Sector coupling and battery storage as flexibility options in the 2050 renewable power system

An assessment of North West Europe and the Netherlands with the IRENA FlexTool

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Sector coupling and batteries as flexibility options in the 2050 renewable power system: an assessment of North West Europe and the Netherlands with the IRENA FlexTool

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Executive summary

In December 2019, the European Union (EU) presented their Green Deal with the aim of becoming the first climate-neutral continent by 2050 (European Commission, 2019). In order to achieve this, the EU member states will have to strongly increase the share of renewable energy sources in the next decade (Newbery, 2020). The international energy agency (IEA) expects that most of this renewable energy will be coming from photovoltaic (PV) and wind (IEA, 2019). However, both PV and wind energy sources depend on uncertain weather conditions, which make them variable over multiple timescales of hours, days, seasons and years (Després et al., 2017). These uncertain weather conditions will increase the need for a more flexible power system (Després et al., 2017). The expectation of the IEA that these goals will be met through integrating more wind and PV into the power system is confirmed by the recently published national energy and climate plans (NCEP) of the EU member states (European Commission, 2020c). These NCEPs shows that both, the North West of Europe (NWEU) and the Netherlands have very ambitious plans for integrating these variable renewable energy sources (VRE) in order to meet the 2050 climate neutral goal of the EU. In which the Netherlands will take a regional approach with their regional energy strategy (RES), dividing the country in 30 regions. This increase in VRE causes both North West Europe and the Netherlands to incorporate more flexibility into their power system (Després et al., 2017; Papaefthymiou et al., 2018).

Traditionally, flexibility in the power system was mostly provided by conventional power plants (Ameli et al., 2020). However, because of the climate neutral goal these have to be phased out eventually. Another important measure to control the balance of supply and demand in the power system is curtailing the excess power of VRE. Since a large amount of renewable energy that is currently integrated into the power system, more renewable energy can be lost through curtailment. This possible increase in curtailment of renewable power could have a negative effect on current and future renewable energy projects. This can eventually result in less investments in these renewable energy projects since they might not be able to get the expected economic benefits (Li et al., 2015). Therefore, it is necessary to find a use for this lost power (Lund et al., 2015; Bussar et al., 2016; Wang et al., 2017; Bloess et al., 2018).

The lost power through curtailment can be used by either battery storage or sector coupling (Carton & Olabi, 2010; Després et al., 2017; Luca & Pregger, 2018; Arabzadeh et al., 2019). Sector coupling is the process of interconnecting different energy sectors (e. g., electricity, heat, gas and transport) with the goal of decarbonizing these sectors, while at the same time enhancing the energy flexibility (Robinius et al., 2017). Sector coupling can provide both: flexibility to the power grid and provide use for the excess power generated by VRE though different options such as power-to-thermal (P2T), power-to-hydrogen (P2H) and vehicle-to-grid (V2G) (Lund et al., 2015). Most studies in current scientific literature focus on only battery technologies (Després et al., 2017; Branco, 2018; Liebensteiner & Wrienz, 2019) and others focus only on one sector coupling option (Guandalini et al., 2015; Arabzadeh et al., 2019). Therefore, this study will focus on the comparison of the different sector coupling options and batteries.

To assess battery storage and sector coupling this study will look the signs of inflexibility, VRE curtailment and loss of load since these are widely used in current scientific literature (Papaefthymiou, 2018; Poncela et al., 2018). The International Renewable Energy Agency (IRENA) has developed the FlexTool in order to assess signs of inflexibility such as VRE curtailment and loss of load in a future or current power system. The literature study of this research showed that many different energy models are used to assess the flexibility of an energy system. And that the IRENA FlexTool is, besides policy documents by IRENA, not yet used in the academic literature found in Google Scholar and Scopus.

This research will focus on the use of batteries and sector coupling options, when the climate goals of the EU are met with only the integration of the renewable energy sources wind and PV for North West Europe and the Netherlands by means of the IRENA FlexTool to answer the following research question:

How can battery storage and sector coupling cost optimally utilize the power that is lost through variable renewable energy curtailment and avoid loss of load for the Netherlands and North West Europe in 2050, using the IRENA FlexTool as modelling approach?

The EU reference scenario 2016 (EUCO) is used as a base scenario for this research because this is a widely used conservative scenario for the EU (Capros et al., 2016) In order to reach the goal of the European Union to become climate neutral in 2050, conventional power sources need to be phased out. Therefore, another scenario was created, in order to assess the problems that arise when the goal of the EU is reached through replacing the conventional power plants by integrating VRE into the power system. Two assumptions were made to alter the EUCO scenario in order to create this scenario. The first assumptions included the phasing out of coal and oil in 2030 and natural gas in 2050. Because this was most in line with the NECPs (European Commission, 2020c) were coal and oil are phased out first. This meant that in the EUCO 2030 scenario coal and oil were phased out and in the EUCO 2050 scenario natural gas was phased out. This resulted in two new scenarios for 2030 and 2050, in this research called the FLEX 30 and FLEX 50 scenario. Where the FLEX 30 scenario is the alteration on the EUCO 2030 scenario and the FLEX 50 scenario is the alteration of the EUCO 2050 scenario.

The use of the IRENA FlexTool placed three main shortcomings on this study. The first shortcoming relates to the disability of running the investment mode when sector coupling is used in the model. Because the calculation time of the FlexTool can become very high and even providing no results when the investment mode is used with sector coupling (IRENA, 2018b). In order to cope with this shortcomming a design of experiments (DOE) is used in this study. The second shortcoming relates to the modelling of the electricity prices, because in the model validation the FlexTool failed to model the peak prices for Germany and the Netherlands in 2018, making the modelling results of the electricity prices less accurate. The third shortcoming relates to the number of nodes that the FlexTool is able to model, which causes to severely reduce the variety in the researched power system. Multiple test runs with 30 regions and 17 regions for the Netherlands were made however this provided no results, indicating that the FlexTool was not able to run the proposed model. Therefore, the regions had to be reduced to 5. The IRENA FlexTool could therefore be better suited to model smaller energy systems to gain a quick insight into the flexibility issues of loss of load and curtailment, and not the electricity price, instead of modelling larger complex energy systems.

The modelling results show that for the North West of Europe an amount of 21,7% of the power generated by renewables is curtailed when coal and oil are phased out and replaced by wind and PV. And 76,2% of the power generated by renewables is curtailed when natural gas is phased out and replaced by wind and PV. For the Netherlands an amount of 22,4% of the power generated by renewables is curtailed when coal and oil are phased out and replaced by wind and PV. And more than double of the power generated by renewables is curtailed when natural gas is phased out and replaced by wind and PV. Regarding the loss of load, for North West Europe 0,4% loss of load occurred in the FLEX 2030 scenario, and 5,7% in the FLEX 2050 scenario. For the Netherlands 0,14% loss of load occurred in the FLEX 2030 scenario and 18,3% in the FLEX 2050 scenario. These results indicate that when natural gas is still a part of the power system, flexibility will not be a very large issue. However, when the goal is climate neutrality and natural gas has to be phased out, flexibility becomes a much larger issue. This increase in curtailment can lower the bankability of new renewable energy projects which can severely jeopardize the goal of climate neutrality of the European Union by 2050.

The modelling results of the IRENA FlexTool show that the costs for utilizing the lost power of curtailment and avoiding loss of load differs for the Netherlands and North West Europe. For North West Europe, batteries have the lowest LCOE when almost all lost power trough curtailment is used and hydrogen provides a good solution for the loss of load. Therefore, both battery storage and hydrogen could be a good substitution for natural gas in NWEU. For the Netherlands hydrogen storage is the option with the lowest LCOE when all lost power through curtailment is used and loss of load is avoided. Therefore, hydrogen could provide a good substitution for natural gas in the Netherlands. The difference in LCOE can be explained through the allocation of the power use of batteries and sector coupling, since this is not included in this study. Future research should focus on the interaction between the different options. This could provide useful results on how to efficiently allocate and use battery storage and sector coupling when they are used in combination with each other.

The academic contribution of this research exists of two parts. The study showed that the IRENA FlexTool is better suited to model smaller energy systems to gain a quick insight into the flexibility issues of loss of load and curtailment, instead of modelling larger complex energy systems. And the study showed a comparison of battery storage, power-to-heat, power-to-hydrogen and vehicle-to-grid for the Netherlands and North West Europe. Where power-to-hydrogen showed to be to most viable option for the Netherlands, and power-to-hydrogen and battery storage for North West Europe.

Preface

Dear reader,

After seven months of hard working this is the end of writing my master thesis for Complex Systems Engineering and Management at the Delft University of Technology. It was a crazy time to write my thesis, starting every day with news about the ongoing pandemic. I can say that I am relieved that I finished my thesis, not due to the subject and difficulties in my thesis but due to the challenges I faced working at home for seven months. Nevertheless, I am proud of the result. At the end of not only my master thesis, but also the end of my student time I would like to use this preface to thank some people. Without these people I wouldn't have finished this thesis.

First, I would like to thank Petra for wanting to guide me when I asked her in December even though I was late asking. Planning remained a difficulty during my entire thesis. Nevertheless, you wanted to guide me and helped me during my thesis with practical feedback when I was stuck. You made time for me regularly and when we couldn't go to the University anymore due to COVID-19, our sessions continued through Skype. Your help and ideas where very essential with the modelling approach. I am very grateful for your help and guidance.

Secondly, I want to thank Sytze from Accenture. The internship was quite different than expected due to the pandemic, nevertheless you were very present during my entire thesis. Thinking that you wouldn't be my supervisor and you had to fill in at the last minute, I can only say that you did a great job. The virtual coffees and Friday drinks made working from home better. Even though the model I used wasn't your expertise, you helped me with every step and were always available to brainstorm. Even when my internship was finished and after working hours you were there to help me. I am very grateful for your help.

Third, I'd like to thank Zofia and Daniël for making time to review my thesis and to provide me with helpful feedback. Daniel for giving me the feedback about the literature and social angle of approach, helping to have a different point of view. And Sofia for your helpful feedback and especially your positive attitude.

I would also like to thank my parents for always being there for me to listen to my struggle about planning and model that did not work. You were there to listen, to help and to put the stress into perspective. Thank you for being there during my thesis and all the years before that.

At last, I'd like to thank my girlfriend Lobke for her utter patience, motivational speeches and humour when I needed it most. Even though working together from home was a challenge itself, I enjoyed the intense time we spend during COVID-19.

My time at the Delft University of Technology was challenging and I learned a lot over the past two years. Not only intellectual but also about myself. I look back at an amazing time in Delft and look forward to what's coming next.

David Ulijn

Utrecht, November 2020

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List of abbreviations

CAPEX	Capital expenditure
DOE	Design of experiments
EU	European Union
EUCO	EU reference scenario 2016
EV	Electric Vehicle
H2	Hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
NECP	National Energy and Climate Plan
NWEU	North West Europe
OPEX	Operational expenditure
P2T	Power-to-Thermal
P2H	Power-to-Hydrogen
RES	Regional Energy Strategy
V2G	Vehicle-to-Grid
VRE	Variable Renewable Energy

1. Introduction

1.1. European climate goals

In December 2019 the European Union (EU) presented their Green Deal with the aim of becoming the first climate-neutral continent by 2050 (European Commission, 2019). In order to achieve this, the EU member states will have to strongly increase the share of renewable energy sources in the next decade (Newbery, 2020). The international energy agency (IEA) expects that most of this renewable energy will be coming from photovoltaic (PV) and wind (IEA, 2019). However, both PV and wind energy sources depend on uncertain weather conditions, which make them variable over multiple timescales, hours, days, seasons and years (Després et al., 2017). These uncertain weather conditions will increase the need for a more flexible power system (Després et al., 2017).

The expectation of the IEA that these goals will be met through integrating more wind and PV into the power system is confirmed by the recently published national energy and climate plans (NCEP) of the EU member states (European Commission, 2020c). These NCEPs show that both the North West of Europe (NWEU) and the Netherlands have very ambitious plans for integrating these variable renewable energy sources (VRE) in order to meet the 2050 climate neutral goal of the EU. The increase in VRE in both North West Europe and the Netherlands will mean they have to incorporate more flexibility into their power system (Després et al., 2017; Papaefthymiou et al., 2018).

1.2. Flexibility in the power system

Flexibility of a power system is defined as the ability to maintain the balance between power demand and supply at any time (Bertsch et al., 2016; Papaefthymiou et al., 2018). When wind and PV, are implemented on a large scale, the uncertain weather conditions will have two major consequences for the power system (Cramton & Stoft, 2008). Firstly, when there is not enough feed-in from solar and wind capacity, enough back-up capacities are necessary in order to provide sufficient power supply when there is not enough VRE generation. Otherwise, an increase or decrease in production of renewable energy can result in price spikes on the wholesale market and to possible black outs, if supply and demand do not match (Cramton & Stoft, 2008). Secondly, the capacity mix needs enough flexibility in order to deal with the volatile renewable energy generation. Either by ramping down the demand or by ramping up the supply on short notice in order to avoid the occurrence of loss of load (Lamadrid et al., 2011; Bertsch et., 2016).

The power system previous to the integration of VRE dealt with the uncertainty and unexpected losses of elements in the power system through supply-side assets (Ulbig & Andersson, 2015). These assets were mainly in the form of advanced thermal generators, hydropower and pumped hydro storage to ramp up supply when demand peaked (IRENA, 2018a). With these assets, the system is currently built in such a way that there is, to a certain point, a capability to cope with the variability and uncertainty in the supply and demand of power (Lund et al., 2015). Natural gas is currently the main provider in covering the electricity supply when renewable energy sources lack in power generation. Natural gas is very suitable due to its quick ramping speeds and its comparatively low emissions compared to other fossil fuel options (Ameli et al., 2020). Increasing the interdependency of the power system with natural gas resources (Ameli et al., 2020). The flexibility provided by natural gas will be important the next decades due to its role of providing stability in the energy system while integrating an increasing amount or renewable energy (Zigurs et al., 2019).

While integrating more and more VRE into the power system, the current transmission infrastructure is not always able to transfer the increased levels of wind and PV generation in certain peak hours. This causes the power system to meet operational or transmission constraints, which causes the system operator to decline PV or wind altough it is available in order to assure grid stability (Lund et al., 2015; Bird et al., 2016; Arabzadeh et al., 2019). Transmission congestion and system balancing are common reasons for the curtailment of VRE (Gu & Xie, 2013).

The transmission congestion could draw grid operators to prefer utilizing power generators with higher marginal-costs over power generated by PV or wind (Bird et al., 2016). The large amount of renewable energy which is currently integrated into the power system, results in more renewable energy that can be lost through curtailment (Lund et al., 2015). This possible increase in curtailment of renewable power could have a negative effect on current and future renewable energy projects as they might not be able to get the expected economic benefits (Li et al., 2015). This could eventually result in less investments in these renewable energy projects (Li et al., 2015). Therefore, it is necessary to either reduce this curtailment by increasing transmission capacity or by finding a use for this lost power (Lund et al., 2015; Bussar et al., 2016; Wang et al., 2017; Bloess et al., 2018).

1.3. Sector coupling and batteries

In order to reach the EU target of a climate neutral continent in 2050, the energy system will need alternative flexibility options that do not rely on conventional generation and do not 'waste' the surplus of generated power by VRE as it can lead to less investments in renewable energy projects (Li et al., 2015). The lost power of curtailment can be used by either battery storage or sector coupling (Carton & Olabi, 2010; Després et al., 2017; Luca & Pregger, 2018; Arabzadeh et al., 2019).

Sector coupling is the process of interconnecting different energy sectors (e. g., electricity, heat, gas and transport) with the goal of decarbonizing these sectors while at the same time enhancing the energy flexibility (Robinius et al., 2017). Sector coupling can provide both flexibility to the power grid and provide use for the excess power generated by VRE though power-to-thermal (P2T), power-to-hydrogen (P2H) and vehicle-to-grid (V2G) (Lund et al., 2015). Power-to-hydrogen makes it is possible to chemically store electricity through three components. The electrolyser produces hydrogen from water with electricity, the electricity can then be stored in a hydrogen reserve and can later, when necessary, be converted back to electricity via a fuel cell (Kauranen et al., 1994; Lund et al., 2015). Power-to-thermal converts electricity into thermal energy, through either a heat pump or electric boiler. This thermal energy can directly be used or stored in a thermal storage unit, which is easier than storing electricity, and can later be used for heating or cooling (Lund, 2012). Electric vehicles are most of the time standing still and can therefore offer charging, storage and discharging options when the vehicle is connected to the power grid (Ekman, 2011). Battery storage can be used to shift the delivery of power in time, which helps in solving short term mismatches between demand and supply (Lund et al., 2015). Batteries have a very fast response which makes them suitable for improving the network stability (Lund et al., 2015). In this research the term “sector coupling” and “sector coupling options” will be interchangeably used to refer to the P2H, P2T and V2G as is described here. The term “flexibility options” will be used in this research to refer to battery storage, P2H, P2T and V2G.

1.4. IRENA FlexTool

As countries need to reform their generation mix including PV and Wind, the International Renewable Energy Agency (IRENA) started with addressing the issue of flexibility to policy makers (IRENA, 2018a). Because the IRENA also notices the need for flexibility in the power system when the goal is to increase the integration of VRE. Therefore, additional flexibility sources need to be planned for on time (IRENA, 2020a). In order to plan for this need in flexibility, IRENA developed the FlexTool. This tool is specifically designed for countries that want to increase their shares of renewables and help them with assessing the flexibility needs in combination with providing solutions to their power grid, with solutions primarily focussed on sector coupling and storage (IRENA, 2020b). Therefore, this could be a useful tool for countries planning their future power grid and help assessing and possibly solving the problem that is stated previously.

Summarizing the practical problem described in this chapter; in order to reach the EU target of a climate neutral continent in 2050, the power system will need alternative flexibility options that do not rely on conventional generation and do not ‘waste’ the surplus of generated power by VRE as it can lead to less investments in renewable energy projects. The lack in investments in VRE can possibly hamper the EU and its member states in achieving their goal of becoming a climate neutral continent in the year 2050. This research will focus on the use of batteries and sector coupling options, when the climate goals of the EU are met with only the integration of the renewable energy sources wind and PV for North West Europe and the Netherlands by means of the IRENA FlexTool. The next chapter will describe how this problem relates to the current scientific literature and how the IRENA FlexTool is used in an academic context. From this description, a knowledge gap and the main objective of this research are derived, along with the research questions

2. Literature review

As stated in the previous chapter the curtailment of renewable energy sources as wind and solar can result in less future investments and integration of variable renewable energy sources, hampering the climate goals of the European Union. This problem will be discussed in this chapter with the relevant academic literature that is currently available. Firstly, the search method that was used to find the relevant literature will be described. Secondly, the in the introduction mentioned concepts of flexibility and sector coupling will be discussed. Thirdly, the in the current scientific literature used indicators to assess the ability of sector coupling and batteries in providing flexibility will be discussed. Fourthly an energy system modelling tool will be derived from the literature which is best suitable to assess these indicators. At last this chapter concludes with a knowledge gap described on the basis of the current academic literature that is available together with the objective and relevance of this research.

2.1. Search method

In this literature research the database that is mainly consulted is Scopus. This database has a specialized disciplinary coverage and is well suited to narrow down the search results. In case that the number of available articles was not sufficient, Google Scholar was consulted as a complementary database. In order to collect the most useful articles, four search strings were used which were specified on the problem described in the introduction. Table 2.1 shows the four used strings with their keywords. As can be seen for the last search, two strings were used. In trying to obtain a more general view of the modelling environment, regarding flexibility, the first string was used. However, in order to obtain certainty of the use of the model that resulted from the first search in scientific literature, the second string was used was well.

Table 2.1. Search strings search method

Part	Search string
2.2. Flexibility indicators	*“Renewable” AND “Energy” AND “Power” AND “System” AND “Flexibility” AND “Indicators”*
2.3. Batteries and sector coupling	*“Renewable” AND “Energy” AND “Curtailment” AND [“Sector coupling” OR “Battery storage” OR “Electric vehicles” OR “hydrogen” OR “heat”].*
2.4. Energy system modelling	*1st “Flexibility” AND “Energy” AND “System” AND “Modelling” AND [“Curtailment” OR “Loss of load” OR “peak price”]* *2nd “IRENA” AND “FlexTool”*

The first limitation to narrow down the results was the restriction of a timeframe from 2016 – 2020. In order to find up to date and therefore possibly more relevant articles, the articles in this selection were sorted on the number of citations (highest to lowest) from which the abstracts were read. When a paper on this basis seemed relevant, it was set aside to form a final selection. Furthermore, other methods such as backward and forward snowballing were used as well. For both parts the final selection of the selected articles is first presented in a table which is followed by a discussion of the selected papers.

2.2. Batteries and sector coupling

2.2.1. Sector coupling and batteries in scientific literature

The results of the search method described in the beginning of this chapter are presented in table 2.2 and are discussed here in further detail.

Table 2.2. Selected papers batteries and sector coupling

Paper	Technological solution
Arabzadeh et al., (2019)	Power to heat
Després et al., (2017)	Battery storage
Branco et al., (2018)	Battery storage
Carton & Olabi (2010)	Power to hydrogen
Liebensteiner & Wrienz, (2019)	Battery storage
Bloess et al., (2018)	Power to heat
Luca & Pregger, (2018)	Electric vehicles
Guandalini et al., (2015)	Power to hydrogen
Kurpat et al., (2017)	Power to heat & power to hydrogen
Pavić et al., (2016)	Electric vehicles

The study of Arabzadeh et al., (2019) focussed on increased integration of renewable energy sources with the combination of curtailment strategies and power-to-heat on a national scale for Finland. This study found that different curtailment strategies have an effect on the level of successful coupling of the heating sector with VRE generation. Where besides curtailment strategies, heat pumps also had a very positive effect on using heat powered by renewable energy (Arabzadeh et al., 2019). Another study that focussed on using heat from the excess power of renewable energy is the paper of Bloess et al., (2018) which performed a literature study on power-to-heat for VRE integration. This study also concluded that heat pumps in combination with thermal storage is the favourable option when coupling the two sectors (Bloess et al., 2018). And in addition, this paper also concluded that the use of power-to-heat technologies could cost effectively support the transition of fossil fuels to renewable energy. The paper of Kurpat et al., (2015) specifically studied the economic losses of the curtailment due to high VRE generation and how this lost power could be avoided with power-to-heat and power-to-hydrogen. Which concluded that power-to-heat could be a viable option for VRE generation. Where heat pumps were optimal in coupling decentralized systems such as households and electrical boilers were better in coupling industrial applications.

