256	83	30155.417	0	1.491044	0	1212.89	57846130	6
2022	105635447	4232938498	40.071	83	30155.417	0	1.497107	0	1207.95	-30896006	5
2023	105205919	3827086107	36.377	104	52155.417	0	2.599899	0	1203.49	-104907207	0
2024	104776391	3579660624	34.165	98	52438.417	0	2.624722	0	1198.69	-45190053	2
2025	104346801	3609836500	34.595	96	52153.417	0	2.621203	1	1193.39	-163035084	2
2026	103917271	3589703568	34.544	95	52073.417	0	2.628000	1	1188.69	-275258504	2
2027	103486187	3740928766	36.149	92	51133.417	0	2.591271	2	1183.88	-375045132	9
2028	103056812	3707049220	35.971	91	51132.217	0	2.602010	2	1175.09	-474068248	8
2029	102627437	3644223804	35.509	94	51130.467	0	2.612811	2	1173.34	-568323361	5
2030	102198063	3617888711	35.401	94	51130.467	0	2.623792	2	1169.00	-657931558	5
2031	101769696	3351975442	32.937	92	55055.467	0	2.837130	0	1161.33	-741526659	0
2032	101340169	3332516895	32.884	90	54430.467	0	2.816811	0	1158.74	-817899033	0
2033	100910641	3372990366	33.426	92	51614.467	0	2.682451	0	1154.33	-890931676	2
2034	100472061	4407282498	43.866	86	49532.067	0	2.585230	14	1144.93	-943880272	39
2035	100051585	3289496166	32.878	88	54532.067	0	2.858415	0	1133.93	-1014470737	0
2036	99622057	3245179700	32.575	88	57532.067	0	3.028668	0	1133.93	-1081699752	0
2037	99192529	3221390416	32.476	87	59482.067	0	3.144882	0	1134.24	-1129653168	0
2038	98763002	3223640510	32.640	84	54342.067	0	2.885620	0	1129.60	-1168889945	0
2039	98333474	3204425243	32.587	84	54342.067	0	2.898224	0	1124.84	-1225961134	0
2040	97903946	3180973598	32.491	83	54341.067	0	2.910886	0	1120.04	-1273520052	0
2041	97474418	3149054593	32.306	83	54341.067	0	2.923713	0	1114.64	-1324977597	0
2042	97044890	3125604513	32.208	83	54341.067	0	2.936654	0	1110.04	-1373883783	0
2043	96615363	3100151508	32.088	83	54341.067	0	2.949709	0	1105.34	-1420525699	0
2044	96185835	3077985784	32.000	83	54341.067	0	2.962882	0	1099.73	-1460199635	0
2045	95756307	3055448124	31.909	83	54341.067	0	2.976172	0	1093.93	-1501582390	0
2046	95326779	3030594845	31.792	83	54341.067	0	2.989582	0	1082.93	-1541770071	0
2047	94897251	3009612503	31.714	82	54340.367	0	3.003075	0	1082.23	-1580043515	0
2048	94467723	2987912774	31.629	81	54289.967	0	3.013932	0	1080.64	-1613129674	0
2049	94038196	2968107491	31.563	78	53287.167	0	2.971773	0	1075.64	-1647831819	0
2050	93608668	2946457042	31.476	76	52286.327	0	2.929337	0	1068.60	-1518772235	0

Table A.10: Overview of the simulation results of the strategic reserve.

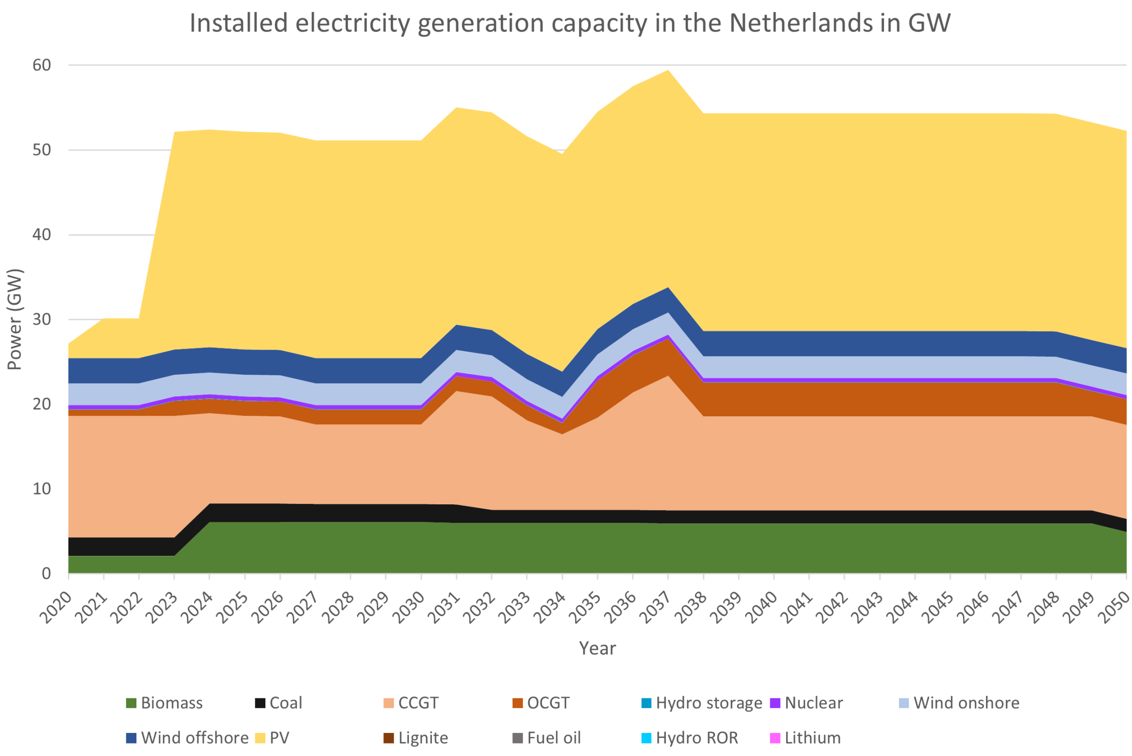

Figure A.28: Installed generation capacity per year in the strategic reserve.

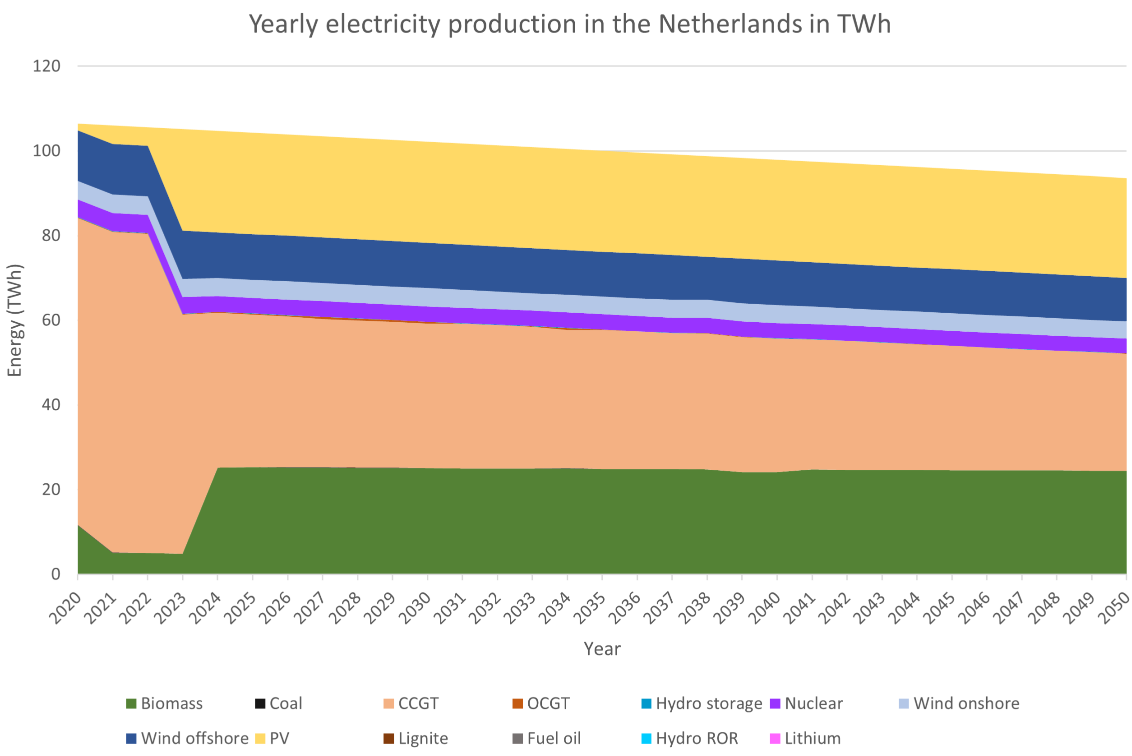

Figure A.29: Electricity production per year in the strategic reserve.

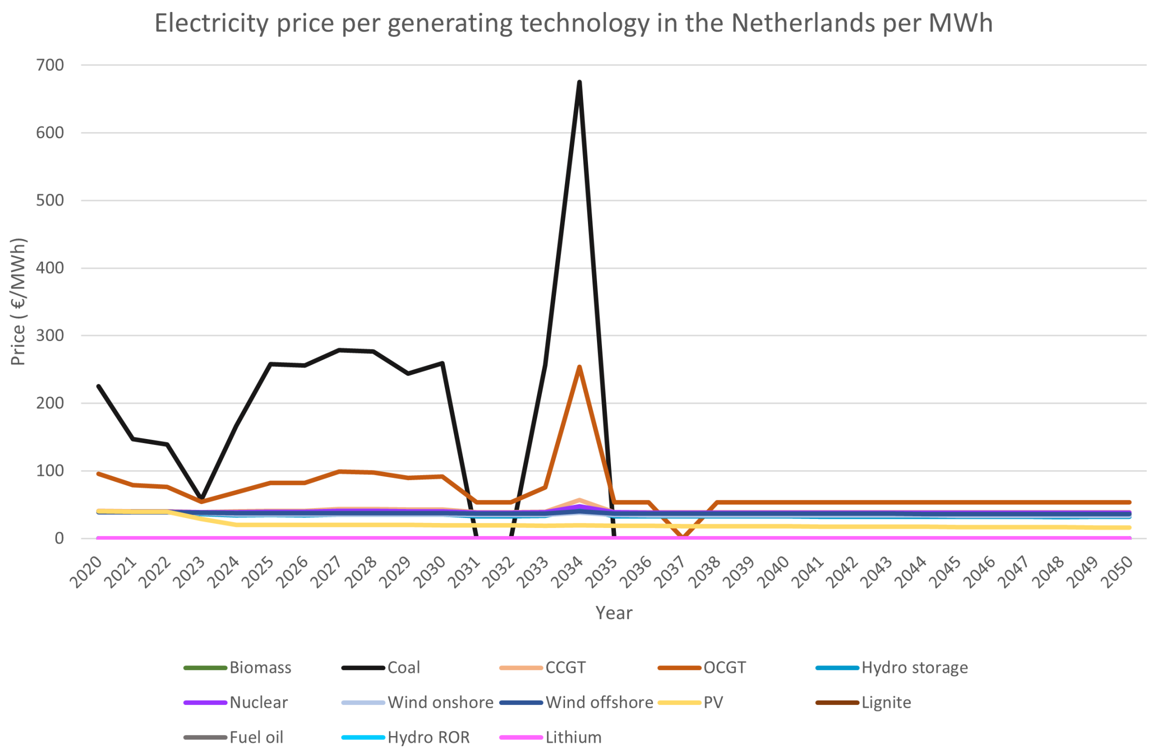

Figure A.30: Electricity price per MWh per year in the strategic reserve.

A.2.5 German strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	2	1.337293	4	1215	112824043	2
2021	106064975	4285469844	40.404	102	34155.417	0	1.688826	4	1215	-142500234	9
2022	105635447	4250297116	40.236	102	34155.417	0	1.695693	4	1215	-392343348	8
2023	105205919	4108178621	39.049	102	36155.417	0	1.802314	4	1215	-637248883	0
2024	104776391	832947829	7.950	98	52082.417	0	2.606903	4	1189	-653803637	0
2025	104346863	811083814	7.773	91	49831.417	0	2.504500	4	1189	-669570070	0
2026	103917336	791812926	7.620	84	47643.417	0	2.404430	3	1182	-683926461	0
2027	103487808	778570356	7.523	80	46145.417	0	2.338496	2	939	-693522099	0
2028	103058280	753322787	7.310	79	46144.217	0	2.348181	2	939	-702660801	0
2029	102628752	733545457	7.148	78	46142.467	0	2.357920	2	939	-711364327	0
2030	102199224	714003157	6.986	77	45842.467	0	2.352435	2	939	-719653399	0
2031	101769696	702469918	6.903	75	45448.467	0	2.342060	1	600	-724897285	0
2032	101340169	691197264	6.821	73	44823.467	0	2.319643	1	1000	-729889781	0
2033	100910641	671536969	6.655	74	42646.467	0	2.216376	1	1000	-736256323	0
2034	100481113	652627478	6.495	73	42644.067	0	2.225725	1	1000	-742124877	0
2035	100051585	644178637	6.438	72	41174.067	0	2.158227	2	2000	-795928116	0
2036	99622057	1122281629	11.265	72	40854.067	0	2.150686	2	2000	-1186334581	32
2037	99192529	1082462890	10.913	71	40804.067	0	2.157356	2	2000	-1567512841	30
2038	98762872	1476410943	14.949	70	40073.067	1	2.127921	2	2000	-2037932048	48
2039	98333422	1410704635	14.346	70	40073.067	1	2.137216	2	2000	-2490077025	45
2040	97903946	1316639596	13.448	70	40073.067	0	2.146593	2	2000	-2927724209	43
2041	97474418	1188873374	12.197	70	40073.067	0	2.156052	2	2000	-3351595176	35
2042	97044890	1135078812	11.696	70	40073.067	0	2.165595	2	2000	-3757511331	33
2043	96615363	1081240308	11.191	70	40073.067	0	2.175222	2	2000	-4145635885	31
2044	96185835	1021629582	10.621	70	40073.067	0	2.184936	2	2000	-4517082359	28
2045	95756307	931153664	9.724	70	40073.067	0	2.194737	2	2000	-4874015351	23
2046	95326779	865037618	9.074	70	40073.067	0	2.204626	2	2000	-5215715989	20
2047	94897251	521938430	5.500	97	55073.067	0	3.043567	2	2000	-5435180119	7
2048	94467684	946849548	10.023	97	53248.467	1	2.956112	2	2000	-5820630454	23
2049	94038196	594135614	6.318	98	63248.467	0	3.527305	1	1000	-6209907161	0
2050	93607042	4677651046	49.971	80	48248.467	2	2.703116	1	1000	-5830239808	12

Table A.11: Overview of the simulation results of the German strategic reserve.