Kurpat et al., (2015) also focussed on power-to-hydrogen for the reduction of curtailed power of VRE. From this study the main conclusion was that the properties and materials of the different electrolysers where of main influence on the potential of power-to-hydrogen (Kurpat et al., 2015). This study also found that PEM electrolysers is the main choice of electrolyser for power to hydrogen as it supports the integration of hydrogen into the already existing gas network (Kurpal et al., 2015). Carton & Olabi, (2010) present similar findings from their research of the combination of electrolysers and wind farms for the coast of Ireland. Here it is also noticed that besides PEM electrolysers, PEM fuel cells are good options for integrating hydrogen into the current system because of their short start up and shut down times (Carton & Olabi, 2010). Guandalini et al., (2015). This also underlines the previous conclusions that power-to-hydrogen through PEM electrolysers and PEM fuel cells can reduce curtailment and benefit the integration of VRE in the power system.

Regarding electric vehicles, two studies were found with the method described in 2.1. Pavić et al., (2016). They studied the integration of VRE in combination with EVs and concluded that integrating the transport sector with the power system provides added system flexibility. This flexibility through EVs resulted in lower operational costs than when this flexibility is provided by conventional power generators as coal and gas (Pavić et al., 2016). The study of Luca et al., (2018) researched the power system of Germany with a high integration wind and PV power plants in combination with EVs. The study concluded that EVs can provide flexibility to a certain extent however, when their charging is not controlled, it can lead to a higher peak load (Luca et al., 2018). Another important conclusion from their study is that in power systems with a high share of VRE, EVs are not able to be the only flexibility solution that provides balancing of the load (Luca et al., 2018).

Three studies were found that focussed on battery storage and renewable energy curtailment. The research of Branco er al., (2018) focussed on the optimalisation of a power system with high integration of VRE and batteries. This study found that increasing the amount of installed battery storage capacity decreased the amount of curtailed renewable energy significantly, resulting in a larger reduction of fossil fuel consumption (Branco et al., 2018). Both papers of Liebensteiner & Wrienz, (2019) and Després et al., (2017) underline the role of battery storage in reducing the amount of curtailed renewable energy. Després et al., (2017) also explicitly states the heavy increase when more VRE sources are implemented into the power system as a means to achieve the 2°C target.

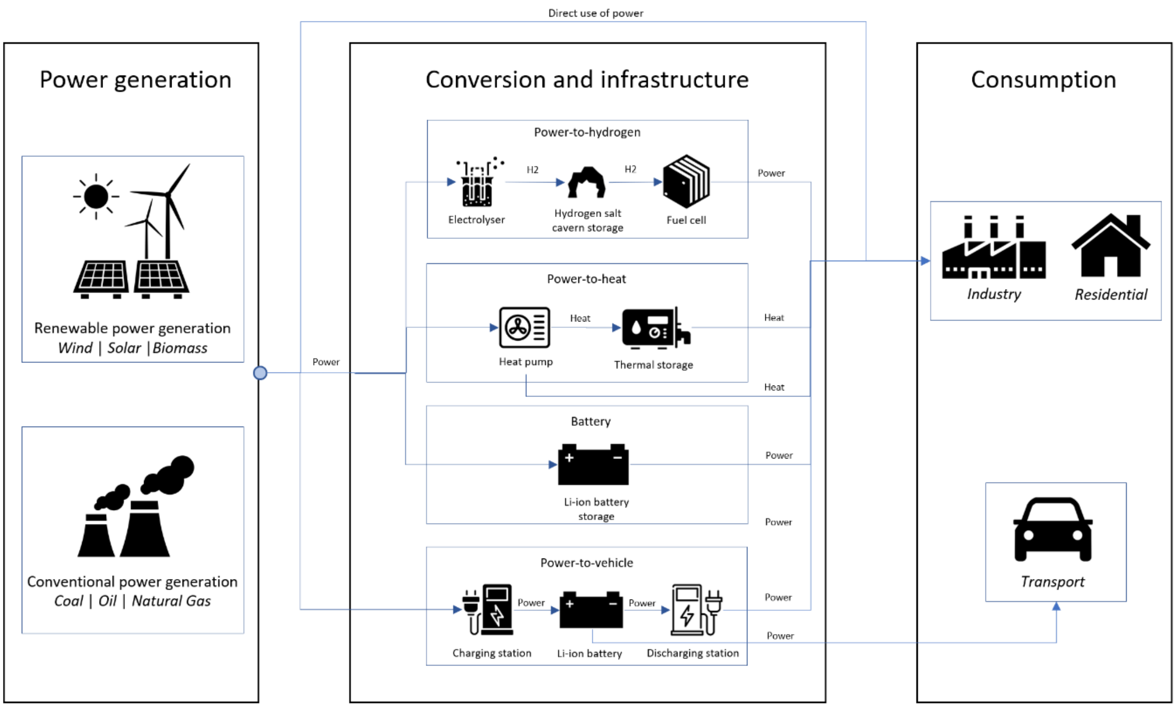
In current literature some papers can be found concerning the use of the lost power of curtailment. However, most studies focus on only battery technologies (Després et al., 2017; Branco, 2018; Liebensteiner & Wrienz, 2019) and others focus only on one sector coupling options (Guandalini et al., 2015; Arabzadeh et al., 2019). With the exception of one paper by Kurpat et al., 2017 which focussed on both coupling the heating sector and hydrogen. As the paper of Bloess (2018) advocated that more research should be done regarding the comparison of the different sector coupling options and batteries in using the lost power through curtailment. Together with the literature analysis of this part it can therefore be concluded that in current literature a gap exists where research is necessary to study the potential of all the sector coupling options and battery storage for using the lost power of curtailment. So, this study will focus on the comparison of the different sector coupling options and batteries.

2.2.2. Sector coupling and batteries in this research

Many different battery storage, P2H, P2T and V2G technologies exist today (Lund et al., 2015; Sabihuddin et al., 2015). This study will focus on the most common technologies used in scientific literature. In the earlier described knowledge gap the conclusion is made to focus this research on the comparison of these technologies. Therefore, this study will focus on the broader view on these technologies and is not an in-depth study to each of the different sector coupling options or battery storage technologies.

Regarding battery storage, in this study li-ion batteries are only taken into account since these batteries are already widely deployed in the current market and are studied widely in today's scientific literature (Lund et al., 2015; Sabihuddin et al., 2015; Child et al., 2019). For the electric vehicles, li-ion batteries are taken into account as well. Mainly with the same argument that these are the most widely deployed batteries in electric vehicles (Lund et al., 2015). From the literature study in 2.2.1, multiple studies used PEM electrolysers and fuel cells because they support the integration of hydrogen into the already existing gas network (Carton & Olabi, 2010; Guandalini et al., 2015; Kurpat et al., 2015). For the hydrogen storage salt cavern storage will be used because this type of storage also integrates easily with the current gas infrastructure (Caglayan, 2020; Wang et al., 2020a). Thus for the P2H option PEM electrolysers, salt cavern storage and PEM fuel cells will be researched in this study. Bloess et al., (2018) conducted an extensive literature on the different technologies of the P2T sector coupling option. This literature review concluded that heat pumps in combination with thermal storage are the most favourable options for P2T (Bloess et al., 2018). Therefore, heat pumps in combination with thermal storage will be researched in this study. Figure 2.1 shows the different sector coupling options and battery storage that will be researched in this study.

Figure 2.1. Sector coupling and battery storage applications in this study (based on Robinius et al., 2017)



2.3. Flexibility indicators

The results of the search method described in the beginning of this chapter are presented in table 2.3 and are discussed here in further detail.

Table 2.3. Selected papers flexibility indicators

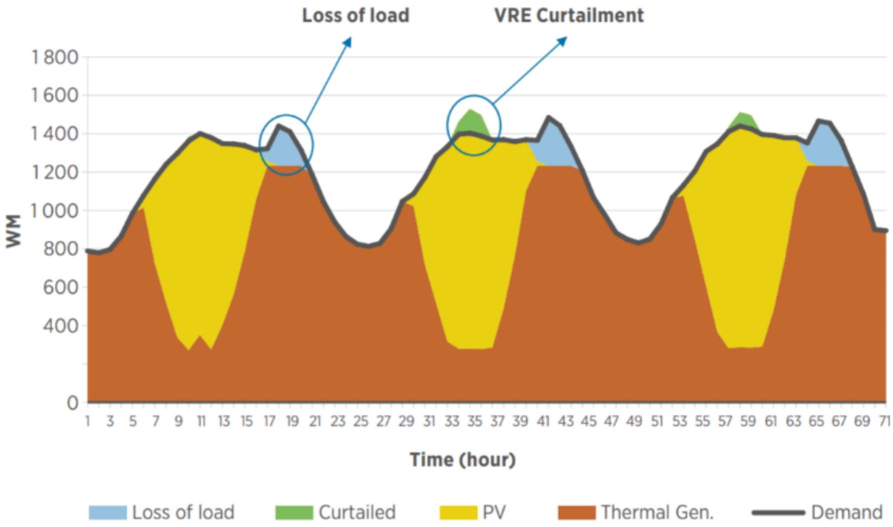
Paper	Topic/Indicator
Abdin & Zio, (2018)	Loss of load, curtailment, Peak prices

Papaefthymiou, (2018)	Loss of load, curtailment, Peak prices
Poncela et al., (2018)	Loss of load, curtailment,
Akrami et al., (2019)	Loss of load, Curtailment, Peak prices
Soroudi et al., (2017)	Curtailment
Haas et al., (2017)	Curtailment

As mentioned in the introduction, power systems need to become more flexible in order to cope with the increasing amount of VRE generation in the coming decades. In the current academic literature, no consensus can be found on the metrics that can best be used to assess the flexibility of a power system (Abdin & Zio, 2018). Therefore, instead of assessing the flexibility of a power system or flexibility options it is better to look at signs of inflexibility such as negative market prices, VRE curtailment, loss of load and price volatility (Papaefthymiou, 2018).

Multiple papers were found in the literature search that underline these signs of inflexibility as a good metric to assess the flexibility of both the power system and flexibility options. So does the paper of Poncela et al., (2018) use VRE curtailment, energy demand not served and peak prices as indicators for a power systems flexibility. Akrami et al., (2019) state the same indicators when assessing the long-term effects of an increase in integration of VRE on the flexibility of a power system. Other papers focus merely on one or two indicators to study the flexibility of a power system. Soroudi et al., (2017) and Haas et al., (2017) both measures the amount of VRE curtailment when assessing demand flexibility and energy storage in low-carbon power systems. Figure 2.2 illustrates the flexibility indicators loss of load and VRE curtailment in a power system with a high share of PV in the generation mix. In this case the VRE curtailment occurs when there is an oversupply of PV generation and the loss of load occurs when there is no PV generation and the demand is at a peak (IRENA, 2018a).

Figure 2.2. Flexibility issues system with high share of PV (IRENA, 2018a)



Resulting from the literature review, the indicators mostly used in current scientific literature to research the effects of flexibility options are VRE curtailment and loss of load. Measures around electricity prices are used as well, but more for the total power system and not specifically for flexibility options. Therefore, this study will use the two indicators of loss of load to assess sector coupling and batteries. This study will use the electricity prices as secondary measure to assess flexibility in the power systems of the Netherlands and North West Europe the power system but not specifically as measurement for the flexibility options.

2.4. Energy system modelling

As described in part 1.4. IRENA developed the FlexTool in order to assess flexibility problems such as curtailment and loss of load of a future or current energy system. Besides, the tool evaluates how these problems could possibly be solved with new technologies such as sector coupling (IRENA, 2020b). The results of the search method for energy system modelling describe the role of the FlexTool in the current literature. The results are presented in table 2.4 and are discussed here in further detail.

Table 2.4. Selected papers energy system modelling

Brouwer et al., (2015) **Dodds & McDowall, (2013)**	MARKAL
Fehrenbach et al., (2014) **Merkel er al., (2017)** **Pavičević et al., (2020).**	TIMES
Connolly et al., (2016)	EnergyPLAN
Welsch et al., (2014)	OseMOSYS
Taibi et al., (2018)	IRENA FlexTool

Four models were found in academic literature through the search method as described in part 2.1. The models were the MARKAL and TIMES model, both developed by the IEA (Brouwer et al., 2015; Merkel er al., 2017), the EnergyPLAN model, developed by the Aalborg University (Connolly et al., 2016) and the OSeMOSYS model which is developed by (Welsch et al., 2014). These models all have a wide variety of applicational use. However, they do often show inadequacies in representing the need to increase the flexibility in the power system (Welsch et al., 2014). Whereas the IRENA FlexTool is specifically designed for assessing the flexibility needs, in combination with providing solutions to the power grid focussed specifically on sector coupling and storage on a country level with the time frame of an hour to a year (IRENA, 2020b)

The IRENA FlexTool is specifically designed to provide the flexibility outputs of curtailment and loss of load. Therefore, this tool connects well to the earlier described flexibility indicators for sector coupling and batteries. In current literature only other models, besides the FlexTool, are used to assess the flexibility of an energy system. In the policy documents where the IRENA FlexTool is used, the FlexTool is used specifically and only on the country level (Taibi et al., 2018; IRENA, 2018a). No studies with a broader international scope could be found. Since the IRENA FlexTool is, besides policy documents by IRENA (IRENA, 2018a, IRENA, 208b), not yet used in the academic literature found in Google Scholar and Scopus according to this search method. It can be concluded that in the current literature a gap exists regarding the use of the IRENA FlexTool in the field of flexibility and energy system studies.

2.5. This research

2.5.1. Knowledge gap

Resulting from the literature reviewed in the previous paragraphs, two specific knowledge gaps were found. The papers found in the current state of the art literature focus on the problem of the abundant curtailed energy from renewable energy, such as wind and PV when their share increases in the generation mix. Most papers focus on solving this issue by one of the mentioned sector coupling options or batteries as mentioned in the introduction. Therefore, a knowledge gap exists in the fact that there is no research that compares all these different sector coupling options and batteries to lower the curtailed power of wind and PV. The researched literature showed that the indicators on which to assess these options are VRE curtailment and loss of load.

The other knowledge gap that exists in the current literature concerns the application of the IRENA FlexTool. As this tool is specifically designed to find solutions regarding flexibility issues of curtailment and loss of load. The researched literature showed that the IRENA FlexTool has not yet been used in the current academic literature. Therefore, there is a knowledge gap in the application of the IRENA FlexTool in an academic research, regarding flexibility issues in the power system.

2.5.2. Objective and scope of the research

As a result of the knowledge gap that is found in the current literature, this study will research the potential of sector coupling options and batteries in utilizing the lost power from VRE curtailment by means of the IRENA FlexTool. As the IRENA FlexTool is specifically designed to focus on the country level, the research will consider the two scales of North West Europe and the Netherlands. To see the difference when the IRENA FlexTool models a country on its own and when the environment of the country is included. The aim of this research is to compare batteries and sector coupling options, when the climate goals of the EU are met with only the integration of the renewable energy sources wind and PV for North West Europe and the Netherlands by means of the IRENA FlexTool.

2.5.3. Research questions

The knowledge gap found in the current literature will be researched according to the following research question:

How can battery storage and sector coupling cost optimally utilize the power that is lost through variable renewable energy curtailment and avoid loss of load for the Netherlands and North West Europe in 2050, using the IRENA FlexTool as modelling approach?

The main research question will be answered by finding the answers on the following sub questions:

1. *Which reference scenario is mainly used in scientific literature as a reference scenario for a European energy system in 2050?*

2. *How much power is lost through curtailment and loss of load occurs when the EU climate goals are met in 2050 by only integrating VRE for the Netherlands and North West Europe using the IRENA FlexTool?*

3. *What are the levelized cost of energy of sector coupling and batteries in 2050 for the Netherlands and North West Europe using the IRENA FlexTool?*

4. *What do the modelling results show about the suitability of the IRENA FlexTool for modelling battery storage and sector coupling for the Netherlands and North West Europe?*

2.5.4. Place of this thesis in the master CoSEM programme

Assessing new flexibility options in the future power system concerns the question of a technical intervention in a complex socio-technical system. Hence, this research topic suits the objectives of a thesis for the master Complex System Engineering and Management. The technical complexity of this study lies in assessing different technological interventions as the integration of renewable energy in the form of wind and PV, sector coupling options and batteries into the power system. The social complexity is addressed by the resulting issues regarding electricity prices in the power system and the influence for policy makers.

2.5.5. Contribution of this research

The academic contribution of the research lies in adding new academic insights regarding both the use of the IRENA FlexTool and the comparison of sector coupling options and batteries in used the curtailed power of renewable energy. As the IRENA FlexTool is never used before in academic literature, this research will contribute by describing the FlexTool and asses two different applications of the tool by looking at both, the Netherlands and NWEU level. The results of this can help further literature through knowledge of when to use, and when not to use this problem in answering other pressing research questions.

The societal contribution of this research is inhabited in the results of the different scenarios that will be researched. As renewable energy integration is evidently necessary to reach the European goal of becoming climate neutral, it is also important to assess the possible problems that arise when trying to accomplish such a goal. This research tries to identify one such problem in the form of curtailed renewable energy that hamper investments in renewable energy. Therefore, this study can benefit policy makers or organizations that are operating in the energy industry in making sounder decisions, regarding the further integration of renewable energy with the help of future flexibility options in the power system.

2.5.6. Structure of this report

In order to answer the research question this research report is structured as follows: at first the method used will be explained in the modelling chapter in chapter 3, this includes the general modelling applications of the IRENA FlexTool, a more in-depth explanation of the mathematical model and ends with the explanation of a design of experiments which is used in order to compare the different technologies. Secondly the scenarios to assess the integration of renewable energy into the power system will be explained together with the scales that are used for the Netherlands and North West Europe in chapter 4. Thirdly the input data used in this research is explained with its corresponding sources in chapter 5. This is followed with the description of the results of the modelled scenarios with the IRENA FlexTool in combination with the DOE in chapter 6. These results will be discussed in chapter 7 together with the research limitations and future work. At last, this report ends with a conclusion of the main results and discussion in chapter 8.

3. Modelling

The following two chapters describe the method that is used in this research. The goal of this chapter is to explain the modelling approach taken in this study. The next chapter will focus on the scenarios that are used. This chapter is structured by first describing the workings of the Flex Tool on a high level. This includes the structure, workings and abilities of the FlexTool. Secondly the part of the mathematical model with the most influence on this research will be presented and shortly described as it is defined by IRENA (2018). Thirdly the method of comparing sector coupling options and batteries will be explained. The chapter concludes with the validation of the IRENA FlexTool by using historical data.

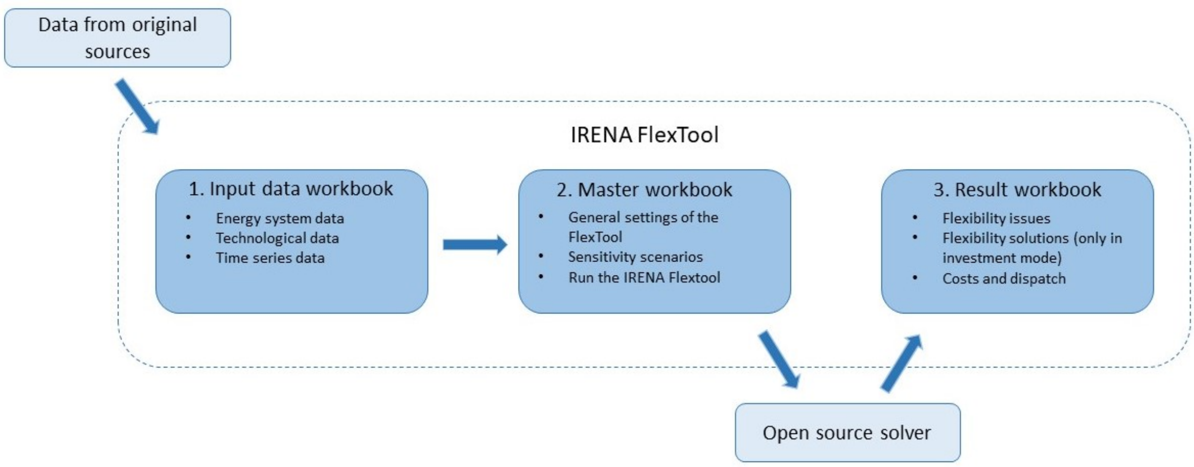
3.1. Description of IRENA FlexTool

The IRENA FlexTool is a dispatch model created to analyse system operations which also able to optimise investments in generation, storage and transmission capacity (IRENA, 2018).

3.1.1. High-level modelling process of the IRENA FlexTool

Figure 3.1 presents the modelling process with the IRENA FlexTool. The model consists of three Microsoft Excel workbooks: the input data, master and result workbook. The input data workbook functions as the base scenario of the model. Data concerning the energy demand, generation mix, costs and technical characteristics of power plants from original sources need to be provided here. Once the input data workbook is set, it can be accessed as base scenario from the master workbook. From the master workbook different input data workbooks can be run and different scenarios can be created

Figure 3.1. Work-process IRENA FlexTool based on IRENA, (2018)



regarding costs, demand, unit and transmission capacity. For each scenario an investment module can be selected in order for the model to optimize investments in capacity and storage if applicable. When this is done and the model ran in either dispatch or investment mode using linear programming via an open source solver, the IRENA FlexTool will create a result workbook. This workbook describes the main results such as the systems total costs in the summary sheet and more detailed outcomes can be examined further through the more detailed result sheets (IRENA, 2018).

3.1.2. Input and output data of the IRENA FlexTool

The main objective of the IRENA FlexTool is to minimize the operating costs, investment and penalty costs of an energy system (IRENA, 2018). The operational cost includes the fuel costs, operation & maintenance cost and the start-up costs. The investment costs are the costs that the FlexTool is able to optimise from. And the penalty costs refer to the costs that need to be paid when a system experiences loss of load, loss of reserve, lack of capacity or when VRE needs to be curtailed (IRENA, 2018). The FlexTool includes a set of constraints in order to simulate the power systems real technical constraints, these constraints together with the objective function will be discussed in more detail in 3.2.

The IRENA FlexTool consists of four basic sets that each need to be defined and provided with external data in the input data workbook:

- Grid: a grid through which energy in different forms (e.g., electricity, gas, heat) can be transferred (IRENA, 2018).
- Node: a node is the collection of energy that is generated, consumed and transferred between nodes that are connected to the same grid (IRENA, 2018).
- Unit: a unit defines a device that is able to generate energy from external sources, decrease or increase energy consumption, or store or convert energy from one form of energy to another (IRENA, 2018).
- Time: is the selected time span that the model runs which has the minimum of an hour and the maximum of a year (IRENA, 2018).