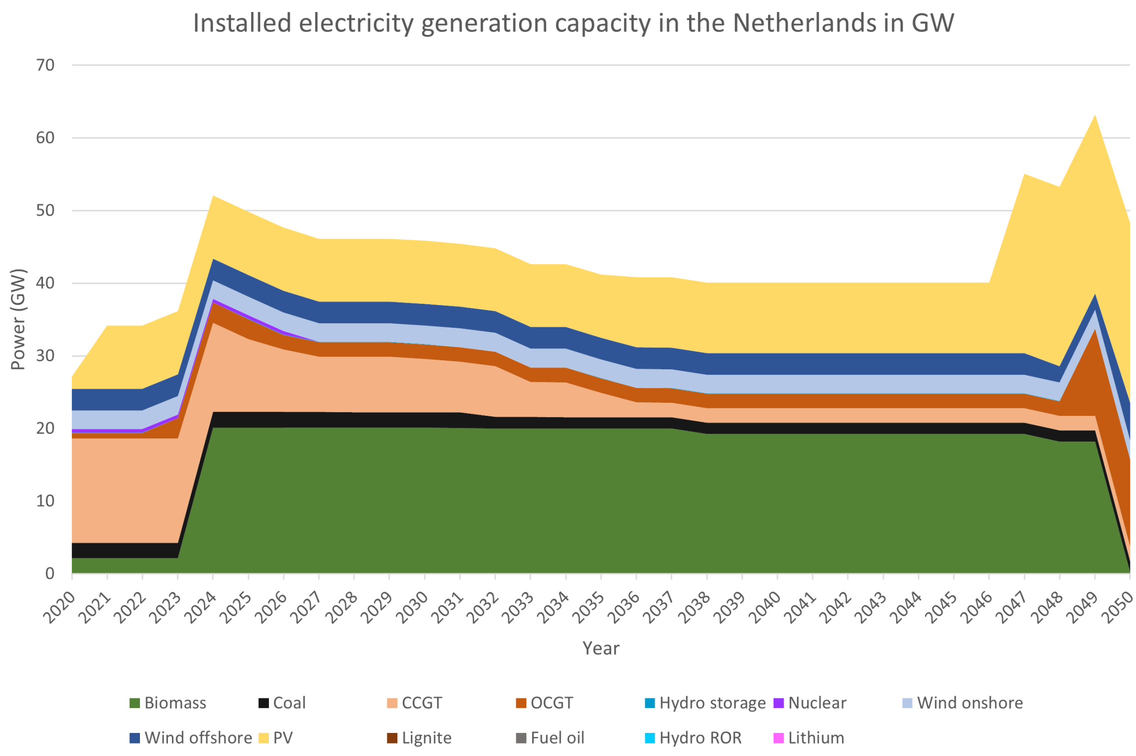

Figure A.31: Installed generation capacity per year in the German strategic reserve.

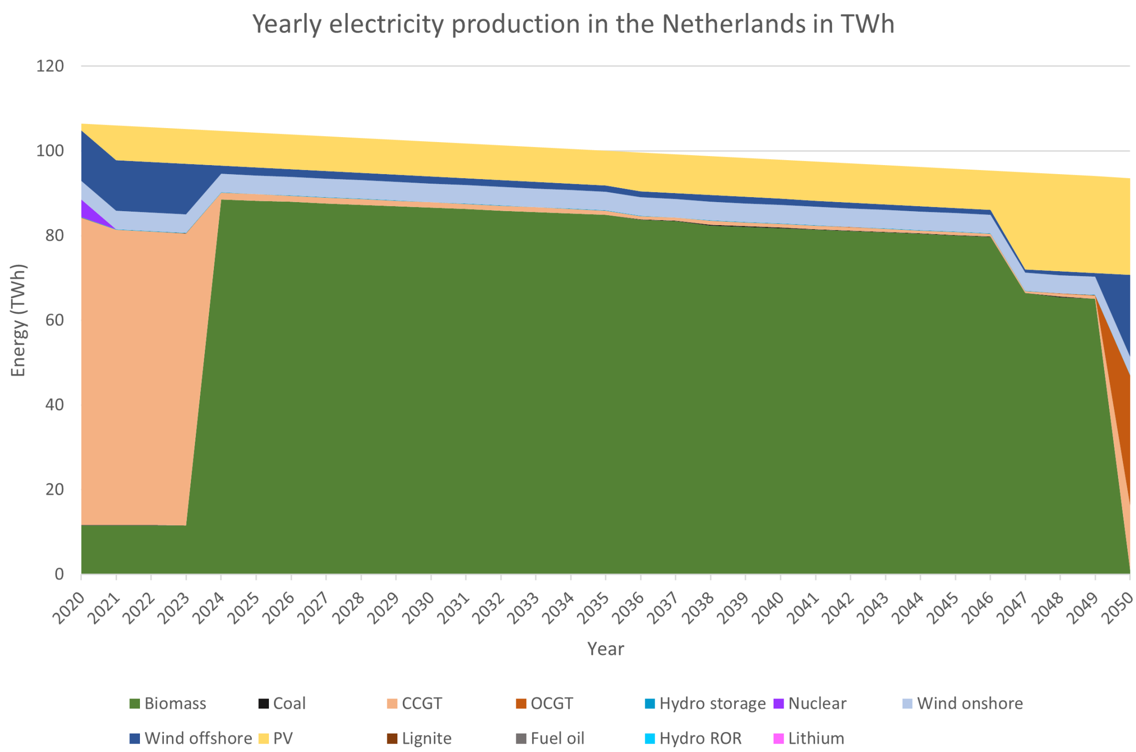

Figure A.32: Electricity production per year in the German strategic reserve.

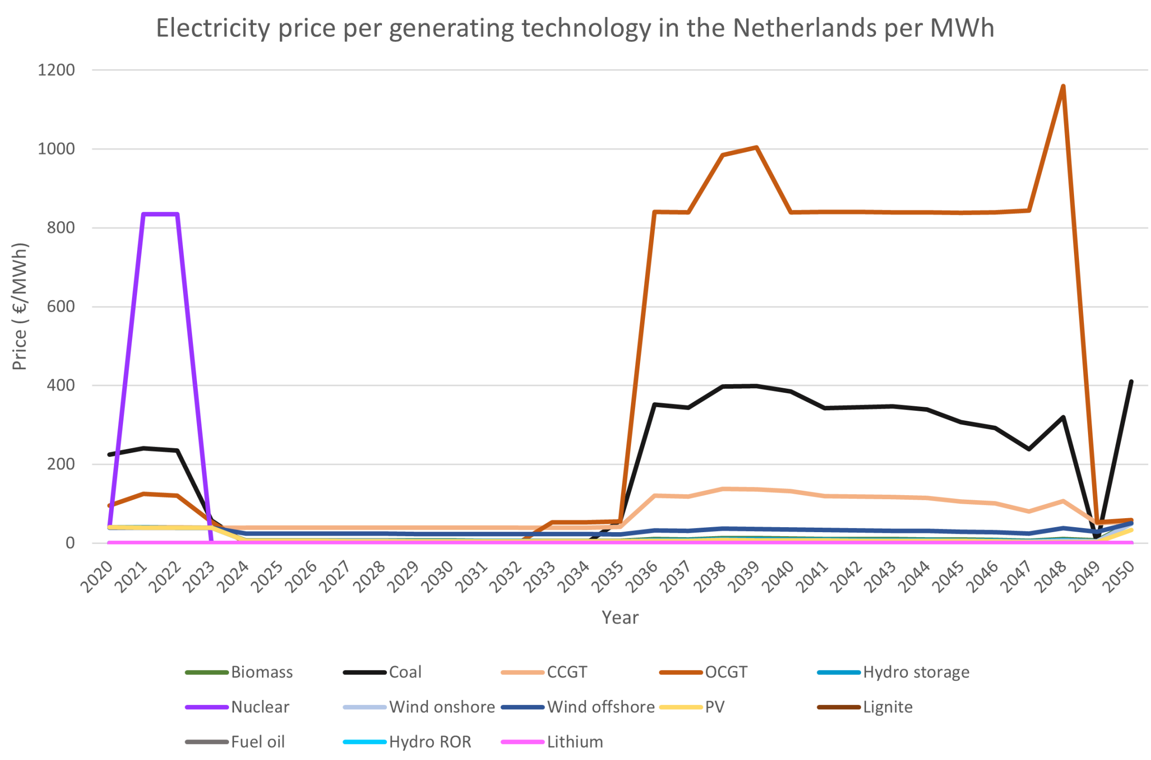

Figure A.33: Electricity price per MWh per year in the German strategic reserve.

A.2.6 Swedish strategic reserve

Year	Market clearing volume (MWh)	Market clearing price (€)	Average price of electricity (€/MWh)	Number of power plants	Total installed capacity (MW)	Shortage hours	Supply ratio	Number of power plants in SR	SR volume (MW)	SR operator cash (€)	Number of hours SR activated
2020	106493608	4300703079	40.385	75	27155.417	2	1.337293	19	1209.81	41487276	2
2021	106064242	4319507899	40.725	82	27155.417	2	1.342708	19	1209.81	34737301	4
2022	105634876	4269240793	40.415	82	27155.417	2	1.348168	18	1208.06	28421082	2
2023	105205919	4128624176	39.243	83	34155.417	0	1.702616	15	1203.46	21949530	0
2024	104776391	4107110634	39.199	83	34155.417	0	1.709596	18	1191.81	16799732	0
2025	104346863	4418143006	42.341	75	31364.417	0	1.576359	14	1193.71	139959038	0
2026	103917336	4431938109	42.649	72	30615.417	0	1.545075	17	1175.06	106894829	0
2027	103487808	4404228010	42.558	72	30615.417	0	1.551487	17	1175.06	73147341	0
2028	103058280	4378267921	42.483	72	30615.417	0	1.557954	17	1175.06	41006877	0
2029	102628752	4353160603	42.417	72	30615.417	0	1.564474	16	1173.86	10434517	0
2030	102199224	4325133748	42.321	69	30594.467	0	1.569974	14	1154.11	-18586058	0
2031	101769696	4298131049	42.234	69	30594.467	0	1.576601	14	1154.11	-46224701	0
2032	101340169	4271060445	42.146	68	29994.467	0	1.552233	14	1154.11	-72547217	0
2033	100910641	4243273811	42.050	68	29994.467	0	1.558840	14	1154.11	-97616281	0
2034	100481113	4217552207	41.974	67	29992.067	0	1.565378	13	1143.31	-118486910	0
2035	100051585	4190268508	41.881	67	29992.067	0	1.572098	13	1143.31	-141027352	0
2036	99622057	4162300265	41.781	67	29992.067	0	1.578876	13	1125.31	-157589587	0
2037	99192529	4138594283	41.723	67	29992.067	0	1.585713	13	1125.31	-178212125	0
2038	98763002	4111592922	41.631	67	29992.067	0	1.592610	13	1125.31	-197852638	0
2039	98333474	4084683621	41.539	67	29992.067	0	1.599566	13	1121.31	-212159320	0
2040	97903946	4061207987	41.482	65	29967.067	0	1.605245	11	1100.31	-229696071	0
2041	97474418	4030452594	41.349	65	29967.067	0	1.612318	11	1100.31	-246397739	0
2042	97044890	4003839935	41.258	64	29966.367	0	1.619417	10	1099.61	-262303402	0
2043	96615363	3975480283	41.147	64	29966.367	0	1.626616	10	1099.61	-277451653	0
2044	96185835	3949534023	41.061	64	29966.367	0	1.633880	10	1099.61	-291878559	0
2045	95756307	3922617294	40.965	64	29966.367	0	1.641209	8	1094.21	-305611055	0
2046	95326779	3895732825	40.867	66	29955.367	0	1.647999	9	1088.61	-318476553	0
2047	94897251	3867870092	40.759	66	29955.367	0	1.655458	8	1084.81	-330926878	0
2048	94467723	3841694994	40.667	65	32954.167	0	1.829465	7	1074.82	-342623063	0
2049	94037814	3921613141	41.703	58	25954.167	2	1.447438	7	1074.82	-353565135	2
2050	93608448	3896044692	41.621	57	25951.727	2	1.453943	4	1068.58	-363967189	2

Table A.12: Overview of the simulation results of the Swedish strategic reserve.

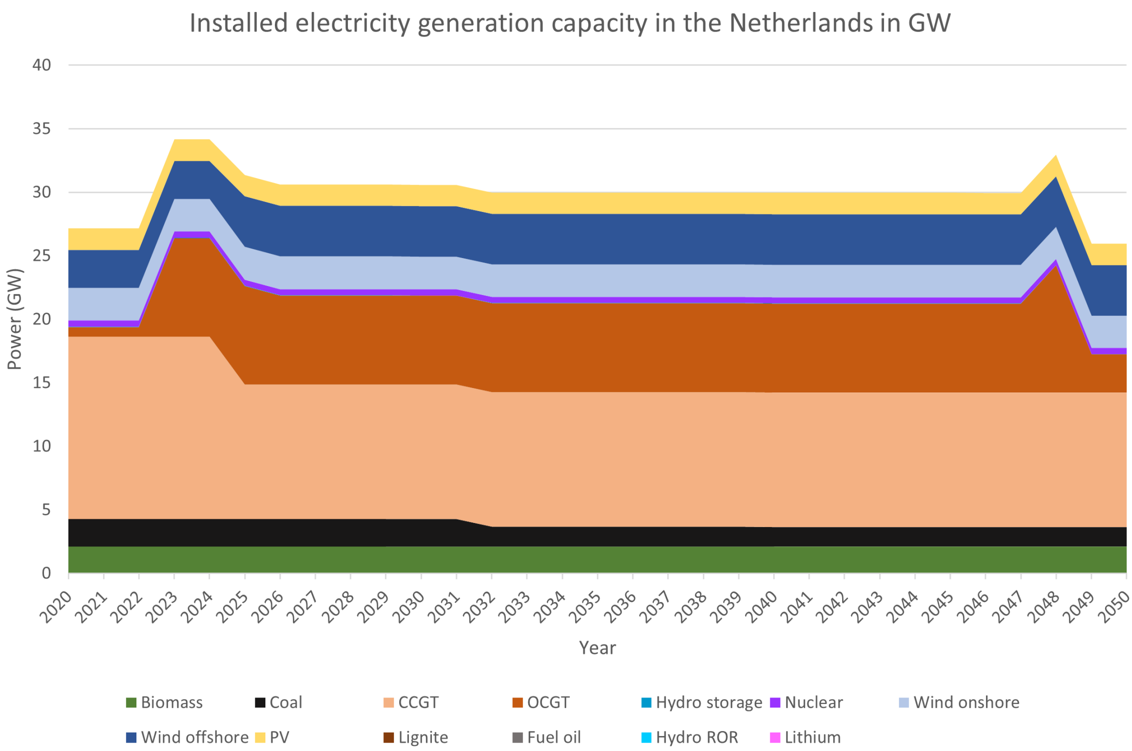

Figure A.34: Installed generation capacity per year in the Swedish strategic reserve.