Figure 3.2 shows the main input data in the grey boxes and the model variables in the orange boxes. The input data is divided across 12 different excel sheets in the input data workbook, table 3.1 describes each sheet and its required input data.

Figure 3.2. input data and model variable FlexTool based on IRENA, (2018)

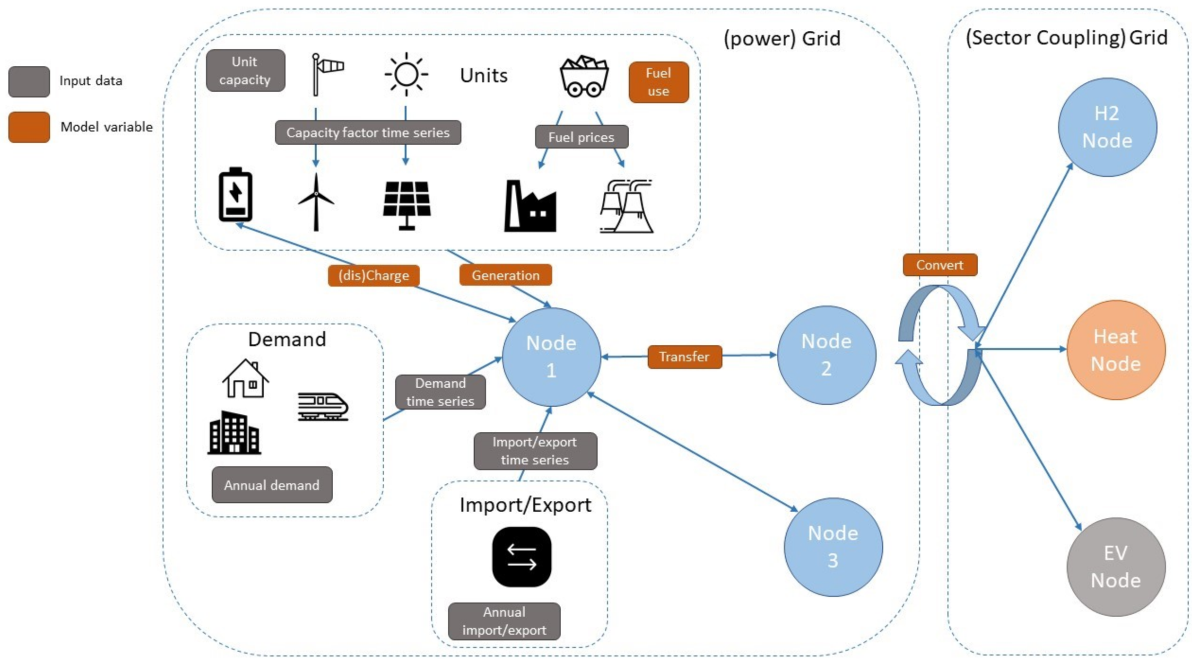


Table 3.1. Data input sheets

Sheet	Description
master	Set settings that affect whole model e.g., CO2 price, penalties and set investment or dispatch mode.
gridNode	Specify the properties (demand, import/export) of the nodes and grids that exist.
unit_type	Specify properties of the units that exist
fuel	Specify available fuels and their prices and CO2 properties.
units	Specify capacity and input of units and set them to specific grid and node.
nodeNode	Specify transmission capacities between nodes.
ts_cf	Specify hourly time series of the capacity factors (0 to 1) for wind and solar.
ts_inflow	Specify hourly time series of absolute energy inflow for units like hydropower.
ts_energy	Specify time series for demand of energy in node
ts_import	Specify energy imports per node that are external to the model.
ts_reserves	Specify time series for the required reserve per node.
ts_time	Specify the time in hours to be ran in the model, min 1, max 8759.

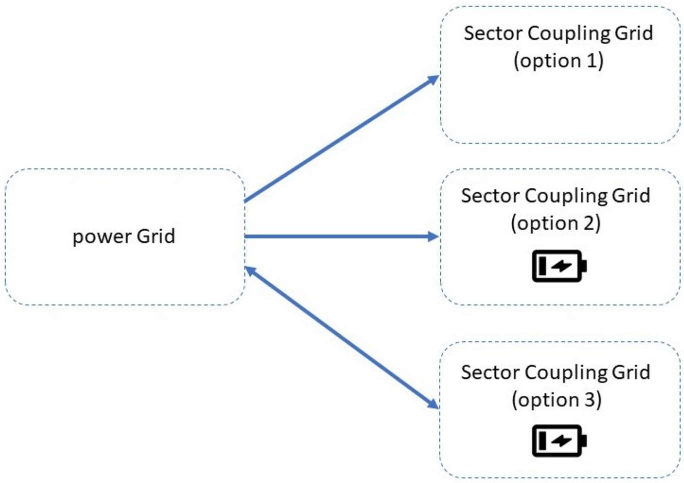
The main model outputs concerning flexibility that are drawn from the different variables are the loss of load, VRE curtailment, Reserves shortage, capacity inadequacy and spillage. Furthermore, the model provides the outputs of the dispatch per generator and node, transmission between nodes, electricity price per node, ramping information and OPEX consisting of fuel, CO2, curtailment, loss of load and O&M costs (IRENA, 2018).

The FlexTool is able to optimise transmission, storage planning and generation for a full year of (sub)-hourly operations. The problem can however become too large to solve when investment variables are included in the model (IRENA, 2018). This can happen because the IRENA FlexTool optimises everything at once (IRENA, 2018). For this study the maximum time horizon was used in every model run to obtain the most accurate results. From the IRENA reports it became clear that the model calculation time would increase a lot when sector coupling options are included in the model. The methodological report from IRENA (2018) stated that when sector coupling options are included and the user wants to run the FlexTool in investment mode, the chance is relatively high that the model would not be able to provide a solution (IRENA, 2018). Therefore, the choice was made to use the FlexTool only as a simulation model and not as an optimisation model via the investment mode. This has the implication that another option for the comparison of sector coupling and batteries had to be found. The study will therefore use a design of experiments in order to compare the sector coupling options and batteries. How and why this is done is described in more detail in 3.3.

3.1.3. Modelling sector coupling with the IRENA FlexTool

As described in section 3.1.2. the IRENA FlexTool can also represent more complex forms of electricity consumption and generation with the use of different energy grids. Figure 3.2 shows that the energy can be converted from one grid to the other, with each sector coupling node also having its own annual demand and demand time series. Through this ability, the different sector coupling options as described in chapter 2 can be modelled. There are three options to model sector coupling with the IRENA FlexTool, these are illustrated in figure 3.3. Option 1 includes only an extra grid with the demand of the added sector, no storage and no return of power to the power grid exists. Option 2 includes a storage option for a temporal shift in power usage, however with no return of power to the power grid. Option 3 does provide the option to return power to the power grid and also store power for a temporal shift in power usage.

Figure 3.3. Options FlexTool for modelling sector coupling



In this research the sector coupling options are modelled according to the following options: EVs are modelled as option 3. This was done by creating a separate grid for EVs. To this grid a node was added that included the EV demand and units. The EV node had a charging unit that converted the energy from the power grid to the EV grid and a charging unit that converted the energy back from the EV grid to the power grid. A storage unit was added that represented the electric vehicles storage capacity. To each EV node a separate annual demand and demand time series were added to represent the use of the electric vehicle. For power-to-hydrogen option 3 with the same method was used. Option 2 was used for power-to-heat. Since the power-to-heat option did not include a charger that converted the thermal energy back to the power grid. Including all the sector coupling options in the model resulted in a total of 4 different energy grids, one for EVS, one for hydrogen, one for heat and one for power.

3.2. Mathematical description of IRENA FlexTool

The main mathematical formulas are explained in this part, the full mathematical model can be found in the IRENA FlexTool Methodology part II (IRENA, 2018) document. Here the objective function, the energy node balance constraint and the energy storage balance constraint of the FlexTool are described and explained mathematically here as defined in the IRENA FlexTool Methodology (IRENA, 2018). Table 3.2. shows the symbols used in the mathematical model with their description. The constraints not included in this chapter are the reserve demand, fuel use, start up, and ramping constraint. The investment variables should not be considered in the equations as these are only used in the investment mode, which is not used in this study.

Table 3.2. Symbols and description mathematical model

Symbols	Description
$\boldsymbol{cf}$	Capacity factor
$\boldsymbol{e}$	Emission
$\boldsymbol{F}$	Fuel
$\boldsymbol{g}$	Grid
$\boldsymbol{h}$	Duration (hours) of the time periods
$\boldsymbol{L}$	A line between nodes
$\boldsymbol{n}$	Node
$\boldsymbol{NN}$	Both directions for a connection between two nodes
$\boldsymbol{N_n}$	Nodes with a line to node n
$\boldsymbol{p}$	Parameter
$\boldsymbol{r}$	Reserve
$\boldsymbol{t}$	Time step index
$\boldsymbol{T}$	Set of time steps t
$\boldsymbol{t - h_t}$	Previous time period
$\boldsymbol{u}$	Unit
$\boldsymbol{U}$	Set of units u
$\boldsymbol{v}$	Variable

As mentioned previously the model minimizes the operational costs as arranged by the objective function. Where the objective function minimized the total penalty costs, operation & maintenance cost, fuel cost and start-up cost of all hours modelled. The objective function is formulated by IRENA, (2018) as follows:

Objective function:

$$v^{obj} = min \sum_t (v_t^{omCost} + v_t^{fuelCost} + v_t^{startupCost} + v_t^{penalties}) * h + v^{investmentCost} \quad (1)$$

Where:

$$v_t^{omCost} = \sum_{\{g,n,u\} \in U_{g,n,u}} (p_u^{omCosts} * v_{g,n,u,t}^{gen}) \qquad \forall\, t \in T \quad (2)$$

$$v_t^{fuelCost} = \sum_{\{n,u,F\} \in F_{n,u,F}} (v_{F,u,t}^{fuelUse} * p_F^{fuelCost}) \qquad \forall\, t \in T \quad (3)$$

$$v_t^{startupCost} = \sum_{u \in U_u^{startup}} (v_{u,t}^{startup} * p_u^{startCost}) \qquad \forall\, t \in T \quad (4)$$

$$v^{investmentCost} = \sum_{\{g,n,u\} \in U_{g,n,u}} (p_u^{investmentCost} * v_{g,n,u}^{investedCapatity}) \quad (5)$$

$$v_t^{penalties} = \sum_n (v_{n,t}^{lossOfLoad} * p_n^{lossOfLoadPenatly} + v_{n,t}^{lossOfReserve} * p_n^{lossOfReservePenalty} + v_{n,t}^{curtail} * p_n^{curtailmentPenalty} + v_n^{capacityInadequacy} * p_n^{capacityInadequacyPenatly}) \quad \forall\, t \in T \quad (6)$$

$$p_{F,n,t}^{fuelCost} = p_{F,n,t}^{fuelprice} + \sum_{e \in E_F} p_{F,e}^{fuelEmission} * p_{n,e}^{emissionTax}) \quad \forall\, t \in T \quad (7)$$

In all the nodes the energy balance needs to be maintained. The conversion variables determine the amount to be converted from one grid or the other as is formulated by the following constrained

$$v_{g,n,t}^{gen} + v_{g,n,t}^{convertIn} + p_{g,n,t}^{import-export} + v_{g,n,t}^{LossOfLoad} = p_{g,n,t}^{demand} + v_{g,n,t}^{charge} + v_{g,n,t}^{transfer} + v_{g,n,t}^{convertOut} \quad (8)$$

Where:

$$v_{g,n,t}^{gen} = \sum_{u \in U^{nonVRE}} v_{g,n,u,t}^{gen} + (\sum_{u \in U^{VRE}} p_{u,t}^{cf} * [p_{g,n,u}^{capacity} + v_{g,n,u}^{invest}]) - v_{g,n,t}^{curtail} \quad (9)$$

$$v_{g,n,t}^{transfer} = \sum_{n2 \in N_n} (v_{n2,n,t-h_t}^{transfer} * p_{n2,n}^{transferEff} - v_{n,n2,t-h_t}^{transfer}) \quad (10)$$

$$v_{g,n,t}^{convertIn} = \sum_{\{g2,n2,u\} \in U_{g2,n2,u,g,n}^{convert}} v_{g2,n2,u,g,n}^{convert} * p_u^{conversionEff} \quad (11)$$

$$v_{g,n,t}^{converOut} = \sum_{\{g2,n2,u\} \in U_{g,n,u,g2,n2}^{convert}} v_{g,n,u,g2,n2}^{convert} \quad (12)$$

The energy balance equation for storage units has to be maintained for all storage units and is formulated by the following constraint:

$$v_{g,n,u,t}^{state} = v_{g,n,u,t-h_t}^{state} + p_{u,t-h_t}^{influx} + \left(v_{g,n,u,t-h_t}^{charge} - v_{g,n,u,t-h_t}^{gen} - v_{g,n,u,t-h_t}^{spill} - v_{g,n,u,t-h_t}^{state} * p_u^{selfDischargeLoss}\right) * h \quad \forall\, u \in U^{storage} \quad (13)$$

The transmission between the nodes are defined by the following constraint:

$$v_{\;n,n2,t}^{\;transfer} \leq p_{\;n,n2}^{\;transferCap} + v_{\;l \in L^{invest}}^{\;transferInvest} \quad \forall\, n, n2 \in NN \quad (14)$$

The curtailment limit has to meet the following constraint as it can never be more that the generated renewable energy:

$$v_{g,n,t}^{curtail} \leq \sum_{u \in U^{VRE}} p_{u,t}^{cf} * (p_{g,n,u}^{capacity} + v_{g,n,u}^{invest}) \quad (15)$$

The conversion limits are provided by the following constraints:

$$v_{g,n,u,t}^{convert} \leq p_{g,n,u}^{capacity} + v_{g,n,u}^{invest} \quad \forall u \in U^{convert} \quad (16)$$

$$v_{g,n,u,t}^{reserve} \leq v_{g,n,u}^{convert} + p_{g,n,u}^{reserveCapability} \quad \forall u \in U^{convert} \quad (17)$$

$$v_{g,n,u,t}^{convert} \geq v_{g,n,u,t}^{online} * p_{g,n,u}^{minLoad} \quad \forall u \in U^{convert} \quad (18)$$

3.3. Design of experiments

Because of the inability to use the investment mode of the FlexTool when modelling sector coupling, another method had to be used to compare the different sector coupling options and batteries. In order to still compare the different sector coupling options and batteries, a factorial design was used. This method is widely used in experimenting and exploring the effect of a factor on a response (Gunst & Mason, 2009).

To use this method in order to compare batteries and sector coupling options, three different levels, low, medium and high were determined, these are discussed in chapter five. Since there are also four options, power-to-hydrogen, power-to-heat, power-to-vehicle and batteries, the full factorial design would consist of 81 experiments. This resulted in the fact that the FlexTool had to run 81 times for both the Netherlands and North West Europe in order to find the relation of the technologies to the objective function and the relation among the technologies. To minimize the amount of experiments, the choice was made to only focus on the main effect of the technologies on the objective function. In order to come up with the minimal amount of experiments for this main effect, an optimal design had to be chosen, instead of running the full factorial design. The software Minitab was used to calculate the optimal design of experiments. This is a data analysis tool that is able to calculate the optimal design of experiments from the full factorial design (Mathews, 2005). Using Minitab for the optimal design of experiments for only the main effect of batteries and sector coupling on the flexibility indicators reduced the number of runs with the FlexTool to 9.

After the DOE was performed, the different technologies were compared on the amount of loss of load (in % of annual demand), curtailment (in % of VRE) and the levelized cost of energy (LCOE) for the three different levels. The first two measurements for the comparison were generated by the model and were shown in the result workbook of the FlexTool. The LCOE had to be calculated separately with different measurements from the result workbook. The LCOE is the price in € per MWh of the electricity produced by the specific technology (Blok & Nieuwlaar, 2016). The levelized cost can be calculated according to the following formula as defined by Blok & Nieuwlaar (2016):

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + OM_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}}$$

Where:
$I = initial\ investment$
$OM = annual\ costs\ for\ operation\ and\ maintenance$
$F = annual\ fuel\ cost$
$E = annual\ energy\ production$
$r = discount\ rate$

3.4. Model validation

To validate the IRENA FlexTool a model of North West Europe with the countries included as shown in figure 3.4 was modelled with data regarding actual load, transmission and installed generation capacity available from the ENTSOE transparency platform (ENTSO-E, 2019a, 2019b, 2019c) for the year 2018. For the variability in solar and wind generation the hourly capacity factors from Pfenninger & Staffell, 2016 are used for the year 2018 as well. The results of this model run were compared with the historical price data from the ENTSO-E (2019d).

Figure 3.4. North West Europe

Figure 3.5 and 3.6 show the results of the IRENA FlexTool and the historical price as given by the ENTSO-E (2019d). The output of the FlexTool concerning electricity price differs from the historical data of hourly electricity prices. The largest difference can be seen in Germany. Especially the peak prices and the prices that go below €0/MWh are not modelled correctly by the IRENA FlexTool.

Figure 3.5. Historical and FlexTool prices Germany

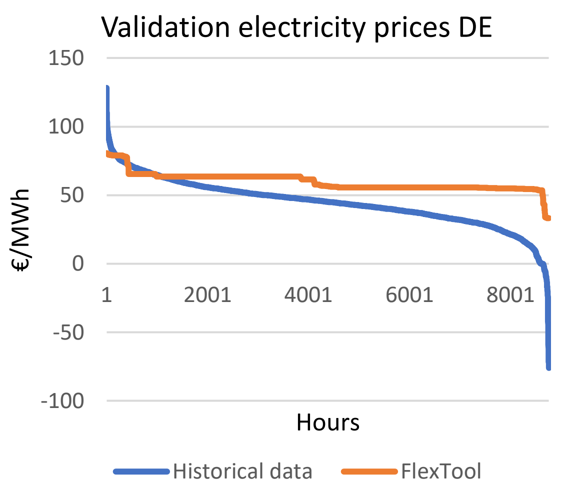
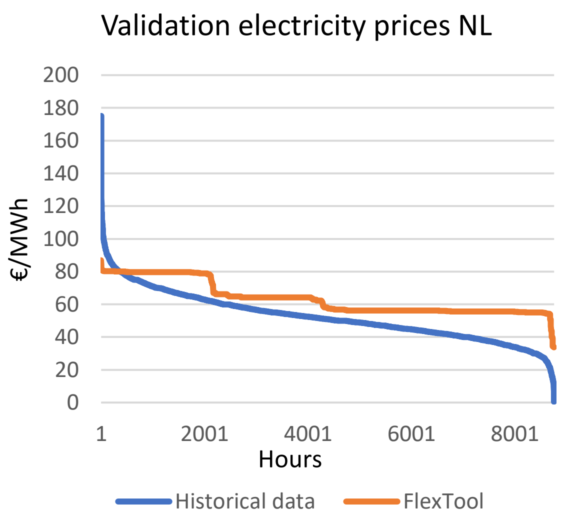


Figure 3.6. Historical and FlexTool prices Netherlands



To check if the FlexTool could still be used, the indicator loss of load from the modelling results was compared to the historical data. The ENTSO-E did not provide specific data on their transparency platform for the loss of load. Therefore, the annual market report 2018 from Tennet (2019a) is used for validation of the loss of load and curtailment in the Netherlands. The model does provide more accurate results regarding the loss of load indicator. The loss of load modelled by the IRENA FlexTool is in both the Netherlands and Germany 0. This does match with the amount of loss of load from the Tennet (2019) report as the loss of load from the 2018 market report is 0 as well.

This chapter described the workings of the FlexTool and the implications from using this tool on this research. Sumarizing this chapter, the main implication is that for the comparison of batteries and sector coupling options the investment mode in the FlexTool did not prove to be a viable option. In order to get around this shortcomming an optimal design of experiments was proposed. The model validation showed that the FlexTool can be used to study the flexibility of the power system of the Nehterlands and North West Europe however, the inaccuracy of modelling the electricity peak prices should be taken into account. The next chapter will describe the scenarios used in this research with the model and method that is described in this chapter.

4. Scenarios

This chapter will provide an elaboration on how and why the two scales of North West Europe and the Netherlands are used in this study. This chapter will, in order to answer the research question and sub question 3, select an energy scenario for Europe towards 2050 from current scientific literature. The scenario found in the literature will function as a base scenario from which a scenario was created where the goals of the EU are met with VRE integration. This scenario will be called the FLEX scenario and was derived from the base scenario by phasing out coal and oil in 2030 and phasing out natural gas in 2050, how this was done is described in 4.2.2. For the two scales of the Netherlands and the North West of Europe, the same scenarios were used. This choice was made to better compare the results of the FlexTool when the Netherlands is modelled on its own and the Netherlands in the NWEU scale.

4.1. Scale

Mentioned in the introduction this research will focus on two different scales, North West Europe and the Netherlands. The North West of Europe is a region defined by the European Commission in their regional policies with a special focus to become an attractive place to work and live on the basis of innovation and sustainability (European Commission, 2020). The goal of the European Commission is to transform North West Europe to a low carbon region. The North West of Europe as defined by the European Commission includes the countries of France, the United Kingdom (UK), Germany, the Netherlands, Belgium, Ireland and Luxembourg (European Commission, 2020). Since these countries have the specific goal to become a low carbon region, they made plans in their NECPs to increase the share of wind and PV in the power mix strongly (European Commission, 2020c).

The Netherlands defined in their climate agreement to use a regional energy strategy (RES) where the country is divided in 30 energy regions. These 30 regions each have to decide where and how they are going to meet the climate targets of the Netherlands for 2030 (RES, 2020). Most energy regions focus on building new wind and PV parks to generate more renewable energy (RES, 2020). Therefore, it is important for these regions to also consider how to build in flexibility into their power system, due to the problem described in the introduction.

4.1.1. The Netherlands

In order to find with how many nodes, the FlexTool would be able to run the 30 regions, multiple test runs with the FlexTool were made. The first test run ran the FlexTool with the 30 energy regions according to how the regions are divided in the RES and with data from the Klimaatmonitor (2020). The input data for the test run with 30 energy regions is presented in appendix V. Figure 4.1 shows the 30 energy regions of the Netherlands. Each energy region was represented as a node. This had the implication that the variability of demand, power generation and import/export for each energy region was determined in their node. Sector Coupling and Batteries were not yet included in this model. While running this 30-energy region model of the Netherlands, the FlexTool could not provide any results.

The FlexTool only provided empty result workbooks. Which, according to IRENA (2018) indicates that the solver is not able to solve the model due to a to large proposed model.

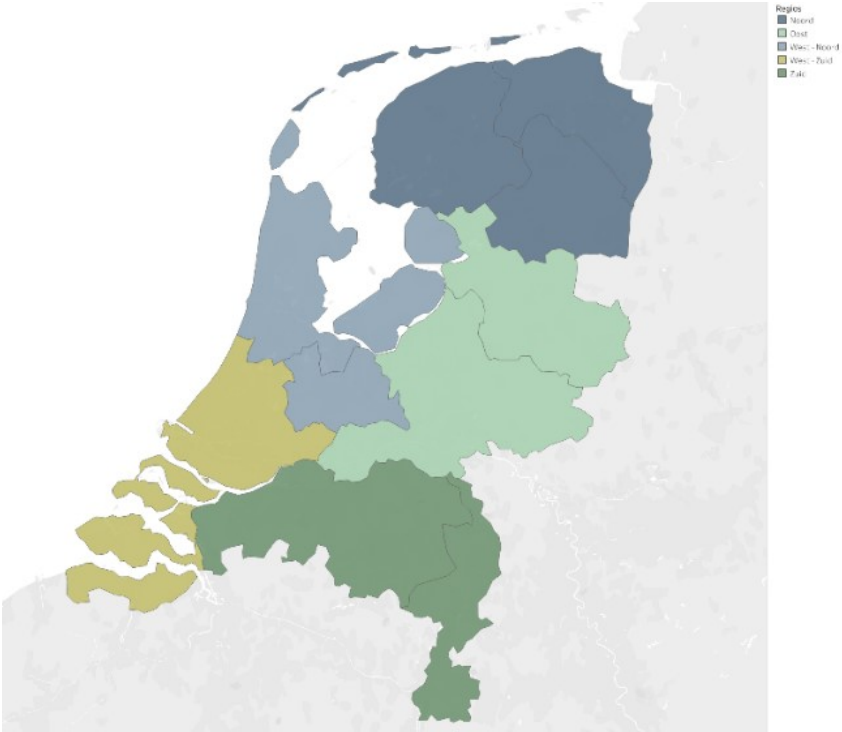
The FlexTool was in this case not able to run a model with 30 nodes, thus a smaller resolution had to be chosen to run the energy regions of the Netherlands. In order to still be able to analyse the flexibility needed in the energy region, the same distribution and variety had to be preserved in the smaller resolution. Therefore, the following rules where used to merge the energy region:

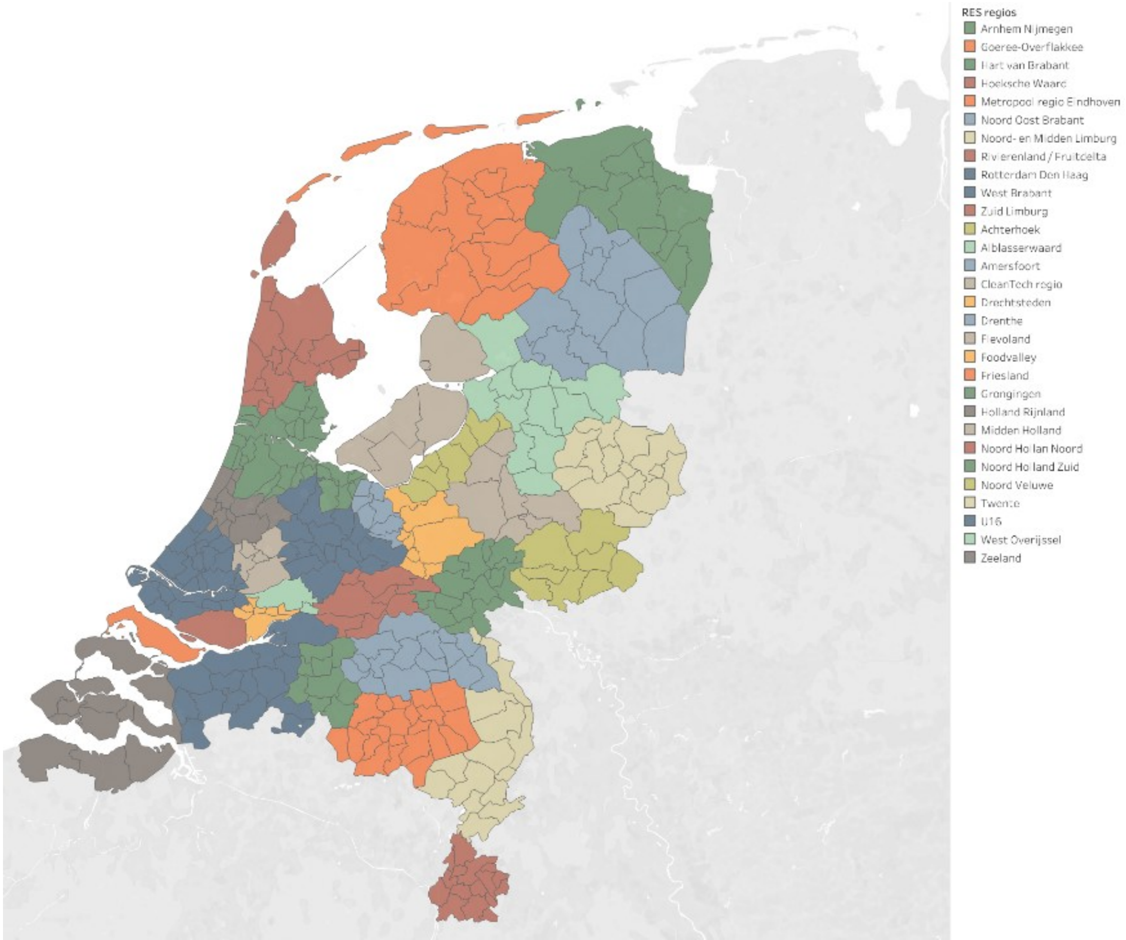
1st Start from the RES region with the smallest population
2nd Combine with neighbour with also the smallest (population)
3rd If a neighbour is already in a group, then combine with second smallest neighbour
4th If no neighbours left then stay singular

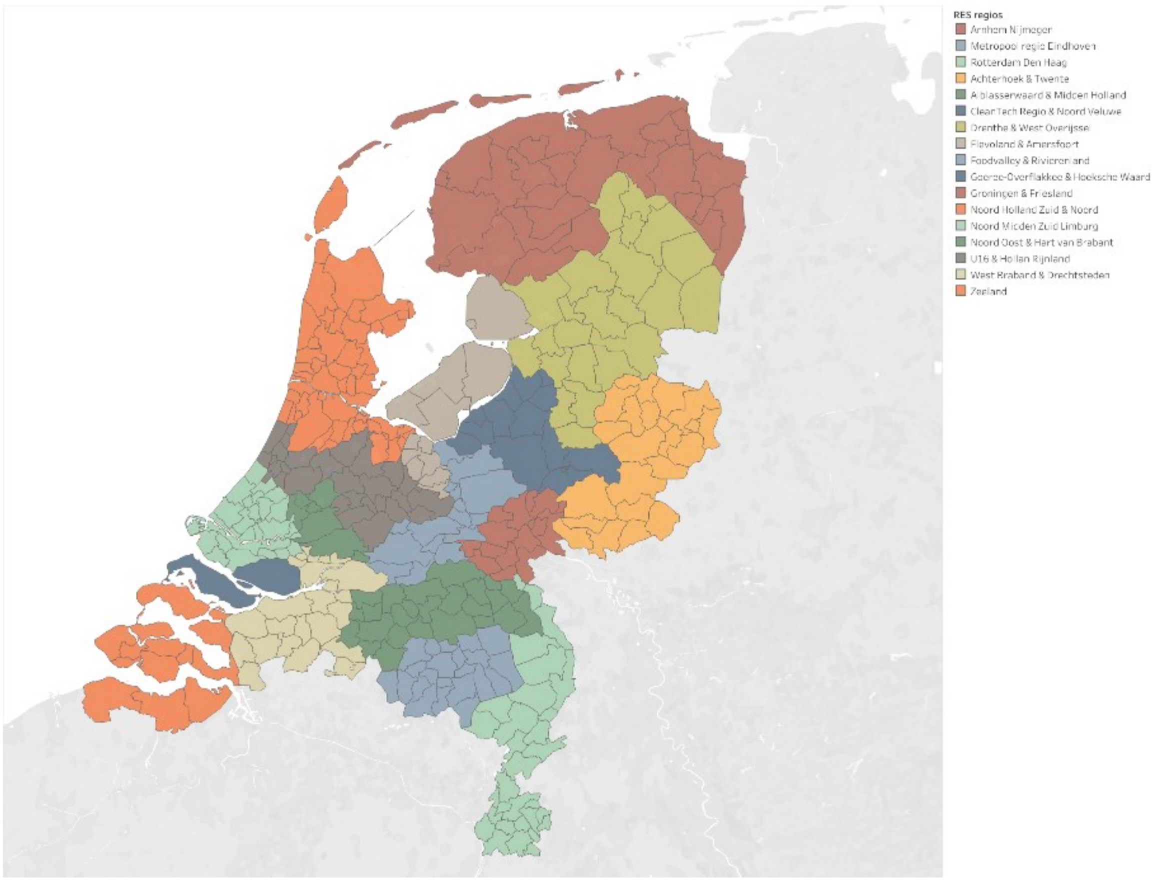
The choice was made to put smaller groups together because in this way the diversification (in population size) of the energy regions is guaranteed. Also, the choice was made to put not more than 2 in a group because this would result that all the smaller regions would be combined with the larger regions and result in lesser diversification in size of the regions. Applying these rules on the 30 energy regions resulted 17 combined energy regions. These 17 combined energy regions are illustrated in figure 4.2.

The first run with this resolution was without including sector coupling and batteries, the input data for this test run with 17 regions is presented in appendix V. The FlexTool did work in this first run and provided a full results workbook. The second run with this resolution did include sector coupling and batteries but resulted in an empty results workbook due to the extra added nodes needed to model sector coupling. In order to cope with this shortcoming, it was tried to mimic the sector coupling options by circumventing the way the FlexTool modelled sector coupling options. This was done by adding the demand of EVs and Heat pumps to the annual demand, and demand time series and adding the units to the power grid. The hydrogen network was removed and only a hydrogen storage was implemented. Through this method, no extra grids had to be used, downsizing the calculation time of the model. However, the model in this case still did not work accordingly. The running time became over 52 hours with no sign in sight of being almost finished, therefore the decision was made to shut down the model run. Therefore, this resolution was also not sufficient to model the energy regions for the Netherlands.

To further decrease the resolution but to still keep the variety of the energy regions as much as possible, the Netherlands was divided in the five regions of North, East, South, South-West and North-West regions. This distribution is defined in the RES as the RES land division based on the 30 energy regions of the Netherlands (Klimaatmonitor, 2020). This was therefore a suitable distribution for a minimum number of regions but where the division is still based on the energy regions. Figure 4.3 shows the Netherlands scale divided in five regions. Here each region is also represented as a node which is connected to the electricity grid. For this scale a test run with the FlexTool was done with sector coupling options which did provide a full results workbook. And therefore, this distribution of the Netherlands was the most suitable to assess the flexibility options of sector coupling and batteries for the 30 energy regions of the Netherlands.




RES regios
Arnhem Nijmegen
Goeree-Overflakkee
Hart van Brabant
Hoeksche Waard
Metropool regio Eindhoven
Noord Oost Brabant
Noord- en Midden Limburg
Rivierenland / Fruitdelta
Rotterdam Den Haag
West Brabant
Zuid Limburg
Achterhoek
Alblasserwaard
Amersfoort
CleanTech regio
Drechtsteden
Drenthe
Flevoland
Foodvalley
Friesland
Grongingen
Holland Rijnland
Midden Holland
Noord Hollan Noord
Noord Holland Zuid
Noord Veluwe
Twente
U16
West Overijssel
Zeeland


RES regios
Arnhem Nijmegen
Metropool regio Eindhoven
Rotterdam Den Haag
Achterhoek & Twente
Alblasserwaard & Midden Holland
CleanTech Regio & Noord Veluwe
Drenthe & West Overijssel
Flevoland & Amersfoort
Foodvalley & Rivierenland
Goeree-Overflakkee & Hoeksche Waard
Groningen & Friesland
Noord Holland Zuid & Noord
Noord Midden Zuid Limburg
Noord Oost & Hart van Brabant
U16 & Hollan Rijnland
West Brabard & Drechtsteden
Zeeland

4.1.2. North West Europe

Figure 4.4 shows the NWEU scale used in this study, it includes the countries of Germany, France, the United Kingdom, the Netherlands and Belgium. Ireland and Luxembourg, which are also part of NWEU according to the definition of the European Commission were left out. These countries are left out because of the results of the test runs with the Netherlands. As the model of the Netherlands with sector coupling worked with five regions, the choice was made to run the NWEU scale with five regions as well, in order to be sure that it would work. The choice of leaving out Ireland and Luxemburg is based on the fact that this would have the least influence on the transmission network of the NWEU power system and still keeping the variety of the region intact.

Each country is represented as a node which is connected to the electricity grid. This has the consequence that the demand, import, generation units and capacity factors are generalized for each country as a whole. This reduces in particular the variation in wind and PV output of different regions in a country. All units and all other necessary data for a country is specified in its country's node as described in figure 3.2 in 3.1. Also, the sector coupling options are modelled for each country as described in 3.1.3 where each sector coupling option has its own grid. The input data for the NWEU scale will be described in chapter 5.

4.2. Scenarios

To assess the use of sector coupling and batteries as flexibility options and the curtailment of a highly renewable energy system for a climate neutral continent in 2050, different scenarios are needed. Firstly, a base scenario is needed in order to assess what will happen if the system will go on as business as usual with relatively small changes until 2050 to assess if there will be any flexibility issues then. And a scenario is needed for when conventional power generation is phased out and replaced with high integration of VRE. This in order to both asses the flexibility issues that arise in a system with high VRE integration with no conventional back-up generators. And to assess the potential of the different sector coupling options and batteries in solving the issues concerning flexibility that arise in such a system.

4.2.1. Reference scenario EUCO

In order to find the right scenarios for this research the literature concerning different pathways regarding the future energy system has been studied. In order for this study to assess the FlexTool with other academic literature it is needed to model a scenario that is widely used in scientific literature. Therefore, a literature review regarding the use of different scenarios is performed. However, since this study only needs a base scenario which is rather conservative only the base scenarios in the scientific literature are collected and put together in order to assess which one is used most.

In order to find the right literature regarding this base scenario, the string “*Energy” AND “Scenarios” AND “2050*” AND “Europe” has been used in Scopus. Followed by the limitation of papers from 2017 to 2020 and sorted from highest to lowest citations, the first 10 papers that used a base scenario were chosen to assess. Table 4.1 shows the results of this search and are discussed below.

Table 4.1. Selected papers search scenarios

Paper	Scenario used as base
Capros et al., (2018)	Reference scenario EU 2016
Fragkos et al., (2017)	Reference scenario EU 2016
Grubler et al., (2018)	Developed own scenario
Antosiewicz et al., (2020)	Reference scenario EU 2016
Zappa et al., (2019)	Reference scenario EU 2016
Purohit & Höglund, (2017)	Reference scenario EU 2016
Child et al., (2019)	Developed own scenario

As table 5 shows, the 2016 EU reference scenario developed by the European Union is used abundantly throughout the scientific literature. Resulting from this literature search the European reference 2016 scenario was used as a base scenario for the Netherlands and North West Europe. This scenario focusses on the EU28 member states and its development regarding the whole EU energy system, greenhouse gas emission and transport developments (Capros et al., 2016). These developments are based on the input of all the EU28 member states experts, and is designed in a group of reference scenario experts of the European Commission (Capros et al., 2016). The time horizon of the reference scenario spans from 2015 till 2050 and the main goal of the scenario is to function as a guideline for analysing future market trends and to help policy making (Capros et al., 2016). In this study, the EU 2016 reference scenario will be named the EUCO scenario.

Figure 4.5. Gross electricity demand per sector (TWh) (Capros et al., 2016)

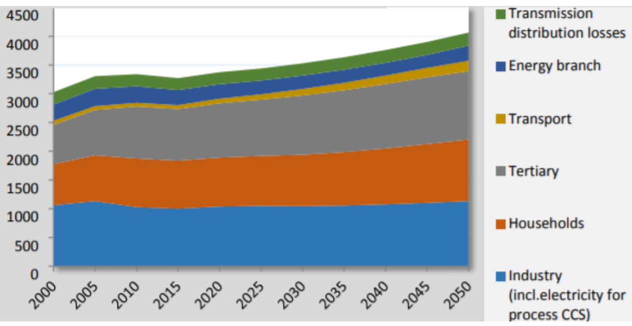


Figure 4.6. Power generation capacities (GW) (Capros et al., 2016)

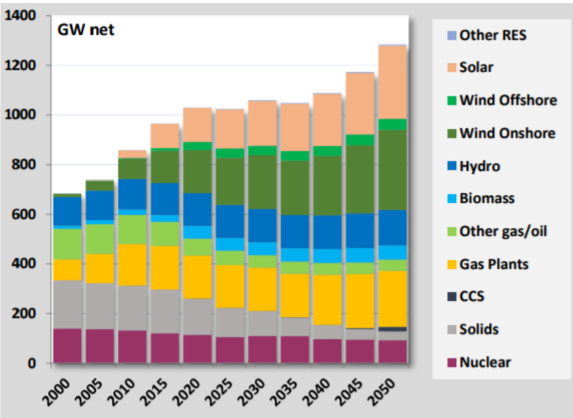


Figure 4.5 and 4.6 show the development of the electricity demand per sector and the installed power generation capacities for the 28 EU member states combined. The EU reference scenario takes an increase of about 1000TWh of electrification compared to 2000 levels into account. The increase of power generation capacity is mostly in the form of onshore wind and solar whereas solids fired power plants are strongly decreased until 2050. Natural gas fired power plants show a strong increase from 2000 to 2050, this is to provide the needed extra flexibility which is lost through the decrease of solids fired power plants (Capros et al., 2016). This scenario is therefore suitable to use as a base scenario

because it does increase the renewable energy sources wind and PV and provide the flexibility by conventional power generation in the form of natural gas.

4.2.2. Phase out scenario FLEX

As mentioned in the problem statement, in order to reach the goal of the European Union to become climate neutral in 2050, conventional power sources need to be phased out. Therefore, a specific scenario was created in order to assess the problems that arise when, as described in the introduction, the goal of the EU is reached through replacing the conventional power plants by integrating VRE into the power system. Two assumptions were made to alter the EUCO scenario in order to create this scenario. The first assumptions included the phasing out of coal and oil in 2030 and natural gas in 2050. Because this was most in line with the NCEPs (European Commission, 2020c) were coal and oil are phased out first. This meant that in the EUCO 2030 scenario coal and oil were phased out and in the EUCO 2050 scenario natural gas was phased out. This resulted in two new scenarios, in this research called the FLEX 30 and FLEX 50 scenario. Where the FLEX 30 scenario is the alteration on the EUCO 2030 scenario and the FLEX 50 scenario is the alteration of the EUCO 2050 scenario.

The second assumption concerned how these conventional power plants are completely replaced by either wind or PV power generation. The replacement of oil, coal and natural gas was done according to the following method: first for both the NWEU scale and the Netherlands, two papers were found that researched the maximum installed capacity of VRE per country for North West Europe (Gils et al., 2017) and per energy region for the Netherlands (Wang et al., 2020). Especially the paper of Wang et al., (2020) provides a good base line of the maximum capacity of VRE. Since in this research the spatial constraints of the energy regions are also taken into account, providing more accurate maximum VRE capacities (Wang et al., 2020). This makes it therefore very suitable for this study. Regarding the maximum installed capacity of North West Europe, the spatial constraints were also taken into account however on a much higher level than in the paper of Wang et al., (2020) since Gils et al., (2017) generalized the maximum VRE capacities for each county in Europe. However, this paper was still sufficient to use in this study since the NWEU was modelled per country as well.

With the maximum capacities from these papers the ratio between the maximum capacity of PV and wind were calculated for each country and region. The amount of installed capacity of oil, coal and natural gas as defined in the EU reference scenario 2016 by Capros er al., (2016) that needed to be substituted was divided by this ratio in order to determine how much of conventional installed capacity should be substituted by either PV or wind. When the replaced conventional capacities were distributed over PV and Wind installed capacities, the total installed capacity of wind and PV had to be determined since their generation is depend on the weather conditions. This was done by retrieving the annual average capacity factors for the year 2018 of PV and Wind for each country in the NWEU and dividing the new installed capacity of wind and PV by their capacity factors. This data was retrieved from the database of Pfenninger & Staffell, (2016). The above described method is illustrated by the following two equations:

$$NCW = \frac{ICC * \frac{MCW}{MCPV}}{CFW} \qquad NCPV = \frac{ICC * \frac{MCPV}{MCW}}{CFPV}$$

Where:

$NCW = New\ Capacity\ Wind$
$NCPV = New\ Capacity\ PV$
$ICC = Installed\ Capacity\ Conventional\ Power\ Generation$
$MCW = Maximum\ Capacity\ Wind$
$MCPV = Maximum\ Capacity\ PV$
$CFW = Average\ Annual\ Capacity\ Factor\ Wind$
$CFPV = Average\ Annual\ Capacity\ Factor\ PV$

Besides the generation capacities, the rest of the input data such as demand and import from the EUCO scenario will be used the same in the FLEX scenarios. Table 4.2 shows the differences in generation capacities and flexibility options used in the different scenarios.

Table 4.2. Generation capacities EUCO and FLEX scenarios

Power generation / Storage	**EUCO 20/30/50**	**FLEX 30**	**FLEX 50**
Coal	X		
Oil	X		
Natural gas	X	X	
Nuclear	X	X	X
Geothermal	X	X	X
PV	X	X	X
Wind	X	X	X
Biomass	X	X	X
Hydro run-of-river	X	X	X
Pumped Hydro storage	X	X	X
Sector Coupling			X
Batteries			X

This chapter showed the specific scales on which the Netherlands and North West Europe are modelled in the FlexTool. Since the increase in calculation time of the sector coupling options both scales had to be reduced to 5 nodes. The chapter also showed how the scenarios that were used in this study were established. The EUCO scenario will be used as a conservative base scenario in the rest of this study, and the FLEX 30 and FLEX 50 scenarios will be used as the scenarios towards the climate neutral goal of the EU in 2050. The next chapter will explain the input data that was used in order to model the two scales for the different scenarios.