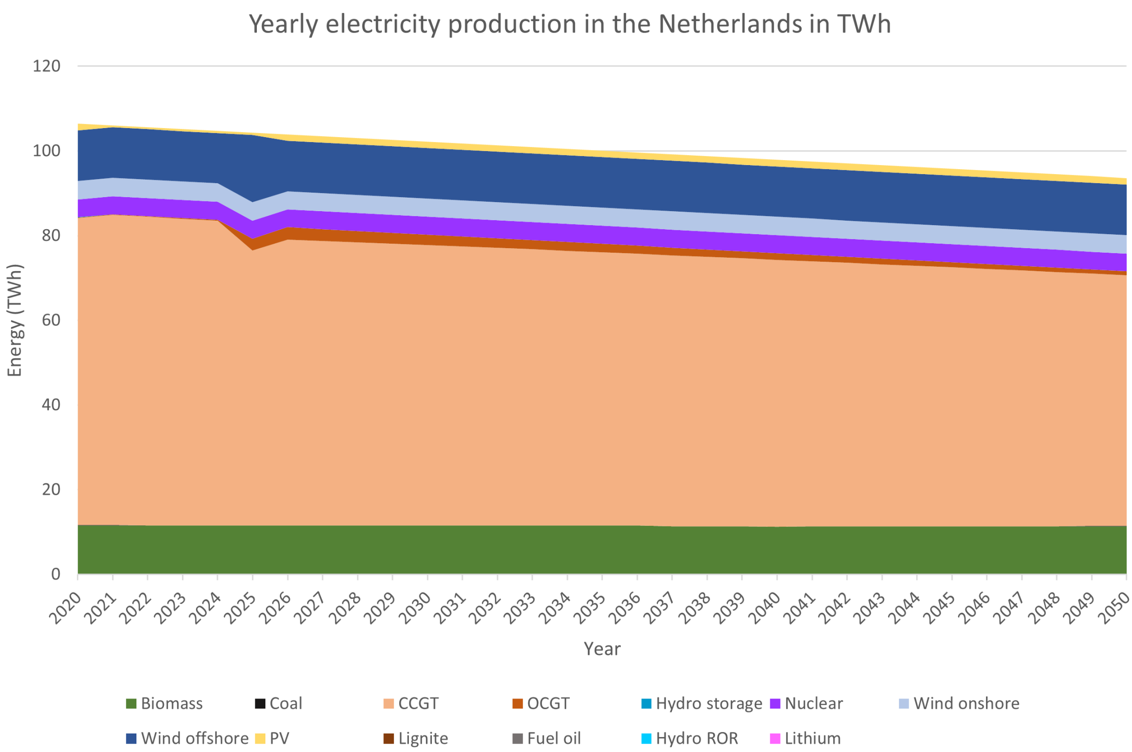

Figure A.35: Electricity production per year in the Swedish strategic reserve.

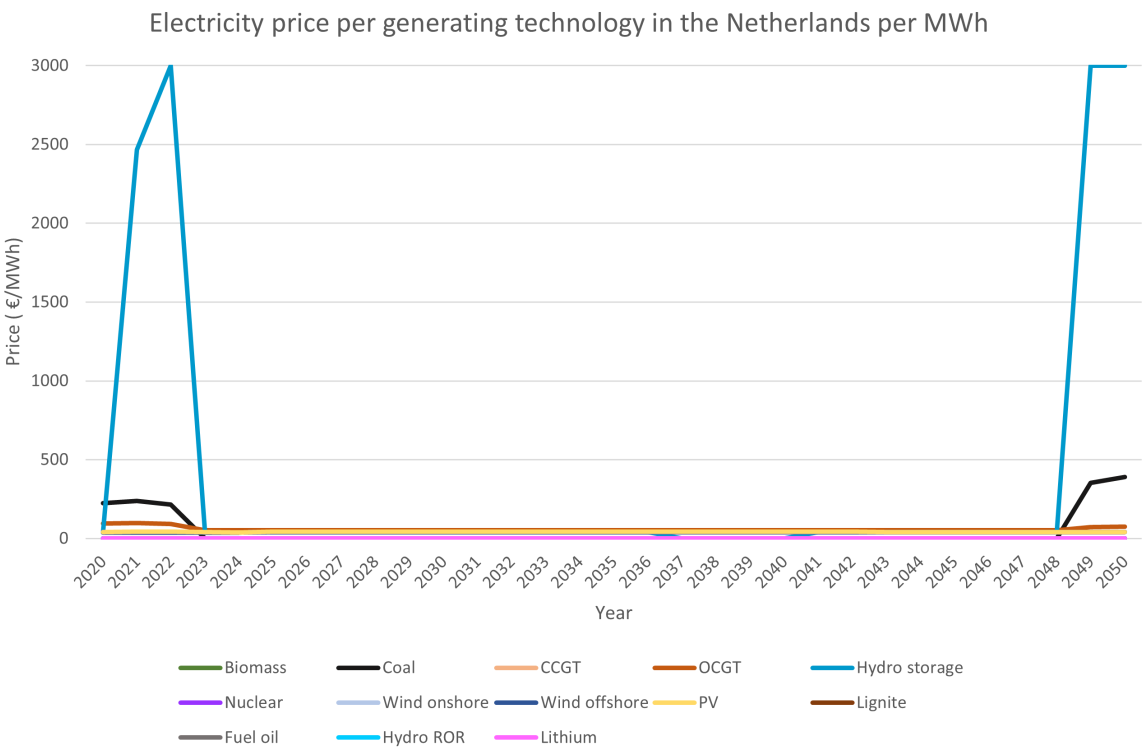

Figure A.36: Electricity price per MWh per year in the Swedish strategic reserve.

B

Simulation Instructions

This instruction will explain in a step-wise manner how to run the simulations in the Spine Toolbox. For the most up-to-date instructions of the needed files and environments, go to: https://github.com/TradeRES/toolbox-amiris-emlab#readme

1. **Install Anaconda**

   Download and install the Python platform Anaconda from:
   https://www.anaconda.com/products/distribution#windows

2. **Install Java**

   Make sure version 8 of Java is installed on your computer. If not it can be downloaded and installed from:
   https://www.java.com/en/download/manual.jsp

3. **Download AMIRIS-EMLab toolbox**

   Download or clone the Git repository AMIRIS-EMLab toolbox to your machine from:
   https://github.com/TradeRES/toolbox-amiris-emlab

4. **Open the Windows command prompt (CMD)**

   When you are working on a remote PC of the TU Delft it is very important that you open the command prompt with administrator rights, for both the installation of the models and running them.

5. **Create AMIRIS environment (iovrmr)**

   In the command prompt go to the toolbox-amiris-emlab folder with:

   ```
   cd location\toolbox-amiris-emlab
   ```

   When in the folder create the virtual conda environment with the following command:

   ```
   conda env create -f environment.yml
   ```

6. **Create EMLABpy environment (emlabpy)**

   To create the EMLABpy environment and install all requirements, in the command prompt go to the toolbox-amiris-emlab folder and run the following commands one by one:

```
conda create -n emlabpy python=3.8
conda activate emlabpy
python setup.py install
python -m pip install .
pip install -r requirements.txt
pip install
 ↪ git+https://github.com/Spine-project/spinetoolbox-dev
conda deactivate
```

7. **Download the Spine Toolbox**

   To download the Spine Toolbox and install all requirements, in the command prompt go to the toolbox-amiris-emlab folder and run the following commands one by one:

```
conda create -n spinetoolbox-dev python=3.8
conda activate spinetoolbox-dev
pip install
 ↪ git+https://github.com/Spine-project/spinetoolbox-dev
git clone https://github.com/Spine-project/Spine-Toolbox
cd Spine-toolbox\
pip install -r requirements.txt
cd bin
upgrade_spine_reqs.bat
conda deactivate
```

8. **Open the Spine Toolbox**

   To open the Spine Toolbox, in the command prompt go to the toolbox-amiris-emlab folder, activate the spinetoolbox-dev environment and open the Spine Toolbox:

```
conda activate spinetoolbox-dev
spinetoolbox
```

9. **Create kernels**

   When in the Spine Toolbox, open the project and make an emlabpy kernel as follows: File → Settings... → Tools → Jupyter console (under Python) → Kernel spec editor → Interpreter: add the path to the python.exe in your emlabpy conda environment (path_to_anaconda/anaconda3/envs/emlabpy/python.exe) → Name: emlabpy → Make kernel specification → OK

10. **AMIRIS input**

    To be able to run AMIRIS within the project it is necessary to add input data in: toolbox-amiris-emlab/amiris_workflow/amiris-config/data

Next up, the amiris folder with the executable, setup.yaml and an empty folder 'result' have to be added in:
toolbox-amiris-emlab/amiris_workflow/amiris

This data is, however, not open-source and permission to use the files should be given by DLR.