5. Data input

This chapter will describe the input data separately for both North West Europe and the Netherlands for the EUCO, FLEX scenarios and the DOE. As described in 3.1 the IRENA FlexTool needs input data regarding demand and import/export both annually and in hourly time series, unit capacity, fuel prices and the hourly capacity factor time series for VRE. For each of these input data a description and source are provided in this part. Also the input data regarding the different the batteries and sector coupling options are described in this chapter.

5.1. North West Europe

5.1.1. EUCO

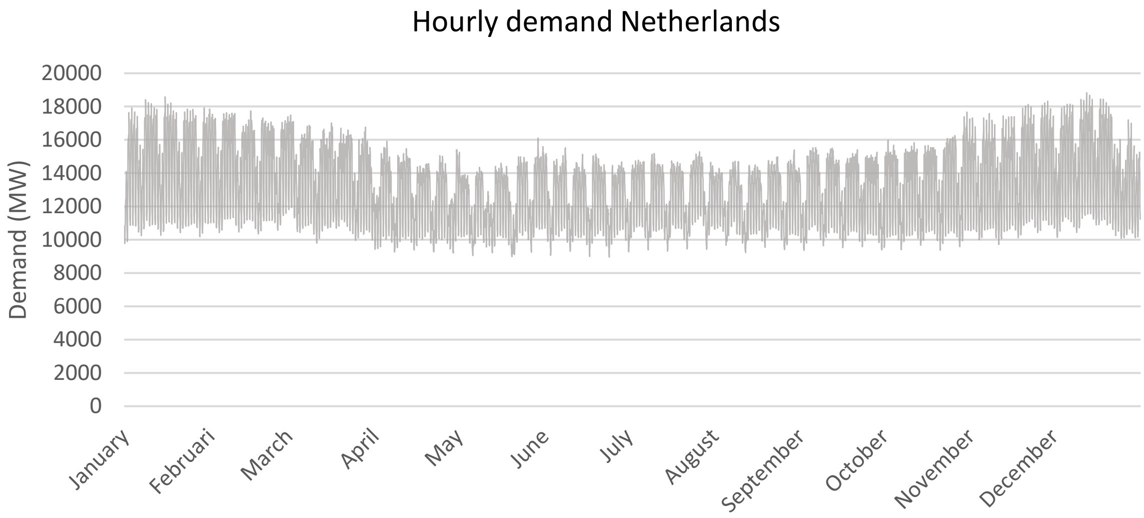
As described in 4.2 the reference scenario 2016 of the European Commission as defined in Capros et al., (2016) is used in this study as the base scenario for the projections regarding the energy transition within Europe. For the NWEU scale the main input data used from this source are the data regarding annual demand (in TWh), annual import/export (in TWh) and the installed capacity per power generation technology (in MW). The reference scenario did not include pumped hydro storage and therefore the installed capacity regarding pumped hydro storage for the year 2019 was used from the ENTSO-E transparency platform (ENTSO-E, 2019a). Table 5.1 shows the annual demand, annual import/export, installed capacity and pumped storage used in the EUCO 2020 scenario. The input data regarding the EUCO 2030 and EUCO 2050 scenario are presented in appendix I.

Table 5.1. Input data EUCO 2020

EUCO 2020		**Germany**	**France**	**United Kingdom**	**Netherlands**	**Belgium**
Annual demand *(TWh)*		580	452	322	110	84
Import/export *(MWh)*		89879	-29181308	385853	441734	89879
Capacity *(MW)*	**Wind**	61832	22130	33421	10096	4558
	PV	52803	20535	11043	5586	3818
	Natural Gas	21891	9181	35332	14406	6270
	Coal	49170	3856	11149	5388	43
	Oil	1674	5008	1235	77	266
	Biomass	7100	2894	17238	2254	869
	Nuclear	6907	61327	8884	485	5055
	Geothermal	170	0	0	0	0
	Hydro ROR	5592	23635	1791	0	119
Storage *(MWh)*	**Pumped hydro**	8918,00	5020,00	0	0	1150,00

The total annual demand is used from the reference scenario 2016, however the hourly time series were not included in this dataset. Therefore, the demand profile for each country is retrieved from the ENTSO-E transparency platform for the year 2018 (ENTSO-E, 2019b). The hourly demand resolution was used for the model since the IRENA FlexTool only modelled the time series on this resolution. For each country the time series were retrieved from the ENTSO-E transparency platform. Figure 5.1 shows the hourly demand in 2018 for the Netherlands.

Figure 5.1. Hourly demand Netherlands (ENTSO-E, 2019b)



To represent the time series of the import and export for the EUCO 2020, 2030 and 2050 scenario, the hourly import and export data for each country are retrieved from the ENTSO-E transparency platform as well (ENTSO-E, 2019c). The year 2018 was used here as well because the demand data and import/export data should be from the same year as this could otherwise provide possibly non-realistic demand patterns. Since the FlexTool subtracts or adds the import or export to the demand in each hour. Only the import and export external to the NWEU system had to be put in as described in 3.1. Therefore, for each country only the hourly transmission data from and to the connecting borders outside of the NWEU scale were used. For the Netherlands this left only the transmission of the Netherlands to and from Norway, as this was the only left direct transmission connection. Figure 5.2 shows the resulting hourly import and export of the Netherlands (ENTSO-E, 2019c). This was done for Germany, France, the United Kingdom and Belgium as well. Table 5.3 shows all the transmission connections for each country that were added as an external import or export source.

Figure 5.2. Hourly import and export selection 2018 Netherlands

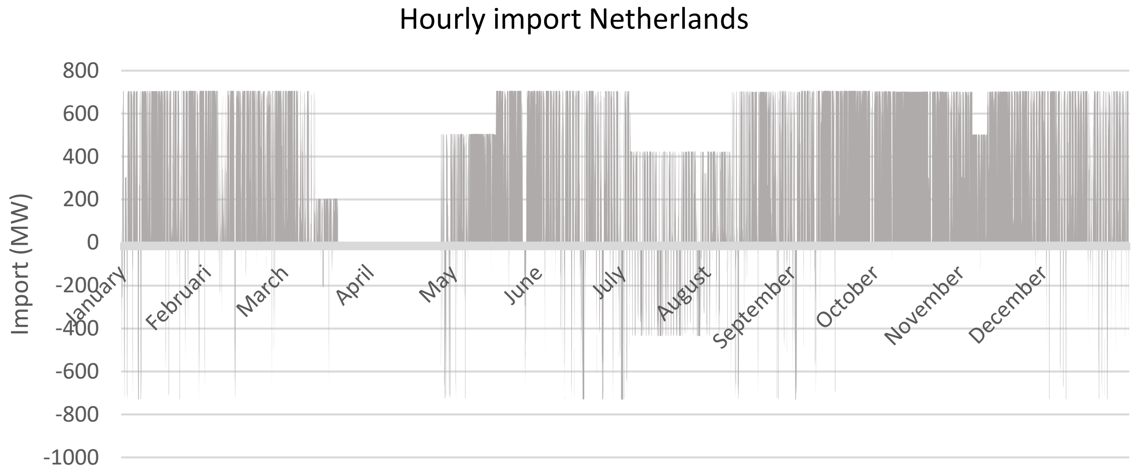


Table 5.2. Transmission in model

Transmission capacity 2020	=> (MW)	<= (MW)
Belgium-Germany	1000	1000
Belgium-France	1800	3300
Belgium-United Kingdom	1000	1000
Belgium-Netherlands	2400	1400
Germany-France	2300	1800
Germany-Netherlands	4250	4250
France-United Kingdom	2000	2000
United Kingdom-Netherlands	1000	1000

Table 5.3. Transmissions outside model

Country	External import/export
Germany	Czech Republic, Denmark, Luxemburg, Poland, Sweden, Switzerland, Austria
France	Italy, Spain, Switzerland
United Kingdom	Ireland
Netherlands	Norway
Belgium	Luxemburg

The data set of the ten-year-network-development-plan (TYNDP) from the ENTSO-E was used to determine the installed transmission capacities for the EUCO 2020, 2030 and 2050 scenario. The TYNDP was used because the TYNDP is the result of a two-year project of the ENTSO-E with collaborative exercises regarding the future of the transmission network of Europe together with the European Commission, ACER and other stakeholders (ENTSO-E, 2019d). Thus, this dataset provides an accurate estimation of the developments regarding the electricity grid of the coming years. The transmission capacities for the NWEU scale for the EUCO 2020 scenario are presented in table 5.2. The transmission capacities of the EUCO 2030 and EUCO 2050 scenario are presented in appendix I.

The only input data left to discuss now are the hourly time series for the capacity factors of wind and PV. For this data the renewables ninja project was consulted. This is a project where you are able to run simulations regarding the wind and solar power plant output on an hourly resolution for each year and each place in the world (Pfenninger & Staffell, 2016). Figures 5.3 and 5.4 show the hourly capacity factors for the Netherlands in the year 2018 that are provided by this source.

Figure 5.3. Hourly capacity factor PV 2018 Netherlands (Pfenninger & Staffell, 2016)

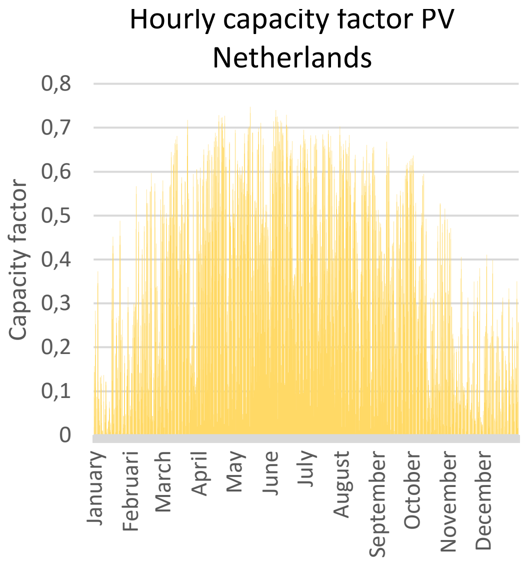
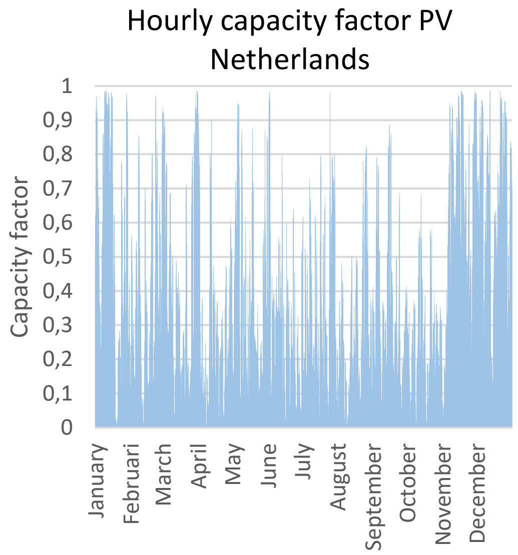


Figure 5.4. Hourly capacity factor wind 2018 Netherlands (Pfenninger & Staffell, 2016)



5.1.2. FLEX

As described in 4.3. the FLEX scenario is mainly based on the EUCO scenario with the only difference that the conventional power generators are phased out, with oil and coal in 2030 and natural gas in 2050. The capacity factors and resulting installed capacities from the method described in 4.2 are described here. Table 5.4 shows the average annual capacity factors of each country as provided by Pfenninger & Staffell, (2016). Using the method described in 4.3 with the maximum capacity of wind and PV for each European country provided by Gils et al., (2017), the tables 5.5 and 5.6 show the resulting new capacities of wind and PV in the FLEX 30 and FLEX 50 scenarios. Tables 5.4 to 5.6 show that offshore wind for the Netherlands is not taken into account, this will be explained in more detail in 5.2.2.

Table 5.4. Annual capacity factors 2018 (Pfenninger & Staffell, 2016)

Annual CF	Germany	France	United Kingdom	Netherlands	Belgium
Wind onshore	0.21	0.25	0.32	0,26	0.34
Wind offshore	0.36	0.47	0.41	X	0.26
PV	0.13	0.14	0.11	0.12	0.13

Table 5.5. New installed capacities wind and PV FLEX 2030

FLEX 2030		Germany	France	United Kingdom	Netherlands	Belgium
Capacity *(MW)*	**Wind onshore**	331680	10609	1616	12396	10569
	Wind offshore	43175	23385	33570	X	1039
	PV	331680	54901	19706	38060	5445

Table 5.6. New installed capacities wind and PV FLEX 2050

FLEX 2050		Germany	France	United Kingdom	Netherlands	Belgium
Capacity *(MW)*	**Wind onshore**	49033	37764	4727	23730	12023
	Wind offshore	57888	41116	86391	X	1941
	PV	551954	253068	254786	160056	109055

5.3. The Netherlands

5.2.1. EUCO

For the Netherlands scale the main input data used for the EUCO scenario are the data regarding annual demand (in TWh), annual import/export (in TWh) and the installed capacity per power generation technology (in MW). However, compared to the NWEU scale the EU 2016 reference scenario did not contain data regarding the different regions of the Netherlands. Therefore the data of the Netherlands in the EU reference scenario was divided over the different regions. This was done according to data available for the year 2018. For the population and annual demand per region, the klimaatmonitor (2020) database was used. For the current installed wind and PV capacity, the sources WindStats (2020) and CBS (2018) were consulted. From these two sources the installed capacity per municipality was retrieved and located in one of the five regions. For the conventional power plants, the data base of Tennet (2018) was consulted, from which the installed capacities of the conventional power plants were retrieved per municipality and were also located to one of the five regions. Table 5.7 shows and the division over the regions from these data sources.

Table 5.7. real data Netherlands

		Noord	Oost	Zuid	Zuid-West	Noord-West
Population (in million)		1,7	3,3	3,6	4,0	4,5
Annual demand 2018 (TWh)		11	16	25	23	24
Current conventional generation capacity (MW)	**Natural gas**	4040	60	2634	3088	4175
	Coal	0	0	1534	1824	650
	Nuclear	0	0	0	492	0
	Biomass	0	0	510	0	182
Current renewable generation capacity (MW)	**Wind**	695	206	269	969	1612
	PV	516	634	677	380	591

The current data described above was used to divide the data of the EUR reference scenario. The annual demand was divided according to the demand retrieved from the klimaatmonitor (2020) and the installed capacity of the power plants were divided according to Tennet (2018), Windstat (2020) and CBS (2018). Table 5.8 shows the annual demand, annual import/export, installed capacity used in the EUCO 2020 scenario for each region resulting from the combining the real data found from table 5.7 with the EU reference scenario data for the Netherlands. The input data regarding the EUCO 2030 and EUCO 2050 scenario are presented in appendix II.

Table 5.8. Input data EUCO 2020

EUCO 2020		Noord	Oost	Zuid	Zuid-West	Noord-West
Annual demand *(TWh)*		12	18	27	25	26
Import/export *(MWh)*		588252	786247	-169026	-309963	0
Capacity *(MW)*	**Wind**	1870	555	725	2608	4337
	PV	1029	1265	1351	758	1179
	Natural Gas	4158	61	2711	3178	4297
	Coal	0	0	2091	2487	886
	Biomass	0	0	862	1025	365
	Nuclear	0	0	0	485	0

Specific demand profiles for the different regions could not be found. Therefore the assumption is made to use the demand time series of the Netherlands as used in the NWEU scenario for the demand time series for each region, as the FlexTool will scale this time series to the total annual demand of each region. Also, specific data for the transmission capacity between the regions could not be found. Therefore the choice is made to use a very 'high' transmission capacity between the regions of 99999MW in order to neglect the transmission between the regions, this will have an influence on the results and will therefore be discussed further in the discussion in chapter 7.

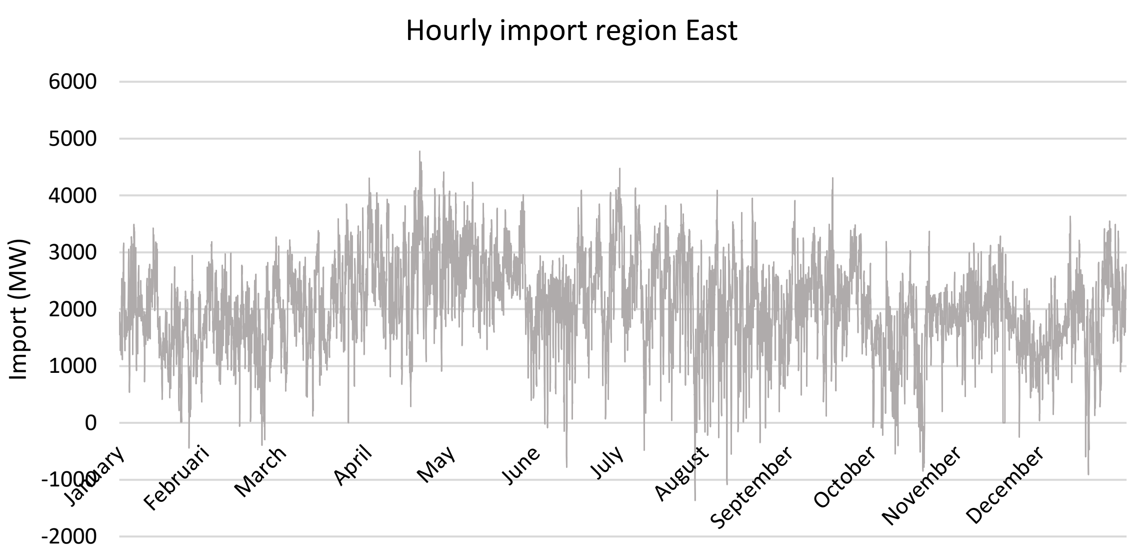
The import and export however, differ in modelling approach from the NWEU scale. Because in the case of only modelling the Netherlands, all international import and export is external to the model. Therefore, the data from the ENTSO-E (2019c) for the hourly transmission from and to the Netherlands is used. Since the model adds the import/export to the demand of a specific node, the regions that imported or exported electricity to neighbouring countries had to be determined. From the grid map from the ENTSO-E (2020) the regions with connecting cross-border transmission lines could be determined. Table 5.9 shows the connection of the different regions to another country, only the North West does not have a connection.

Table 5.9. International connection regions

Region	Connected country
North	Norway
East	Germany
South	Belgium
South-West	United Kingdom

The annual import export was added to the concerned node. And the hourly time series regarding the export per country was also added to the time series of the specific node. Figure 5.4 illustrates the hourly import from Germany to the East region of the Netherlands. The other regions have a similar time series added to their demand.

Figure 5.4. Hourly import and export Germany to/from east region



The only input data left to discuss now for the EUCO scenario are the hourly time series for the capacity factors of wind and PV. For this data the renewables ninja project is consulted as is for NWEU. The hourly capacity factors are determined for each region individually. The middle of the border of the connected provinces is taken as the place from which the capacity factor is derived. This to obtain the capacity factor that best represents the different provinces included in each region. Figures 5.5 and 5.6 show the hourly capacity factors for the region East in the year 2018 that are provided by Pfenninger & Staffell, (2016).

Figure 5.5. Hourly capacity factor East 2018 (Pfenninger & Staffell, 2016).

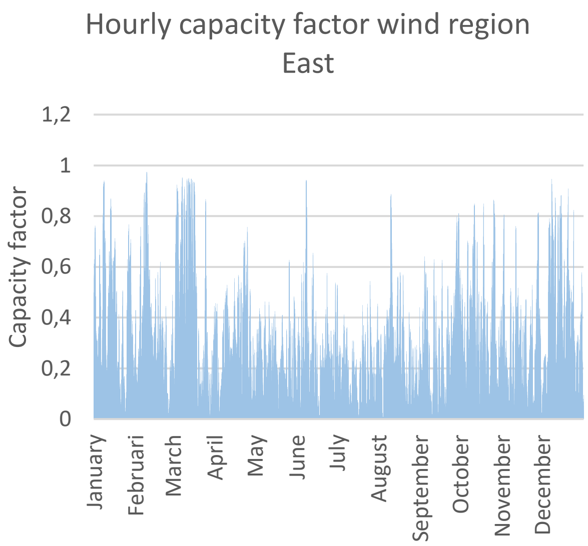
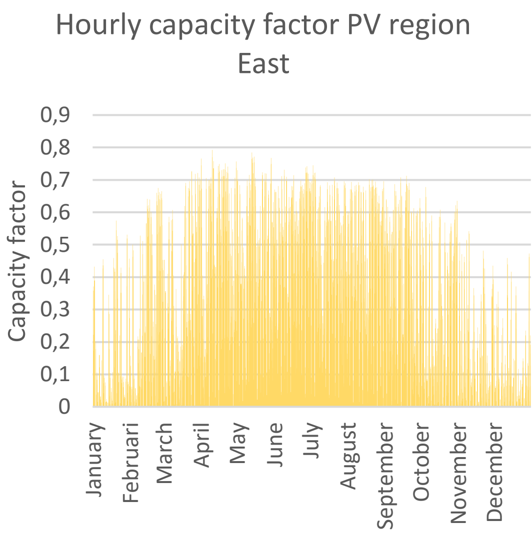


Figure 5.6. Hourly capacity factor PV East 2018 (Pfenninger & Staffell, 2016).



5.2.2. FLEX

As described in 4.3. the FLEX scenario is mainly based on the EUCO scenario with the only difference that the conventional power generators are phased out, with oil and coal in 2030 and natural gas in 2050. For the Netherlands the same total installed capacity is used as for the Netherlands in the NWEU scale as was calculated in the method described in 4.3. The capacity was however divided over the regions according to the ratio of maximum installed capacity of wind and PV per region as defined by Wang et al., (2020). As only onshore wind was available from this source, the offshore wind is left out of scope for the Netherlands. This has in particular consequences on the volatility of the total wind output and therefore the results and will be further discussed in the discussion in chapter 7. The tables 5.10 and 5.11 show the resulting new capacities of both wind and PV in both the FLEX 2030 and FLEX 2050 scenarios.

Table 5.10. New capacities wind and PV FLEX 2030

FLEX 2030		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Capacity *(MW)*	**Wind**	2833	1126	906	2824	4706
	PV	10911	8755	6367	4850	7173

Table 5.11. New capacities wind and PV FLEX 2050

FLEX 2050		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**

Capacity *(MW)*	**Wind**	6944	3417	1783	4332	7252
	PV	48001	36892	25234	20225	29700

5.3. Input data sector coupling and batteries

In the first two parts of this chapter the input data was described separately for the Netherlands and North West Europe. The rest of this chapter will combine the two scales since the input data for them are the same. However, the data for the Netherlands is adjusted in two different ways. The total amount of heat pumps and electric vehicles are divided according to the ratio of the population of a region to the total population of the Netherlands. The ratio of the population is chosen because both electric vehicles and heat pumps are used by households and therefore their distribution is dependent on the population. The number of electrolysers, fuel cells and batteries are divided according to the ratio of the amount of VRE installed capacity in a region to the total VRE installed capacity in the Netherlands. The total amount of electric vehicles, heat pumps, electrolysers and fuel cells for each country and region is presented in appendix III.

5.3.1. Electric vehicles

The input data for modelling the electric vehicles was obtained from three main sources, the amount of electric vehicles in use in 2050 were retrieved from Nijland et al., (2012), the weekly load profiles were retrieved from Schäuble et al., (2017), the technological data regarding the capacity of charging points and electric vehicles were retrieved from IRENA (2017) and the demand for transport was retrieved from the EUCO scenario. Schäuble et al., (2017) is used because this study focussed on the load profiles of Germany and are similar to other studies researching EV load (Schäuble et al., 2017). Nijland et al., (2012) is used because it is an extensive study conducted by the PBL on which multiple policies are based (Nijland et al., 2012).

Figure 5.7 shows a general weekly load profile of electric vehicles as defined in the research of Schläube et al., 2017. As can be seen in this figure the load profile differd when comparing weekdays with weekend days. The capacity and storage capacity of electric vehicles as defined by IRENA (2017) are 50 kW and 60 kWh by 2030. No studies were found with projections up to 2050, therefore the projections untill 2030 where used. For the charging capacity of the charging points the study by Todts (2020) was used. They state a charging capacity of 16,5 kW per tri-phase AC chargers, since the European electricity network is mostly tri-phase AC (Todts, 2020), this charging capacity is used. The assumption was made that for every electric vehicle also 1 electric charging point is installed with the rationale that every electric vehicle should be able to charge/discharge at any time. The total amount of electric vehicles on the road where calculated according to a study by the Planbureau voor Leefomgeving (PBL) (Nijland et al., 2012). This research stated that for a fully electric vehicle transport system, the number of cars will increase between -5 to 45% compared to 2004 levels. The average from this, 20% is taken in this study with the 2004 levels retrieved from the EEA, (2020). The total demand for private cars an motorcycles is retrieved from the EUCO scenario (Capros et al., 2016).

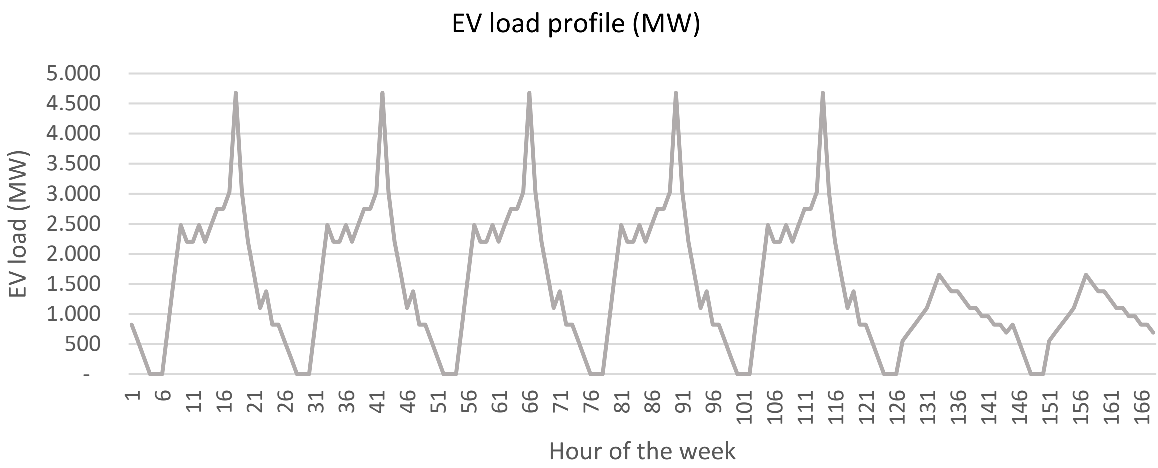


Figure 5.7. load profile EVs (Schäuble et al., 2017)

5.3.2. Hydrogen storage

The input data for hydrogen storage was obtained from three main sources. Tennet (2019) and Wang et al., (2020a) provided the input data regarding the hydrogen network on respectively the North West Europe and the Netherlands scale. These two sources were used since they are published by GasUnie and Tennet, therefore their estimations are used in this study to represent the estimations used in reality. Whereas the study from Caglayan (2020) provided the countries total potential of hydrogen storage in salt cavern and the locations of those salt caverns as this was the only data source available regarding the potential amount of salt cavern storage in Europe.

Figure 5.8 illustrates the European hydrogen backbone by Wang et al., (2020a). For this research on the North West European scale the number of pipelines crossing each countries border are multiplied by the capacity of the pipeline, which is 10000MW on average according to Wang et al., (2020a). For the scale of the Netherland the same average amount of capacity is taken and the pipelines are connected in the model via the regions that are connected according to the network proposed by Tennet (2019) as shown in figure 5.9.

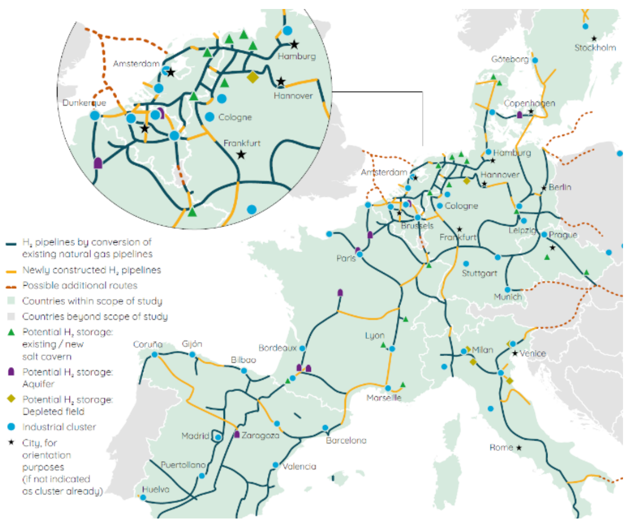


Figure 5.8. European hydrogen backbone (Wang et al., 2020)

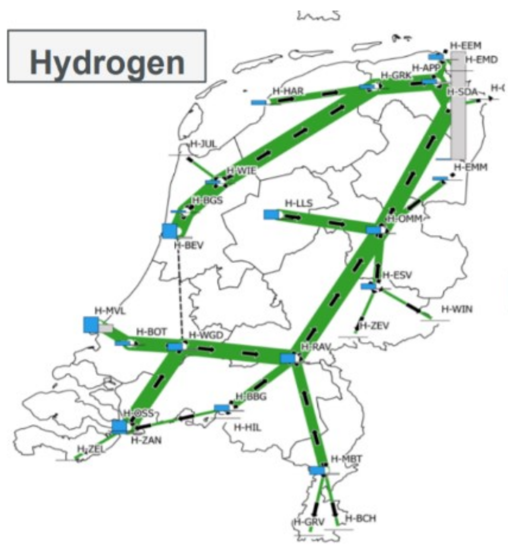


Figure 5.9. Hydrogen network tennet (Tennet, 2019)

Figure 5.10 shows the total salt cavern storage per country according to the study of Caglayan (2020). In this study the total amount of salt cavern storage is taken into account in order for the model to optimize the allocation of electrolyser and fuel cell use of the installed capacities. For the salt cavern storage, no investment costs are calculated because the rationale is used that for the future hydrogen network the existing gas structure is mainly used as in the study of Wang et al., (2020a).

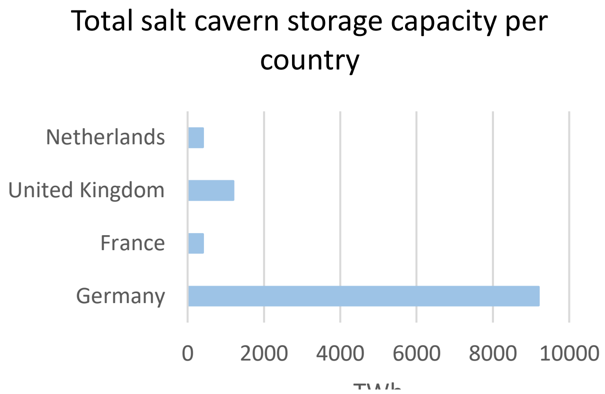


Figure 5.10. Salt cavern storage (Caglayan, 2020)

5.3.3. Batteries & Heat pumps

The allocation of the battery capacity per country is based on an extensive study of the European union on energy storage (European Commission, 2020a). In the study of the European Commission (2020a) the current and projected projects regarding batteries are researched and an optimal amount of battery storage is calculated. The total amount of batteries installed per country can be found in appendix III.

The total amount of heat pumps per country can be found in appendix III. For the total annual heat demand the data from the EUCO scenario (Capros et al., 2016) was used. The study of Ruhnau et al., (2019) is part of the *Open Power System Data* project (Ruhnau et al., 2019) and provides yearly time series for heat demand of 16 European countries and are freely available. The heat demand time series of the year 2018 is used in this study because this in line with the demand and import data used from the ENTSO-E. Figure 5.11 shows the heat demand for the Netherlands for a week in winter in 2018.

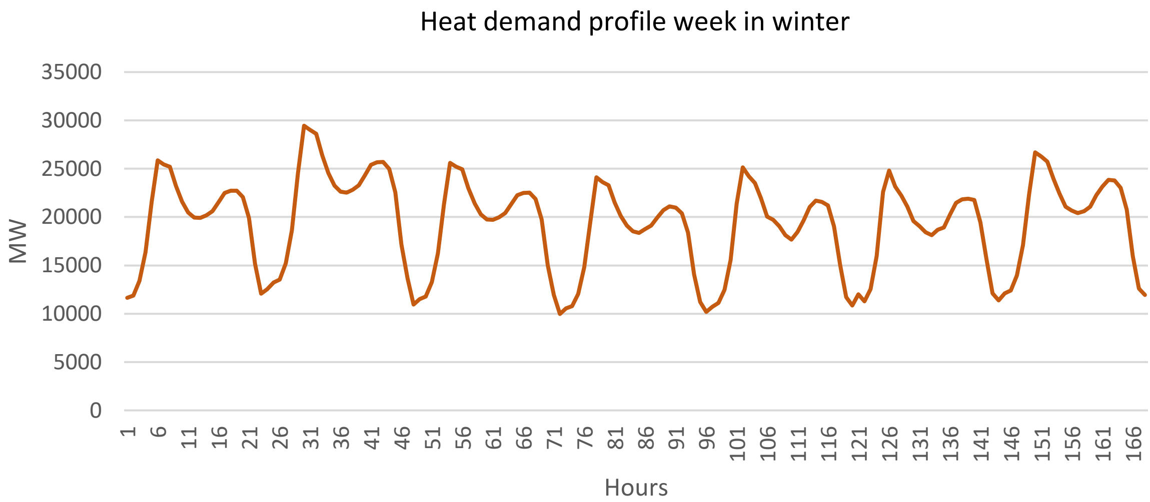


Figure 5.11. Heat demand profile (Ruhnau et al., 2019)

5.3.4. Costs and efficiencies

Most cost and efficiency data were already included in the IRENA FlexTool. The efficiency data regarding EVs, li-ion batteries and heat pumps and the operational costs of EVS were already included.

Therefore the data regarding electrolysers, fuell cells, hydrogen storage and heat storage had to be included from external sources. The operational cost, efficiency and lifetime of electrolysers and fuel cells were retrieved from a study conducted by the International Energy Agency (IEA, 2015). This study was used because it is widely used in scientific literature in the use of technological properties (Körner et al., 2015). The operational cost from Li- ion Batteries and Heat pumps are retrieved from Sabihuddin et al., (2015). This study was used because it contained an extensive literature review of the current properties of storage technologies (Sabihuddin et al., 2015). The study conducted by Sabihuddin et al., (2015) summarized the current technical properties found in the literature of the most used storage technologies and from this study all discharge values and the CAPEX from heat storage are derived. For the other CAPEX and lifetime values the research of Murray et al., (2018) was used. This source was used because this study provided a review of costs towards 2050, and is used in other academic studies as well. In order to calculate the LCOE, the discount rate of 6,0% used in the study of Murray er al., (2018) was used. Table 5.12 to 5.14 show the life time, CAPEX, Operational costs, efficiencies and discharge rates per technology as used in the model.

Table 5.12. Efficiency, discharge rate, Operational costs technologies (IEA,2015; Sabihuddin et al., 2015)

	Electric vehicle	Li- ion Battery	PEM electrolyser	PEM fuel cell	Hydrogen storage	Heat pump	Heat storage
O&M (€/kW)	3	10	27	28	0	3,8	0
Efficiency	1,00	0,85	0,86	0,57	0,9	X	0,7
Coefficient of performance	X	X	X	X	X	4	X
Discharge rate (%/hour)	0,0075	0,0075	X	X	0	X	0,03125

Table 5.13. CAPEX technologies (Sabiduddin et al., 2015; Murray et al., 2018)

Technology	Capex		
	2020	*2030*	*2050*
Li- ion Battery (€/kWh)	535	446	356
PEM electrolyser (€/kW)	2037	1389	703
PEM fuell cell (€/kW)	2116	1336	890
Heat pump (€/kW)	1481	1389	1296
Heat storage (€/kWh)	132	132	132

Table 5.14. Lifetime technologies (IEA 2015; Murray et al., 2018)

Technology	Lifetime (years)		
	2020	*2030*	*2050*
Li- ion Battery	11,5	11,5	11,5
PEM electrolyser	4,5	8,6	8,6
PEM fuell cell	6,8	9,1	9,1
Heat pump	20	20	20
Heat storage	30	30	30

5.4. Design of experiments.

The design levels for the different experiments are derived from the sources mentioned in the previous section. To obtain a broad perspective on the different technologies, a large difference between the low, medium and high level was chosen. For the electric vehicles this is based on the study of the PBL where a scenario with 100% electric vehicles is outlined (Nijland et al., 2012). From there the other levels are drawn which are half of the previous level. For the Heat pumps the TYNDP is used as the low scenario. Projections made by the IRENA (2019) stated an 27% provision of electric heat pumps by 2050. However to obtain a broader field a 50% provision of heat pumps was used. With the medium level as the average of low and high, resulting in 28,75% which is close to the projections of the IRENA (2019). For the design levels of hydrogen the European Comissions hydrogen strategy of 80000MW installed capacity of electrolysers (European Commission, 2020b) is used as a reference. To obtain a broader field, 25% was added and used as the high level, and the med an low levels are determined as the half of the previous level. The high level of li-ion batteries is determined according to an extensive study of the European union on energy storage (European Commission, 2020a), this study calculated a 187 GWh installed capacity for the European Union. Since this amount is for the whole European union this same amount can be used as the extreme level for the North West Europe as it should then also be sufficient for this region. The med an low levels are, as well as with hydrogen and EVs, determined as the half of the previous level. The design levels are summarized in tables 5.15 and 5.16 and the total amount of installed capacity per technology for each scale can be found in appendix III. The sources of the PBL, TYNDP and the European commission were used in order to keep the estimated levels as close to the estimations used in real life by governments and transmission system operators.

Table 5.15. Design levels the Netherlands

Technology	Low	Medium	High
HPs (% of heat demand)	7.5	28.75	50
EVs (% of total cars electric)	25	50	100
Batteries (total installed capacity MWh)	5241	10483	20966
H2 (total installed capacity MW)	2796	5591	11182

Table 5.16. Design levels North West Europe

Technology	Low	Medium	High
HPs (% of heat demand)	7.5	28.75	50
EVs (% of total cars electric)	25	50	100
Batteries (total installed capacity MWh)	46875	93750	187500
H2 (total installed capacity MW)	25000	50000	100000

Table 5.17 shows the optimal design of experiments with 9 points and 1 term, only taking into account the main effects for the technologies on the curtailment and loss of load, from the full factorial design as calculated with Minitab.

Table 5.17. Optimal design Minitab

	EV	Battery	H2	Heat pump
DOE 1	High	High	High	High
DOE 2	Low	Low	Low	High
DOE 3	Low	Med	High	Low
DOE 4	Low	High	Med	Med
DOE 5	High	Low	Med	Low
DOE 6	Med	Low	High	Med
DOE 7	Med	Med	Med	High
DOE 8	Med	High	Low	Low
DOE 9	High	Med	Low	Med

This chapter showed the different data sources used as input data for the IRENA FlexTool to model the scenarios and scales described in chapter 4. From these data sources the different low, medium and high levels for the DOE were derived. The next chapter will show the results from the model described in chapter 3 that runs the scenarios from chapter 4 in combination with the input data described in this chapter.

6. Results

The results from the IRENA FlexTool and the DOE are described in this chapter. The following approach is used to describe the results in a structured way. First the two scales will be discussed separately regarding the EUCO scenario and the FLEX scenario in order to provide a clear overview of the amount of curtailed VRE and loss of load. Secondly the two scales will be discussed together regarding the DOE. In this way the different technologies can be compared better on the North West European and the Netherlands scale.

6.1. North West Europe

6.1.1. Reference scenario EUCO

As described in 4.2, the EUCO scenario acts as a conservative reference scenario to portray the power system when a moderate increase of VRE is combined with an increase of the conservative flexibility option of natural gas. Table 6.1 shows the main results from the model runs with the EUCO scenario. The loss of load is in 2020, 2030 and 2050, 0% of the annual demand and the curtailed VRE only shows an increase of 0,6%. The reference scenario shows a small decrease in the total CO2 emissions and the share of renewables have a small decrease and increase. Figures 6.1 and 6.2 also show that, despite an increase of installed PV and wind, the absolute generation of fossil fuelled power plants increases from 2020 to 2050 for each country except Germany. The power system does show an increase of operational costs from 2020 to 2050 due to the increase in power generation by natural gas.

Table 6.1. Main results EUCO NWEU

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NWEU	2020	0	0	340	35	61155
	2030	0,1	0	329	38	59448
	2050	0,6	0	316	43	65967

Figure 6.1. Total generation EUCO NWEU

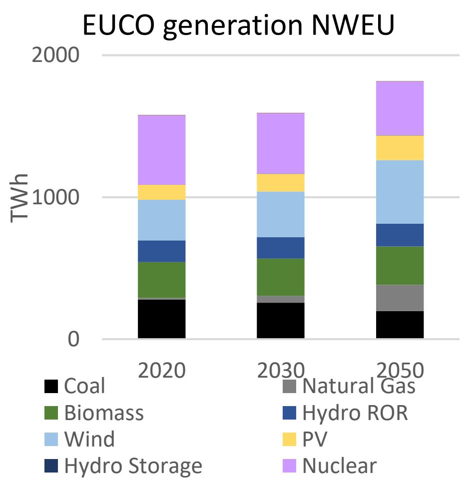


Figure 6.2. Total generation EUCO per country

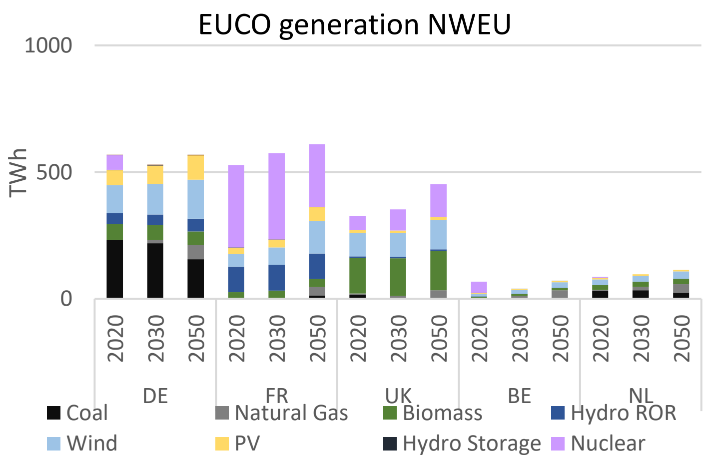


Figure 6.3 shows that the electricity prices in the Netherlands, Belgium and Germany increase slightly from 2020 to 2050. Whereas France and the UK show a larger increase in electricity price from 2030 to 2050. For the NWEU system as a whole, figure 6.4 shows a slight increase of variability, in the range of low to high prices from 2020 to 2030.

Figure 6.3. Hourly electricity price EUCO NWEU

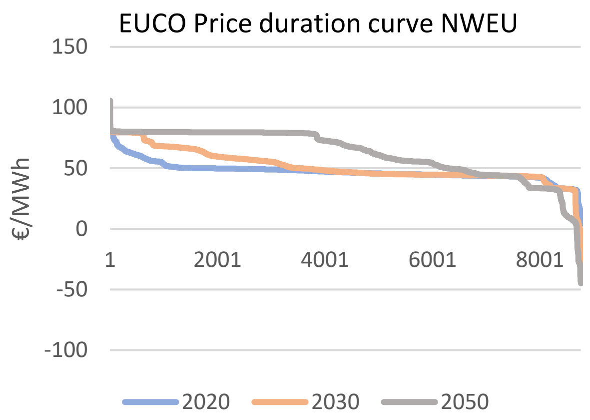
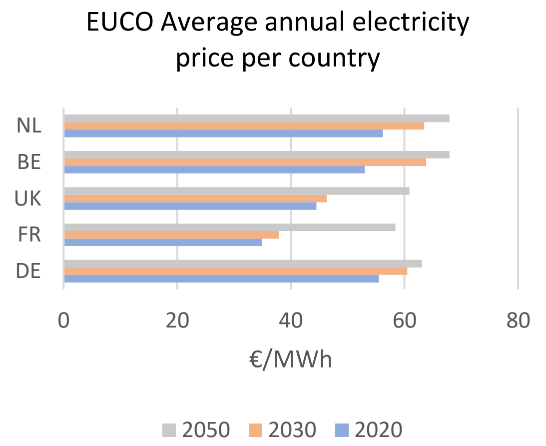


Figure 6.4. Annual electricity price EUCO per country



The EUCO scenario shows that when the North West of Europe follows a conservative path regarding renewable energy no flexibility issues arise. The loss of load will remain zero and a low amount of VRE will be curtailed. The natural gas that replaces coal and oil in the system also provides the needed back up for increase in wind and PV. Since the electricity prices are relatively stable over the whole year for 2020, 2030 and 2050. The increase of natural gas does results in a higher average electricity price since natural gas has a higher fuel price then coal and oil. When the North West of Europe would follow the EUCO scenario, the power system will not need new or other flexibility options besides natural gas. The region would however experience higher electricity prices throughout the year. However, most importantly, the climate goals of the EU for 2050 will not be met.