Bibliography

[1] IPCC, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers.," Cambridge University Press, Cambridge, UK, 2021. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

[2] ——, "Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers.," Cambridge University Press, Cambridge, UK, 2014. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf.

[3] UNFCCC, "Paris Agreement," United Nations Framework Convention on Climate Change, Paris, 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[4] European Commission, "Energy roadmap 2050," Publications Office of the European Union, Luxembourg, 2012. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf.

[5] VEMW. (Accessed, Aug. 2021). "Handelsplaatsen elektriciteit," [Online]. Available: https://www.vemw.nl/Elektriciteit/Elektriciteitsmarkt/Handelsplaatsen.aspx.

[6] ——, (Accessed, Aug. 2021). "Prijsvorming elektriciteit," [Online]. Available: https://www.vemw.nl/Elektriciteit/Elektriciteitsmarkt/Prijsvorming.aspx.

[7] G. Morales-Españau, H. Algarvio, L. De Vries, R. Faia, R. Hernandez-Serna, and S. Johanndeiter, "Market design for a reliable ∼100% renewable electricity system," Delft University of Technology, 2020. [Online]. Available: https://traderes.eu/wp-content/uploads/2021/04/D3.5_MarketDesignOptions_H2020.pdf.

[8] P. Bhagwat, "Security of supply during the energy transition: The role of capacity mechanisms," Ph.D. dissertation, Delft University of Technology, Delft, 2016. [Online]. Available: http://resolver.tudelft.nl/uuid:9dddbede-5c19-40a9-9024-4dd8cbbe3062.

[9] L. J. De Vries, "Securing the public interest in electricity generation markets. the myths of the invisible hand and the copper plate.," Ph.D. dissertation, Delft University of Technology, Delft, 2004. [Online]. Available: http://resolver.tudelft.nl/uuid:126e09db-29cb-46d8-9302-98bb85793843.

[10] K. Neuhoff and L. J. De Vries, "Insufficient incentives for investment in electricity generations," *Utilities Policy*, vol. 12, no. 4, pp. 253–267, 2004, Infrastructure Regulation and Investment for the Long-Term, ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2004.06.002. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957178704000682.

[11] P. C. Bhagwat, K. K. Iychettira, J. C. Richstein, E. J. L. Chappin, and L. J. De Vries, "The effectiveness of capacity markets in the presence of a high portfolio share of renewable energy sources," *Utilities Policy*, vol. 48, pp. 76–91, 2017, ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2017.09.003. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957178716300406.

[12] G. Strbac, D. Papadaskalopoulos, N. Chrysanthopoulos, A. Estanqueiro, H. Algarvio, F. Lopes, L. de Vries, G. Morales-España, J. Sijm, R. Hernandez-Serna, J. Kiviluoma, and N. Helisto, "Decarbonization of Electricity Systems in Europe: Market Design Challenges," *IEEE Power and Energy Magazine*, vol. 19, no. 1, pp. 53–63, 2021. DOI: 10.1109/MPE.2020.3033397.

[13] TradeRES. (Accessed, Sep. 2021). "New Markets Design & Models for 100% Renewable Power Systems," [Online]. Available: https://traderes.eu/.

[14] TenneT, "Annual Market Update 2020," TenneT, Apr. 2021. [Online]. Available: https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Technical_Publications/Annual_Market_Update_2020.pdf.

[15] E. van Damme, "Liberalizing the Dutch Electricity Market: 1998-2004," *The Energy Journal*, pp. 155–179, 208, 2005. [Online]. Available: https://www-proquest-com.tudelft.idm.oclc.org/scholarly-journals/liberalizing-dutch-electricity-market-1998-2004/docview/222022127/se-2?accountid=27026.

[16] EPEX SPOT. (Accessed, Sep. 2021). "Basics of the Power Market," [Online]. Available: https://www.epexspot.com/en/basicspowermarket.

[17] Á. Cartea and P. Villaplana, "An analysis of the main determinants of electricity forward prices and forward risk premia," in *Quantitative Energy Finance: Modeling, Pricing, and Hedging in Energy and Commodity Markets*, F. E. Benth, V. A. Kholodnyi, and P. Laurence, Eds. New York, NY: Springer New York, 2014, pp. 215–236, ISBN: 978-1-4614-7248-3. DOI: 10.1007/978-1-4614-7248-3_8. [Online]. Available: https://doi.org/10.1007/978-1-4614-7248-3_8.

[18] A. Bublitz, "Capacity remuneration mechanisms for electricity markets in transition," Ph.D. dissertation, Karlsruher Institut für Technologie (KIT), 2019, 360 pp. DOI: 10.5445/IR/1000096476.

[19] A. Weidlich, *Engineering Interrelated Electricity Markets - An Agent-Based Computational Approach*. Heidelberg: Physica-Verlag HD, Oct. 2008, ISBN: 978-3-7908-2068-3. DOI: 10.1007/978-3-7908-2068-3.

[20] S. Deng and S. Oren, "Electricity derivatives and risk management," *Energy*, vol. 31, no. 6, pp. 940–953, 2006, Electricity Market Reform and Deregulation, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2005.02.015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544205000496.

[21] R. Huisman and M. Kilic, "Electricity futures prices: Indirect storability, expectations, and risk premiums," *Energy Economics*, vol. 34, no. 4, pp. 892–898, 2012, ISSN: 0140-9883. DOI: https://doi.org/10.1016/j.eneco.2012.04.008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140988312000850.

[22] P. N. Biskas, D. I. Chatzigiannis, and A. G. Bakirtzis, "European electricity market integration with mixed market designs—part i: Formulation," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 458–465, 2014. DOI: 10.1109/TPWRS.2013.2245923.

[23] M. Reguant, “Complementary Bidding Mechanisms and Startup Costs in Electricity Markets,” *The Review of Economic Studies*, vol. 81, no. 4, pp. 1708–1742, Jun. 2014, ISSN: 0034-6527. DOI: 10.1093/restud/rdu022. [Online]. Available: https://doi.org/10.1093/restud/rdu022.

[24] M. Madani and M. Van Vyve, “Computationally efficient mip formulation and algorithms for european day-ahead electricity market auctions,” *European Journal of Operational Research*, vol. 242, no. 2, pp. 580–593, 2015, ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2014.09.060. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0377221714007991.

[25] C. Brandstätt, G. Brunekreeft, and K. Jahnke, “How to deal with negative power price spikes?—flexible voluntary curtailment agreements for large-scale integration of wind,” *Energy Policy*, vol. 39, no. 6, pp. 3732–3740, 2011, ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2011.03.082. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421511002795.

[26] F. Genoese, M. Genoese, and M. Wietschel, “Occurrence of negative prices on the german spot market for electricity and their influence on balancing power markets,” in *2010 7th International Conference on the European Energy Market*, 2010, pp. 1–6. DOI: 10.1109/EEM.2010.5558703.

[27] K. De Vos, “Negative wholesale electricity prices in the german, french and belgian day-ahead, intra-day and real-time markets,” *The Electricity Journal*, vol. 28, no. 4, pp. 36–50, 2015, ISSN: 1040-6190. DOI: https://doi.org/10.1016/j.tej.2015.04.001. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1040619015000652.

[28] D. Böttger, M. Götz, M. Theofilidi, and T. Bruckner, “Control power provision with power-to-heat plants in systems with high shares of renewable energy sources – an illustrative analysis for germany based on the use of electric boilers in district heating grids,” *Energy*, vol. 82, pp. 157–167, 2015, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2015.01.022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544215000419.

[29] S. Mitra, L. Sun, and I. E. Grossmann, “Optimal scheduling of industrial combined heat and power plants under time-sensitive electricity prices,” *Energy*, vol. 54, pp. 194–211, 2013, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2013.02.030. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544213001448.