6.1.2. Phase out scenarios FLEX

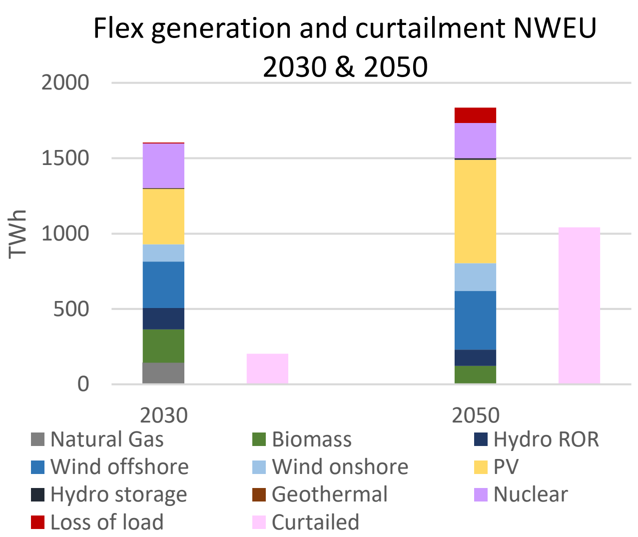
Described in 4.2. the FLEX scenario portrays the replacement of coal and oil by VRE in 2030 and natural gas in 2050 to obtain a carbon neutral energy system. Table 6.2 shows a summary of the results. In 2030, where natural gas still provides electricity in the power system, there is not a large flexibility issue. The loss of load only shows an increase of 0.4%, while 21,7% of the VRE is curtailed. Compared to the EUCO scenario there is 266Mt less CO2 emitted. Therefore, replacing only coal and oil already has a very large impact on the CO2 emissions of the NWEU. When natural gas is completely phased out and the power system does not emit any CO2 anymore, there is a significant problem regarding flexibility. This is shown by the 5,7% of the annual demand that cannot be met, despite 76,2% of VRE generation being curtailed. The operational cost increase from 2030 to 2050 due to the increase in absolute energy generation. However, the costs for both years show a decrease compared to the EUCO scenario, since more VRE is used.

Table 6.2. Main results NWEU FLEX

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational costs (in million €)
NWEU	2030	21,7	0,4	62,2	59,3	48351
	2050	76,2	5,7	0	75,7	59997

Figure 6.5 shows the total generated electricity by power sources compared to the total amount of VRE curtailed for 2030 and 2050. For the whole NWEU in 2050, a total amount of over 1042 TWh is curtailed while about 103 TWh of demand is not being served. Indicating the absolute discrepancy between demand and VRE generation in a system with high penetration of wind and PV, with no back up to provide flexibility.

Figure 6.5. Generation FLEX NWEU



When comparing the different countries in the power system, some differences can be noticed. For the year 2030, only Germany shows a large amount of curtailed energy and together with the Netherlands a small amount of loss of load, as figure 6.6 shows. For 2050 the curtailment per country increases much more, and in the Netherlands and Belgium it exceeds the total amount of generated power in that year. For the loss of load there are more differences to be noticed per country, which figure 6.7 shows. Germany and the Netherlands show the highest amount of loss of load, with respectively 75,3 TWh and 21,7 TWh, followed by Belgium and the UK with 3,3 TWh and 2,8 TWH and France does not experience any loss of load.

Figure 6.6. FLEX generation per country

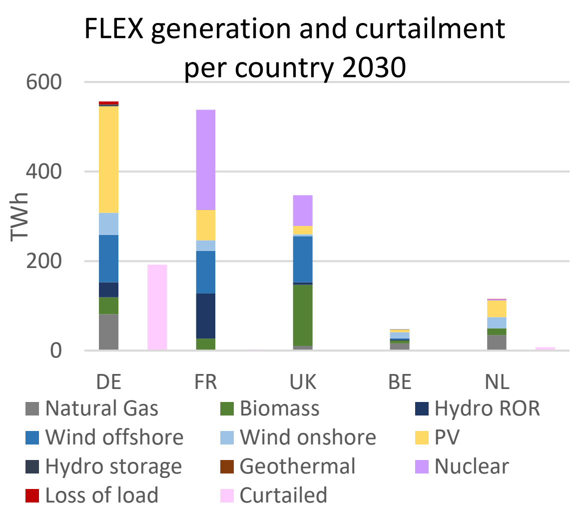
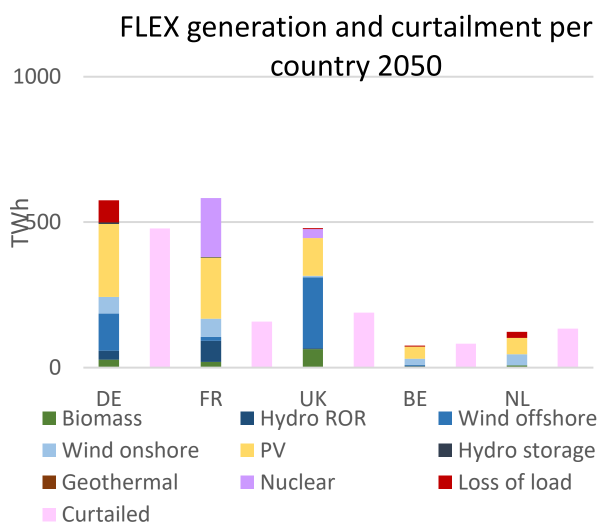


Figure 6.7. FLEX generation per country



The flexibility indicators show a large difference between the five countries. This difference could be explained through the installed nuclear capacity. Since France and the UK are the only two countries that include nuclear power generation and both experience no or little loss of load. This means that the incentive to obtain new flexibility options can differ a lot between countries in the NWEU region. So will Germany see the flexibility issues as a major problem to their power system. Whereas this problem does not exist for France. This could make it easier for some countries to phase out natural gas and replace it with wind and PV then others.

The modelling results regarding the electricity prices in both scenarios show a large increase of the amount of peak prices, illustrated in figure 6.8. Where 2030 shows around 1000 hours of peak prices, for 2050 this is almost half of the year for the NWEU power system as a whole. Figure 6.9 shows the annual electricity price per country, where Germany, the Netherlands and Belgium show a very high electricity price in 2050. For both France and the UK, the large increase of annual electricity price is much less. France does not show any changes in electricity price, whereas the UK only shows a strong increase in the FLEX 2050 scenario. This can also be explained through how the model used nuclear power, since the installed capacity of nuclear energy causes less loss of load for France and the United Kingdom and thus resulting in lower prices.

Figure 6.8. FLEX hourly electricity price

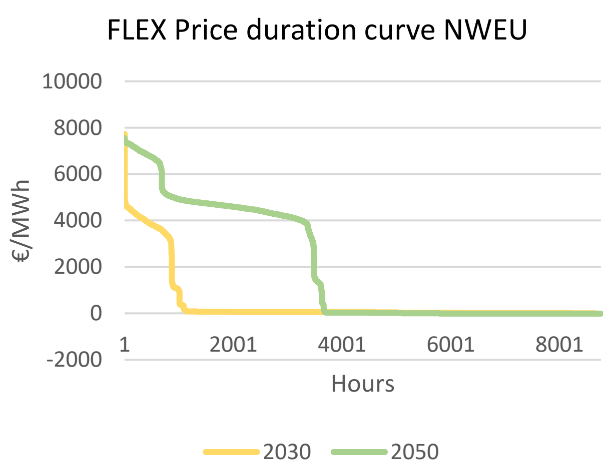
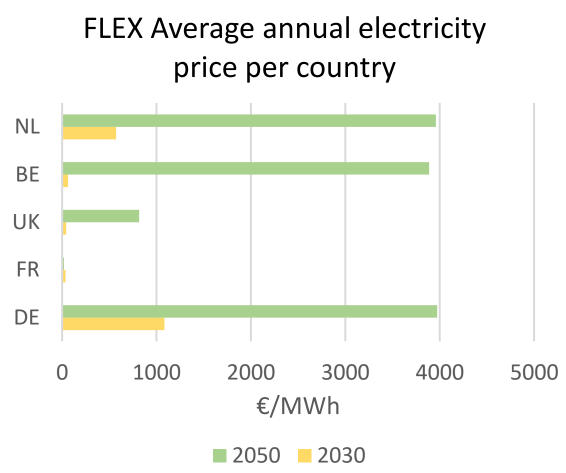


Figure 6.9. FLEX annual electricity price



The curtailment results of 21,7% in 2030 and 76,2% in 2050 show that a large amount of the available renewable energy generation is not used in the power system. These amounts can severely threaten the profitability of renewable energy projects, and could result in investors to withhold investments in renewable energy. The modelling results also show that with a large expansion of renewable energy in the power system, the electricity prices are very likely to become either zero or very high when not sufficient flexibility is installed. The high prices are in this case determined by the penalty of loss of load in the FlexTool and are therefore very dependent on how the FlexTool models this. However, these very high prices do indicate a broken pricing system when the power system becomes fully depended on VRE generation.

6.2. The Netherlands

6.2.1. Reference scenario EUCO

As described in 4.2 the EUCO scenario acts as a conservative reference scenario to portray the power system when a moderate increase of VRE is combined with an increase of the conservative flexibility option of natural gas. The results presented in table 6.3 from the model of the Netherlands show that also here, no loss of load occurs, and a very low percentage of VRE is curtailed in the EUCO scenario. However, they show some differences when compared to the NWEU model. Here the CO2 emissions do not decline from 2020 to 2050, instead the emissions rise from 2020 to 2050 with a peak in 2030. This means that the increase in electricity demand is mostly served with more natural gas generation then renewable generation. For the VRE share they increase with 0.8% from 2020 to 2050 with a prod of 6.3% in 2030. The operational costs increase from 2020 to 2050 due to the increase of natural gas use. As seen in the results of NWEU, the Netherlands model also shows an increase in absolute amount of fossil fuel use despite the increase of wind and PV capacity in the generation mix. With only a decline in the south-west region, illustrated in figure 6.10 and 6.11.

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational Costs (in million €)
NL	2020	0,025	0	50,7	33.7	4859
	2030	0	0	58,1	27.4	6244
	2050	0,0061	0	52,5	34.5	6761

Table 6.3. Main results EUCO Netherlands

Figure 6.10. Total generation EUCO Netherlands

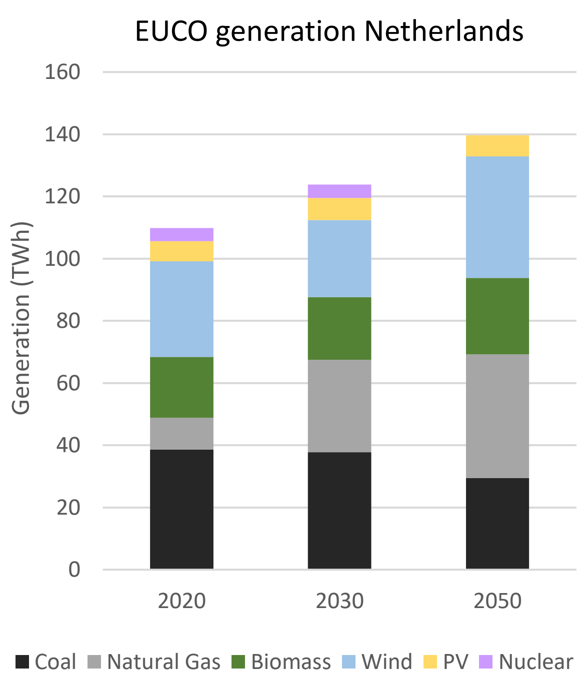


Figure 6.11. Total generation EUCO per region

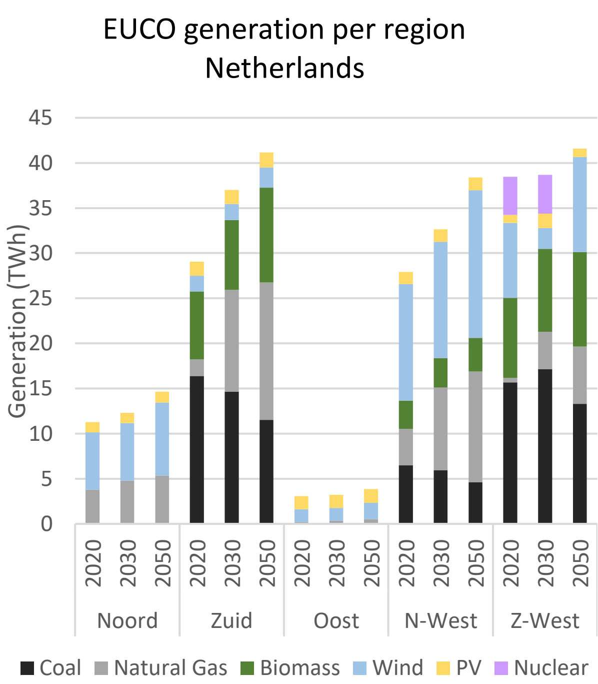


Figure 6.13 shows that the electricity prices in the Netherlands increase from 2020 to 2030 and are the same in 2030 and 2050, figure 6.12 also shows this in the hourly pattern. Compared to the NWEU results this shows a difference, as the Netherlands does in that power system also shows an increase between 2030 and 2050. The prices are however for each year higher than in the NWEU model, where the annual electricity price for the Netherlands in 2020 is €56/MWh and in €67/MWh in 2050. Whereas in the model of the Netherlands the annual electricity price in 2020 is €67/MWh and €76/MWh in 2050.

Figure 6.12. Hourly electricity price Netherlands EUCO

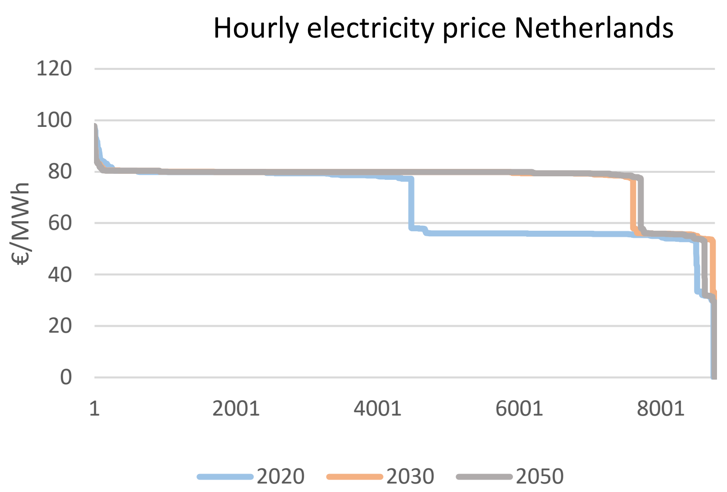
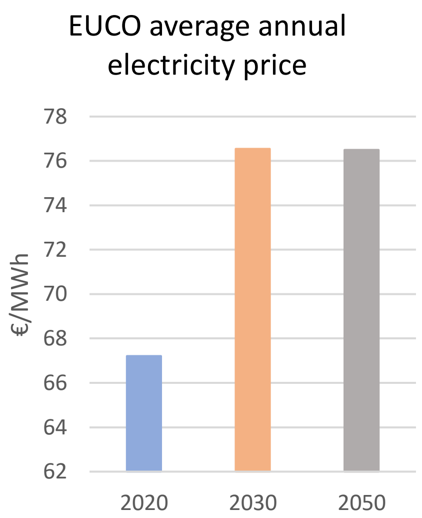


Figure 6.13. Average annual electricity price



The EUCO scenario shows that when the Netherlands follows a conservative path regarding renewable energy no flexibility issues arise. The results are very similar to the NWEU results despite the earlier increase in electricity price in 2030 than 2050 due to the increased natural gas in the system. Thus, when the Netherlands would follow the EUCO scenario, the power system will not need new or other flexibility options besides natural gas. The Netherlands would however experience higher electricity prices throughout the year. However, most importantly, the climate goals of the EU for 2050 will not be met.

6.2.2. Phase out scenario FLEX

Described in 4.3. the FLEX scenario portrays the replacement of coal and oil by VRE in 2030 and natural gas in 2050 to obtain a carbon neutral energy system. Table 6.4 shows a summary of the results. In 2030, where natural gas still provides electricity in the power system, there is not a large flexibility issue shown of only an increase of 0.14% of loss of load. However, compared to the EUCO scenario there is 35.7Mt less CO2 emitted. When natural gas is completely phased out and the power system does not emit any CO2 anymore, there is a significant problem regarding flexibility as 18.3% of the annual demand cannot be met. Regarding the curtailment of VRE, the amount in 2050 is above 100%, this is due to the fact that the model compares the curtailed VRE to the VRE generation that is used for the demand, so not for the total VRE. The curtailed renewable energy is therefore 1,46 times higher than the VRE share that is used to serve demand. The operational costs do decline severely between 2030 and 2050. This is can be explained through the decline in total power generation in combination with the increase of VRE generation.

Table 6.4. Main results FLEX Netherlands

		Curtailment (% of VRE gen)	Loss of load (% of annual demand)	CO2 (in Mt)	VRE share (% of annual demand)	Operational costs (in million €)
NL	2030	22,4	0,14	16,8	57,2	4852
	2050	146,2	18,3	0	78,1	2588

Figure 6.14 shows that the amount of curtailment and loss of load increases in absolute terms when natural gas is phased out and replaced by solar and wind. Comparing this with the Netherlands in the NWEU power system the absolute amount of curtailed VRE is 2.6 TWh higher in the model of the Netherlands in 2050. The regional difference in power generation and curtailment is illustrated in figure 6.15. Most renewable energy is curtailed in the North region, followed by the Eastern, North-West, South and South-West region. The region where the most demand cannot be met is in the South with 11 TWh, this is almost half of the total loss of load in the Netherlands.

Figure 6.14. FLEX total generation Netherlands

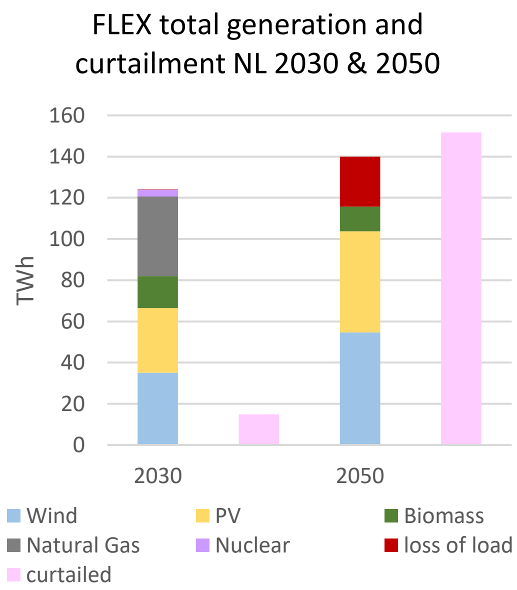
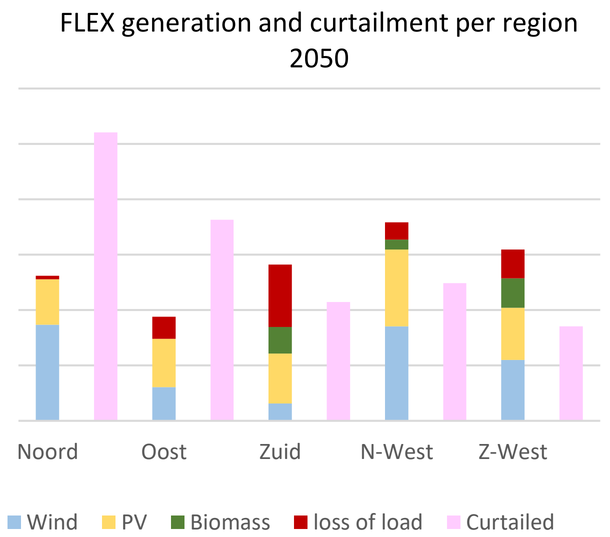


Figure 6.15. FLEX total generation per region



The flexibility indicators show a difference between the five regions in the need for flexibility. The curtailment in the North is very high, whereas the loss of load in the South is very high. This can be explained by the North of the Netherlands having the most potential for the placement of VRE capacities. The South of the Netherlands has the much more potential for PV then for wind and has the lowest installed capacity of wind of all the regions. Since PV is highly dependent on the shining of the sun and in the winter months the sun shines much less and the generation of wind does not change much, the loss of load in the south is much higher. The difference in potential for installed capacities of VRE will therefore also influence the difference in needed flexibility per region.

The electricity prices in 2050 show a large increase of the amount of peak prices, illustrated in figure 6.16. The FLEX 2030 scenario shows around 172 hours of peak prices, for 2050 this is half of the time for the power system of the Netherlands with peak prices around the €10000/MWh and the other half of the time with prices around €0/MWh. Hence the average annual electricity price becomes much

Figure 6.16. Hourly electricity price FLEX Netherlands

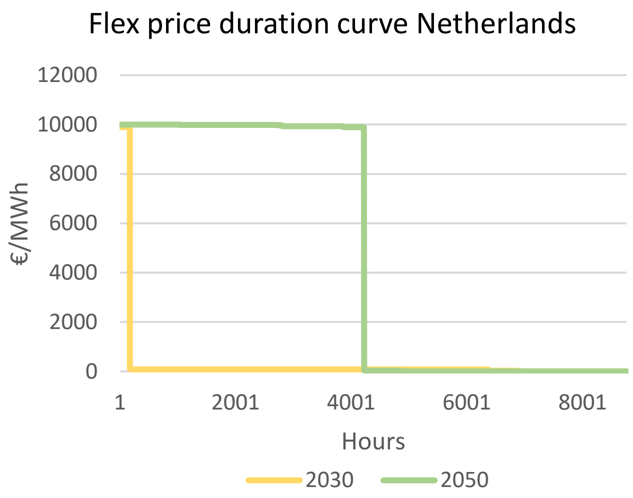
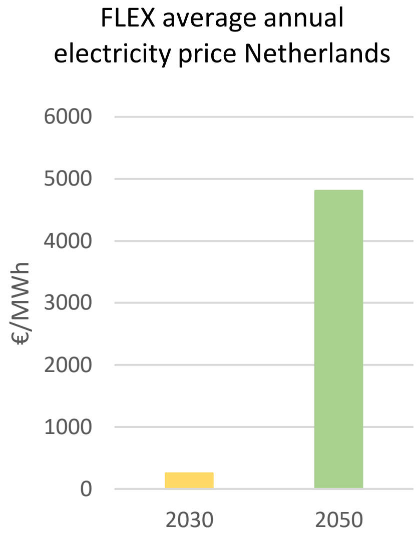


Figure 6.17. Annual electricity price Netherlands



higher, as figure 6.17 shows, when natural gas is replaced with wind and PV generation in 2050. Furthermore, figure 6.16 shows that for 2050, the electricity price is almost binary, the price is €0/MWh or either around €10000/MWh. The penalty for loss of load in the FlexTool is set at €10000/MWh and therefore sets the high price of electricity. In the NWEU case the prices already showed a similar pattern. However, there the total electricity prices were lowered by the electricity prices of France and the United Kingdom. In the case of the Netherlands the modelling results show much more evidently that when the power system becomes fully dependent on VRE generation the price system does not work.