[30] C. Weber, “Adequate intraday market design to enable the integration of wind energy into the european power systems,” *Energy Policy*, vol. 38, no. 7, pp. 3155–3163, 2010, Large-scale wind power in electricity markets with Regular Papers, ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2009.07.040. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421509005564.

[31] A. von Selasinsky, “The integration of renewable energy sources in continuous intraday markets for electricity,” Ph.D. dissertation, Technische Universität Dresden, 2016, 212 pp. [Online]. Available: https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa-202130.

[32] N. Kraftwerke. (Accessed, Sep. 2021). “What is the merit order curve in the power system?” [Online]. Available: https://www.next-kraftwerke.be/en/knowledge-hub/merit-order-curve/.

[33] E. Ela, M. Milligan, A. Bloom, A. Botterud, A. Townsend, and T. Levin, "Long-Term Resource Adequacy, Long-Term Flexibility Requirements, and Revenue Sufficiency," in *Electricity Markets with Increasing Levels of Renewable Generation: Structure, Operation, Agent-based Simulation, and Emerging Designs*, F. Lopes and H. Coelho, Eds. Cham: Springer International Publishing, 2018, pp. 129–164, ISBN: 978-3-319-74263-2. DOI: 10.1007/978-3-319-74263-2_6. [Online]. Available: https://doi.org/10.1007/978-3-319-74263-2_6.

[34] L. Söder, E. Tómasson, A. Estanqueiro, D. Flynn, B.-M. Hodge, J. Kiviluoma, M. Korpås, E. Neau, A. Couto, D. Pudjianto, G. Strbac, D. Burke, T. Gómez, K. Das, N. A. Cutululis, D. Van Hertem, H. Höschle, J. Matevosyan, S. von Roon, E. M. Carlini, M. Caprabianca, and L. de Vries, "Review of wind generation within adequacy calculations and capacity markets for different power systems," *Renewable and Sustainable Energy Reviews*, vol. 119, p. 109 540, 2020, ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2019.109540. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032119307488.

[35] G. Hawker, K. Bell, and S. Gill, "Electricity security in the European Union—The conflict between national Capacity Mechanisms and the Single Market," *Energy Research & Social Science*, vol. 24, pp. 51–58, 2017, Conflict, Cooperation, and Change in the Politics of Energy Interdependence, ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2016.12.009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214629616303048.

[36] D. Hach, C. K. Chyong, and S. Spinler, "Capacity market design options: A dynamic capacity investment model and a GB case study," *European Journal of Operational Research*, vol. 249, no. 2, pp. 691–705, 2016, ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2015.08.034. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0377221715007894.

[37] G. Doorman and L. De Vries, "Electricity market design based on consumer demand for capacity," Brussels, Jun. 2018. [Online]. Available: https://www.researchgate.net/publication/349368698_Electricity_market_design_based_on_consumer_demand_for_capacity.

[38] Conseil International des Grands Réseaux Électriques. Comité d'études C5, *Capacity Mechanisms: Needs, Solutions and State of Affairs*. CIGRÉ, Feb. 2016, ISBN: 978-2-85873-350-7. [Online]. Available: https://books.google.nl/books?id=tePknQAACAAJ.

[39] ACER, "Capacity Remuneration Mechanisms and the Internal Market for Electricity," Agency for the Cooperation of Energy Regulators, Ljubljana, 2013. [Online]. Available: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/CRMs%20and%20the%20IEM%20Report%20130730.pdf.

[40] P. Cramton, A. Ockenfels, and S. Stoft, "Capacity Market Fundamentals," *Economics of Energy & Environmental Policy*, vol. 2, Sep. 2013. DOI: 10.5547/2160-5890.2.2.2. [Online]. Available: https://www.researchgate.net/publication/263506349_Capacity_Market_Fundamentals.

[41] S. Stoft, *Power System Economics : Designing Markets for Electricity*. New York: IEEE Press, 2002.

[42] P. Joskow and J. Tirole, "Reliability and Competitive Electricity Markets," *The RAND Journal of Economics*, vol. 38, no. 1, pp. 60–84, 2007, ISSN: 07416261. [Online]. Available: http://www.jstor.org/stable/25046292.

[43] K. Spees, S. A. Newell, and J. P. Pfeifenberger, "Capacity Markets - Lessons Learned from the First Decade," *Economics of Energy & Environmental Policy*, vol. 2, no. 2, Sep. 2013, Copyright - Copyright 2013, The International Association for Energy Economics; Last updated - 2021-05-16. [Online]. Available: https://www.proquest.com/scholarly-journals/capacity-markets-lessons-learned-first-decade/docview/2524747980/se-2?accountid=27026.

[44] R. J. Shanker, "Comments on Standard Market Design: Resource Adequacy Requirement," Federal Energy Regulatory Commission, Docket RM01-12-000, 2003.

[45] L. J. De Vries, "Generation adequacy: Helping the market do its job," *Utilities Policy*, vol. 15, no. 1, pp. 20–35, 2007, ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2006.08.001. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957178706000488.

[46] Great Britain: Department of Energy and Climate Change, *Planning our electric future: a white paper for secure, affordable and low-carbon electricity*, ser. Cm (Series) (Great Britain. Parliament). Stationery Office, 2011, ISBN: 9780101809924. [Online]. Available: https://books.google.nl/books?id=pG6ZCiAg9UEC.

[47] European Commission, "Generation Adequacy in the internal electricity market - guidance on public interventions. Commission Staff Working Document.," European Commission, Brussels, 2013.

[48] P. Holmberg and T. Tangerås, "Strategic Reserves versus Market-Wide Capacity Mechanisms," Research Institute of Industrial Economics (IFN), Stockholm, 2021. [Online]. Available: https://www.ifn.se/media/byddy5yr/wp1387.pdf.

[49] B. F. Hobbs, M.-C. Hu, J. G. Inon, S. E. Stoft, and M. P. Bhavaraju, "A Dynamic Analysis of a Demand Curve-Based Capacity Market Proposal: The PJM Reliability Pricing Model," *IEEE Transactions on Power Systems*, vol. 22, no. 1, pp. 3–14, 2007. DOI: 10.1109/TPWRS.2006.887954.

[50] NYISO Capacity Market Products, "Installed Capacity Manual," New York Independent System Operator, Rensselaer, NY, version 6.49, 2021. [Online]. Available: https://www.nyiso.com/documents/20142/2923301/icap_mnl.pdf/234db95c-9a91-66fe-7306-2900ef905338.

[51] G. Doorman, "Capacity subscription: Solving the peak demand challenge in electricity markets," *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 239–245, 2005. DOI: 10.1109/TPWRS.2004.841230.

[52] L. J. de Vries, A. F. Correljé, H. P. A. Knops, and R. van der Veen, "SEN1522 Reader: Electricity - Market design and policy choices," TU Delft, Delft, 2019.

[53] M. Wooldridge, *An Introduction to Multi-Agent Systems*. John Wiley and Sons, 2002.

[54] L. Tesfatsion, "Chapter 16 agent-based computational economics: A constructive approach to economic theory," in, ser. Handbook of Computational Economics, L. Tesfatsion and K. Judd, Eds., vol. 2, Elsevier, 2006, pp. 831–880. DOI: https://doi.org/10.1016/S1574-0021(05)02016-2. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1574002105020162.

[55] C. M. Macal and M. J. North, "Tutorial on agent-based modelling and simulation," *Journal of Simulation*, vol. 4, no. 3, pp. 151–162, Sep. 2010. [Online]. Available: https://www-proquest-com.tudelft.idm.oclc.org/docview/749101997.

[56] J. H. Holland and J. H. Miller, "Artificial adaptive agents in economic theory," *The American Economic Review*, vol. 81, no. 2, pp. 365–370, 1991, ISSN: 00028282. [Online]. Available: http://www.jstor.org/stable/2006886.

[57] M. Deissenroth, M. Klein, K. Nienhaus, and M. Reeg, "Assessing the plurality of actors and policy interactions: Agent-based modelling of renewable energy market integration," *Complexity*, vol. 2017, Dec. 2017, ISSN: 1076-2787. DOI: 10.1155/2017/7494313. [Online]. Available: https://doi.org/10.1155/2017/7494313.

[58] M. Klein, U. J. Frey, and M. Reeg, "Models Within Models – Agent-Based Modelling and Simulation in Energy Systems Analysis," *Journal of Artificial Societies and Social Simulation*, vol. 22, no. 4, p. 6, 2019, ISSN: 1460-7425. DOI: 10.18564/jasss.4129. [Online]. Available: http://jasss.soc.surrey.ac.uk/22/4/6.html.

[59] F. Sensfuß, M. Ragwitz, M. Genoese, and D. Möst, "Agent-based simulation of electricity markets -a literature review-," *Energy Studies Review*, vol. 15, Oct. 2007. DOI: 10.15173/esr.v15i2.507.

[60] P. Ringler, D. Keles, and W. Fichtner, "Agent-based modelling and simulation of smart electricity grids and markets – a literature review," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 205–215, 2016, ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2015.12.169. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S136403211501552X.

[61] E. Bonabeau, "Agent-based modeling: Methods and techniques for simulating human systems," *Proceedings of the National Academy of Sciences*, vol. 99, no. suppl 3, pp. 7280–7287, 2002, ISSN: 0027-8424. DOI: 10.1073/pnas.082080899. eprint: https://www.pnas.org/content/99/suppl_3/7280.full.pdf. [Online]. Available: https://www.pnas.org/content/99/suppl_3/7280.

[62] E. J. L. Chappin, *Simulating Energy Transitions*, 2011. [Online]. Available: http://resolver.tudelft.nl/uuid:fb224ffe-0a3b-4780-9e5b-b2020ac0ce3c.

[63] E. J. L. Chappin, L. J. de Vries, J. C. Richstein, P. Bhagwat, K. Iychettira, and S. Khan, "Simulating climate and energy policy with agent-based modelling: The Energy Modelling Laboratory (EMLab)," *Environmental Modelling & Software*, vol. 96, pp. 421–431, 2017, ISSN: 1364-8152. DOI: https://doi.org/10.1016/j.envsoft.2017.07.009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364815216310301.

[64] E. J. L. Chappin. (Accessed, Oct. 2021). "EMLab-generation Overview," [Online]. Available: http://emlab.tudelft.nl/generation.html#1.

[65] E. J. L. Chappin, L. de Vries, J. Richstein, and P. Bhagwat, "EMLab-Generation Factsheet," TU Delft, Delft, 2013. [Online]. Available: http://emlab.tudelft.nl/generation/emlab-generation-factsheet.pdf.

[66] K. Nienhaus. (Accessed, Oct. 2021). "Agent-based simulation model AMIRIS," [Online]. Available: https://www.dlr.de/ve/en/desktopdefault.aspx/tabid-16023/25972_read-66759/.

[67] M. Klein, “Agent-Based Modeling and Simulation of Renewable Energy Market Integration – The Case of PV-Battery Systems,” Ph.D. dissertation, Universität Stuttgart, Stuttgart, 2020. DOI: 10.18419/opus-11132. [Online]. Available: https://elib.uni-stuttgart.de/handle/11682/11149.

[68] B. den Ouden, J. Kerkhoven, J. Warnaars, R. Terwel, M. Coenen, T. Verboon, T. Tiihonen, and A. Koot, “Klimaatneutrale energiescenario’s 2050,” Berenschot, Utrecht, Mar. 2020. [Online]. Available: https://www.berenschot.nl/media/hl4dygfq/rapport_klimaatneutrale_energiescenario_s_2050_2.pdf.

[69] Quintel Intelligence. (Accessed, Oct. 2021). “About Quintel Intelligence,” [Online]. Available: https://quintel.com/.

[70] ——, (Accessed, Oct. 2021). “II3050 - Regionale sturing,” [Online]. Available: https://pro.energytransitionmodel.com/saved_scenarios/9184.

[71] ——, (Accessed, Oct. 2021). “II3050 - Nationale sturing,” [Online]. Available: https://pro.energytransitionmodel.com/saved_scenarios/9185.

[72] ——, (Accessed, Oct. 2021). “II3050 - Europese sturing,” [Online]. Available: https://pro.energytransitionmodel.com/saved_scenarios/9186.

[73] ——, (Accessed, Oct. 2021). “Netherlands - II3050 Internationale sturing,” [Online]. Available: https://pro.energytransitionmodel.com/saved_scenarios/9187.

[74] J. Kiviluoma, T. O’Donnell, E. Delarue, L. Söder, and J. Dillon. (Accessed, July. 2022). “Spine Toolbox,” [Online]. Available: http://www.spine-model.org/index.htm.

[75] Wikipedia. (Accessed, June. 2022). “Lijst van elektriciteitscentrales in Nederland,” [Online]. Available: https://nl.wikipedia.org/wiki/Lijst_van_elektriciteitscentrales_in_Nederland.

[76] ——, (Accessed, June. 2022). “Wind power in the Netherlands,” [Online]. Available: https://en.wikipedia.org/wiki/Wind_power_in_the_Netherlands#Offshore_wind_power.

[77] ——, (Accessed, June. 2022). “Lijst van zonne-energie-installaties in Nederland,” [Online]. Available: https://nl.wikipedia.org/wiki/Lijst_van_zonne-energie-installaties_in_Nederland.

[78] Centraal Bureau voor de Statistiek. (Accessed, June. 2022). “Renewable electricity; production and capacity,” [Online]. Available: https://www.cbs.nl/en-gb/figures/detail/82610ENG.

[79] J. Weibezahn, R. Weinhold, C. Gerbaulet, and F. Kunz. (Accessed, June. 2022). “Open Power System Data Conventional power plants,” [Online]. Available: https://data.open-power-system-data.org/conventional_power_plants/2020-10-01.

[80] Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. (Accessed, June. 2022). “Global Power Plant Database,” [Online]. Available: https://datasets.wri.org/dataset/globalpowerplantdatabase.

[81] Wikipedia. (Accessed, June. 2022). “List of offshore wind farms in Germany,” [Online]. Available: https://en.wikipedia.org/wiki/List_of_offshore_wind_farms_in_Germany.

[82] Bundesnetzagentur. (Accessed, June. 2022). “Power plant list,” [Online]. Available: https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/GeneratingCapacity/PowerPlantList/start.html.

[83] Quintel Intelligence. (Accessed, Jul. 2022). “Nederland 2020,” [Online]. Available: https://pro.energytransitionmodel.com/.

[84] P. C. Bhagwat, J. C. Richstein, E. J. Chappin, and L. J. de Vries, “The effectiveness of a strategic reserve in the presence of a high portfolio share of renewable energy sources,” *Utilities Policy*, vol. 39, pp. 13–28, 2016, ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2016.01.006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957178716300169.

[85] “The Capacity Market Rules 2014,” Gas and Electricity Markets Authority, London, 2014. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/340046/capacity_market_rules.pdf.

[86] S. Babaeinejad Sarookolaee, S. H. Elyas, and A. Akbari Foroud, “A reformed capacity subscription market in restructured power systems,” in *ISGT2011-India*, 2011, pp. 368–373. DOI: 10.1109/ISET-India.2011.6145344.

[87] J. Cejie, “The Strategic reserve - why and how?” Ministry of the Environment and Energy Sweden, Stockholm, 2019. [Online]. Available: https://ec.europa.eu/competition/sectors/energy/strategic_reserve_en.pdf.

[88] Centraal Bureau voor de Statistiek. (Accessed, August. 2022). “Hoe groot is onze broeikasgasuitstoot?” [Online]. Available: https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/hoe-groot-is-onze-broeikasgasuitstoot-wat-is-het-doel-.