The curtailment results of 22,4% in 2030 and 146,2% in 2050 show that a large amount of the available renewable energy generation is not used in the power system. As in the NWEU case, these amounts of curtailed power can severely threaten the profitability of renewable energy projects, and could result in investors to withhold investments in renewable energy which jeopardizes reaching the climate neutral goal of the EU.

6.3. Design of Experiments

The outcomes of the DOE were analysed with the Minitab software to find the 1 term relation between each factor. In this case EVs, batteries, hydrogen storage and heat pumps on the loss of load and VRE curtailment. The effects of the technologies on the outcomes of the curtailment and loss of load and the LCOE per technology are presented here for both the NWEU and Netherlands scale. First the main results as provided by the IRENA FlexTool and the DOE will be presented. Secondly the implications and difference between the results for the Netherlands and North West Europe will be discussed. The numerical results of all the experimental runs can be found in appendix IV.

6.3.1. The Netherlands

6.3.1.1. Main effects loss of load and curtailment

Figure 6.18 shows the relation between the levels of the different technologies and the percentage of VRE generation that is curtailed. For both the EVs and batteries there is a decline from low to medium to high regarding the total amount of curtailed VRE. For EVs this decline entails 15,5% from low to medium and 2,5% from medium to high. For batteries this decline is 2,3% from low to medium and 2,3% from medium to high. For both hydrogen and heat pumps the percentage of curtailment does decline from low to medium. With 5,6% for hydrogen storage and 3.6% for heat pumps. However, for both options the VRE curtailment increases from medium to high, with the heat pumps increasing to above the percentage of VRE curtailment of a low integration of heat pumps with 5,2%. And hydrogen storage increases with 2,8% more curtailed VRE with high integration.

Figure 6.19 shows the main effect of the technologies on the total loss of load of the power system. This figure shows that for both the hydrogen storage and batteries, the loss of load declines from the low to medium and medium to high integration. With a decline of 1,8% from low to medium and 0,47% from medium too high for hydrogen. For battery storage this is 0,04% from low to medium and 0,5% from medium to high. However, the two other technologies show a different pattern. For heat pumps there is an increase in loss of load from low to medium and from medium to high of respectively 0.23% and 0.27%. Whereas EVs first show a decline from low to medium of 0.26% followed by an increase of 0.26% from medium to high.

Figure 6.18. Main effects curtailment

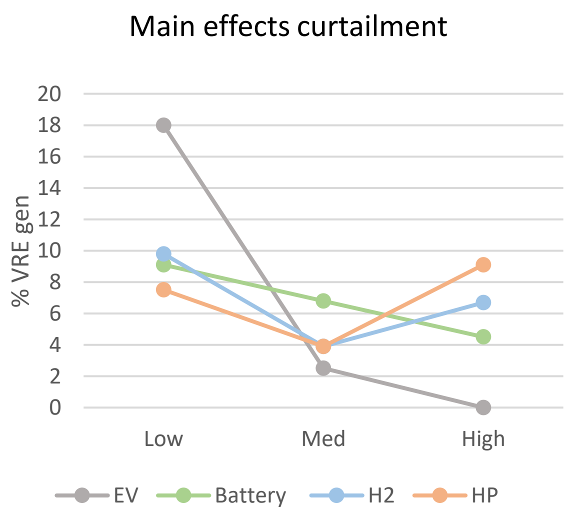
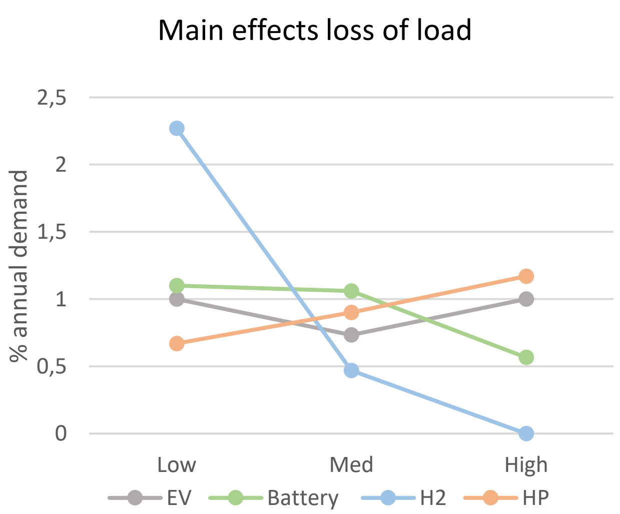


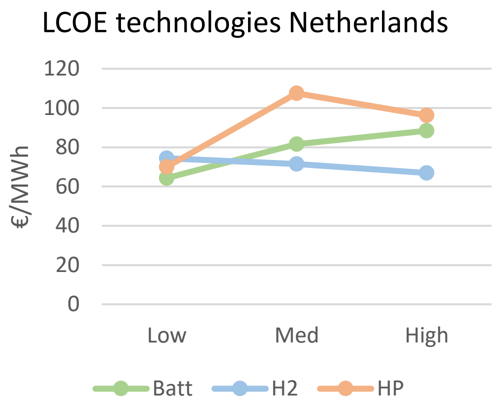
Figure 6.19. Main effects loss of load



6.3.1.2. Levelized cost of energy

Figure 6.20 shows the relation between the levels of the different technologies and the LCOE. The Heat pumps show the lowest LCOE also at their low level with €70,0/MWh, then the LCOE increases to €107,5/MWh for the medium level and decreases again to €96,3/MWh. For the batteries storage, the LCOE is also at its lowest point in the low level with €64/MWh. The LCOE then only shows an increasing line with a LCOE of €81,5/MWh in the medium level and €88,4/MWh in the high level. For hydrogen the pattern is the other way around compared to batteries. Since it highest LCOE is in the low level with €74,4/MWh. From there on, it only shows a decreasing line with a LCOE of €71,4/MWh in the medium level and €66,9/MWh in the highest level. When comparing the technologies with each other, hydrogen has, at the low level the highest LCOE and battery storage the lowest. Whereas in the high-level hydrogen becomes the technology with the lowest LCOE, heat pumps with the highest and batteries in the middle of the three, but more towards the same price as heat pumps.

Figure 6.20. Levelized cost of energy



6.3.2. North West Europe

6.3.2.1. Main effects on loss of load and curtailment

Figure 6.21 shows the relation between the levels of the different technologies and the percentage of VRE generation that is curtailed. The EVs show a decline from low to medium with 9,2% and from medium to high with 2,3%, regarding the total amount of curtailed VRE. For both hydrogen and heat pumps the percentage of curtailment does decline from low to medium, with 2,1% for hydrogen storage and 3,6% for heat pumps. However, both technologies increase from medium to high, with the heat pumps increasing to above the percentage of VRE curtailment of a low integration of heat pumps with 5,2%. And hydrogen storage increases with 2,8% more curtailed VRE with high integration. Batteries show again a different patter with an increase from low to medium of 1,5% and a decline from medium to high of 1,3%.

Figure 6.22 shows the main effect of the technologies on the total loss of load of the power system. This figure shows that for both the hydrogen storage and EVs the loss of load declines from the low to medium and medium to high integration. With a decline of 0,11% from low to medium and 0,10% from medium too high for hydrogen. For EVs this is 0,223% from low to medium and 0,04% from medium to high. However, the two other technologies show a different pattern. For heat pumps there is an increase in loss of load from low to medium and from medium to high of respectively 0.03% and 0.03%. Whereas batteries first show a decline from low to medium of 0.03% followed by an increase of 0.01% from medium to high.

Figure 6.21. Main effect curtailment

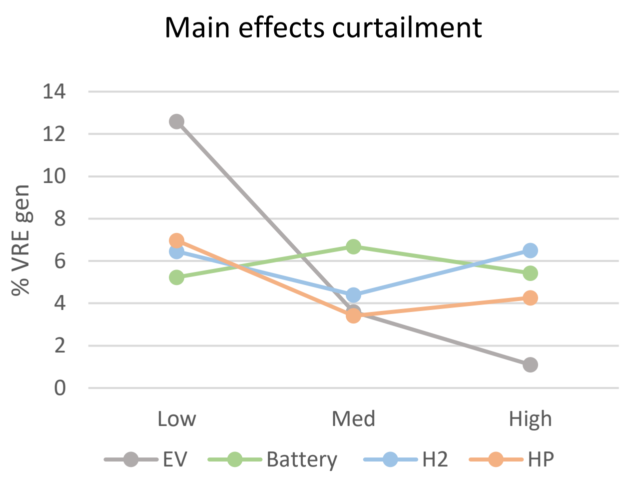
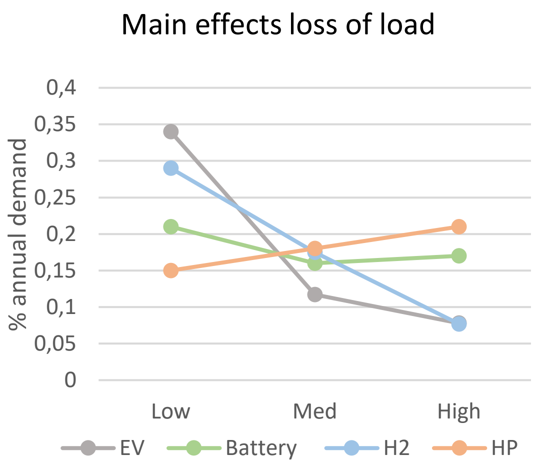


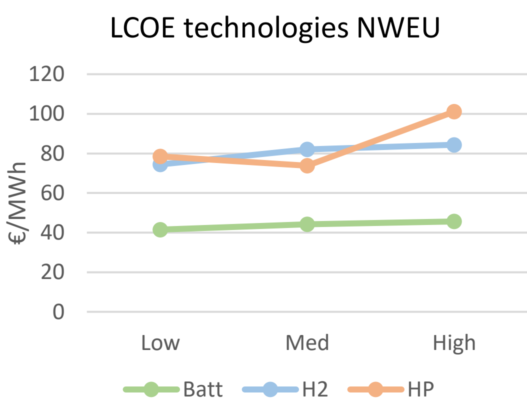
Figure 6.22. Main effect loss of load



6.3.2.2. Levelized cost of energy

Figure 6.23 shows the relation between the levels of the different technologies and the LCOE. The Heat pumps show a LCOE of €78,5/MWh at their low level, then the LCOE decreases to €73,8/MWh for the medium level and increases again to €101,1/MWh. For the batteries as flexibility option the LCOE is at its lowest point in the low level with €41,5/MWh. The LCOE then only shows an increasing line with a LCOE of €44,2/MWh in the medium level and €45,6/MWh in the high level. For hydrogen the pattern is the same as for batteries. The lowest LCOE is in the low level with €74,4/MWh. From there on only an increasing line with a LCOE of 81,9/MWh in the medium level and €84,4/MWh in the highest level is shown. When comparing the technologies with each other, heat pumps have, at their low level, the highest LCOE and battery storage the lowest. This is the same in the high level. However, the medium level is the only place where this is different since the LCOE of hydrogen becomes the highest there. Batteries have in all levels the lowest LCOE, whereas the costs of hydrogen and heat pumps is closer to each other.

Figure 6.23. Levelized cost of energy



6.3.3. Comparison of North West Europe and the Netherlands

When comparing the results of the two different scales regarding the main effects of the technologies on the curtailed power, a similar pattern between EVs, hydrogen and heat pumps can be noticed from figure 6.18 and 6.21, however where the heat pumps in the Netherlands show a much steeper increase from medium to high. However not all technologies show the same pattern. Where in the Netherlands scope the batteries show a decline from low to high, for NWEU the batteries peak in the medium level.

Regarding the loss of load in both scales, similar patterns are shown by the technologies of heat pumps and hydrogen, however hydrogen shows a much steeper decrease from low to medium for the

Netherlands. The EVs do show a difference in its pattern from low to high. Where they showed in NWEU only a decline in loss of load, for the Netherlands figure 6.19 shows that the loss of load does increase again from medium to high. Batteries also do show a different pattern in both scales. Whereas in the Netherlands the loss of load only decreases from low to high, in NWEU the loss of load does increase with 0,01% from the medium to high level.

The most differences can be noticed when comparing the LCOE for the two scales. Only the batteries as flexibility option show a similar pattern of an increasing loss of load from the low to high level, however with a steeper increase in the Netherlands. Furthermore, the absolute LCOE are €20-€30/MWh lower in the NWEU compared to the Netherlands for the battery technology. Hydrogen however shows an opposite pattern in both scales. Where the LCOE decrease from low too high in the Netherlands, the LCOE increase in NWEU. With the absolute LCOE of hydrogen is almost the same at €74/MWh, in the Netherlands this decreases to €66,9/MWh and in NWEU the LCOE increases to €84,4/MWh. For heat pumps the two scales also show an opposite pattern. Where the peak in LCOE price in the Netherlands is at the medium level, for the NWEU this peak is in the high level. However, the lowest LCOE is in the Netherlands at the low level, however for NWEU this point is at the medium level. The absolute prices of the peak levels are almost the same, whereas this in the Netherlands is €107,5/MWh in NWEU this is €101,1/MWh. And the prices for the lowest LCOE are also close for both scales as in the Netherlands this price is €70,0/MWh and in NWEU this price is €73,8/MWh.

For the Netherlands the results regarding sector coupling and battery storage indicate that hydrogen provides the best solution regarding the loss of load and LCOE. For NWEU this is similar for the loss of load, since hydrogen only shows a decline, and with higher levels for the DOE chosen, hydrogen could completely reduce the loss of load in NWEU. Therefore, ahigh integration of hydrogen is the only option that can reduce the loss of load for both the Netherlands and NWEU, whereas the other options cannot. This can be explained through the fact that hydrogen is able function as a bridge between the different seasons. Since salt cavern storage has a very low discharge rate it is able to store the power generated in the summer by PV and use this energy in the winter when much less PV generation is available. For the other options this is not the case because their discharge rate is much higher and are therefore not able to store the power for such long periods.

The other main difference between the regions is the LCOE of battery storage. This difference can be explained through the fact that the batteries in NWEU generate more power back to the power system proportionally to their OM costs compared to the Netherlands. This means that they produce relatively more power and therefore their LCOE is lower. Regarding the curtailment of VRE, the EVs in both the Netherlands and the NWEU provide the best solution, since in both cases they reduce the total curtailment to almost 1%. This indicates that when everyone will drive an electric car the EVs will use a lot of the generated power by VRE. Which will change demand patterns and can result in more loss of load.

This chapter showed the total amount of curtailed renewable energy in both power systems of the Netherlands and the North West of Europe and the costs of the different technologies which make use of the curtailed power. These result which will be discussed in more detail in the discussion in the next chapter.

7. Discussion

The main goal of this study was to compare the different sector coupling options and batteries with the IRENA FlexTool for the Netherlands and North West Europe. Since the findings of the comparison are dependent on the use of the IRENA FlexTool, the FlexTool will be discussed first. After the discussion of the FlexTool, the research limitations will be described. Then the results regarding sector coupling, batteries and the flexibility indicators will be discussed. From this, the key findings, future research and policy recommendations will be presented.

7.1. IRENA FlexTool

Before discussing the results related to the main question the findings related to the IRENA FlexTool will be discussed first to provide the right context to interpret the results. Resulting from chapters 3 and 4, the IRENA FlexTool has three main shortcomings. The first shortcoming relates to the disability of running the investment mode when sector coupling is used in the model. The second shortcoming relates to the modelling of the electricity prices, which fails to model the peak prices in the model validation. The third shortcoming relates to the number of nodes that the FlexTool is able to model, which causes to severely reduce the variety in the researched power system.

Starting from the model validation in chapter 3.5, the model showed, especially for the historical prices of Germany, a large difference. The peak and low prices from 2018 did not came out as a result of the FlexTool. This could have an effect on the outcomes of this study; however, this study did not research the specific effects of this. The electricity prices for both the NWEU and the Netherlands in the FLEX 2050 scenario became very high. Showing almost a binary price, where the price is half of the time zero and the other half as high as the loss of load penalty in the FlexTool. This is especially evident in the price graph for the Netherlands, as in the NWEU price graph the price is also altered by the prices of France and the UK that show less or no effects of high integrations of VRE on the electricity price. This could indicate a broken price system when the power system will switch to fully renewable energy. However, since the modelled prices in the model validation were not very accurate, this study cannot draw any conclusions regarding the electricity prices. Therefore, further research on the effect of a fully renewable power system on the pricing system of electricity should be conducted.

The second shortcoming relates to the number of nodes that the FlexTool is able to model. The research initially focussed on the 30 RES regions of the Netherlands, however the FlexTool could not provide results for that many nodes. Modelling sector coupling options in the combined regions as described in chapter 4 did not provide any results as well. Therefore, the number of regions for the Netherlands had to be reduced severely from 30 to 5 regions, taking away some of the variety of the regional energy strategy taken in the Netherlands. Therefore, the results are prone to more simplification and the conclusion can only be drawn on a less detailed level. The FlexTool itself comes with multiple template examples of models used by IRENA. In those templates the models are never larger than 6 nodes in total, including the different sector coupling options. And the sector coupling options are never modelled together in one model, but always in separate templates. The FlexTool is thus suitable to indicate the problems of curtailment and loss of load, but less suitable to compare different sector coupling options as the calculation time of the model becomes too large or it does not provide any results anymore. The IRENA FlexTool could therefore be better suited to model smaller energy systems to gain a quick insight into the flexibility issues of a country or region, instead of modelling a very complex energy system. However, as this is the first study that included this model, more research should be done to confirm this statement.

The third shortcoming of the FlexTool was the inability to use the investment mode. The FlexTool has the feature to freely optimise investments in generation or storage units, and therefore also in sector coupling options and batteries. However, chapter 3 showed that it was better to not use the investment mode when modelling multiple sector coupling options. In order to cope with this shortcoming a design of experiments was used. By using the design of experiments, a comparison became possible, however this brought extra limitations to the research.

7.2. Research limitations

The use of a DOE instead of letting the model freely choose the investments has its downsides. The levels that had to be chosen in order to perform the DOE influenced the results. Since the levels of the DOE in this research are chosen to reach a very broad spectrum, the answers of this research regarding sector coupling and batteries can also only be interpreted broadly. Another shortcoming of the DOE in this research is that it only considered a 1 term analysis. Therefore, only the relation of a sector coupling option and batteries to the objective is measured and not the relation between the options. This does alter the results because all options are modelled in each run on either a low, medium or high level. While the interaction of these options is not taken into account in the DOE. Therefore, the results of each sector coupling option and battery storage on the curtailment, loss of load or peak prices is not a direct effect, but is influenced by the other options. In order to find a more specific answer, in the case with the IRENA FlexTool, two options are possible. Either by doing a full factorial analysis and including more levels that are more narrowly scoped. Or by modelling a smaller system, in which, for example the Netherlands is only modelled as one node, with other nodes only representing the sector coupling options. The second option makes it possible to use the investment mode of the IRENA FlexTool and therefore the model is able to freely choose investments in the sector coupling solutions or batteries. Providing more accurate results regarding the needed installed capacity of the flexibility option.

Another limitation of this research is the lack of accurate transmission capacity data for the Netherlands scale which resulted in the assumption of very high transmission capacities between the regions. The effect of this is that the power system would function as a copper plate and that the excess generated power can always be placed somewhere else, resulting in less curtailment. The results of this research show however, that still a significant amount of renewable energy is curtailed. Indicating that the curtailment cannot only be solved by adding more transmission capacity.

The research has another limitation in the determination of the new capacities of wind and PV. In this study the ratio between the maximum installed capacity of solar and wind is taken. The maximum of solar capacity was in both papers much higher than the maximum capacity of wind. Therefore, in this study the amount of solar energy increases much more than wind. This could have an effect on the curtailment and loss of load that resulted from this study. And in reality, the possibility exist that the installed capacity of wind increases more than solar. The assumption made regarding the offshore wind capacity for the Netherlands has effects on the results as well. The main effect of this is the difference in capacity factors and thus the volatility of the renewable power generation and not the overall capacity of wind generated power. By how the FLEX scenarios are derived, the main effect of this is the difference in capacity factors and thus the volatility of the renewable power generation and not the overall installed capacity of wind. The annual volatility of offshore wind is slightly higher than onshore wind according to the IEA (2019a). And therefore, the amount of curtailment and loss of load could be slightly higher for the Netherlands when offshore wind was included.

7.3. Key findings and future research recommendations

7.3.1. Curtailment and loss of load

This study found that a significant amount of renewable energy provided by wind and PV will be curtailed in the Netherlands and North West Europe when conventional power generation is substituted with renewable energy generation in the form of wind and PV. However, when natural gas was still part of the power system, the integration of VRE resulted in much less loss of load and curtailment. This has the implication that the first steps towards a renewable energy system will not cause much problems related to flexibility. However, when the Netherlands or NWEU want to accomplish the goal of climate neutrality, the integration of VRE will cause flexibility problems. These large amounts of curtailed power for VRE in a climate neutral power system can severely threaten the bankability of renewable energy projects. This could result in investors withholding their investments in renewable energy and in return hampering the Netherlands and the NWEU in reaching the goal of climate neutrality. However, these problems are not uniform for all the countries in the North West of Europe.

Both France and the United Kingdom show differences in loss of load to the other countries in the NWEU. These differences could be explained due to the nuclear power that is installed in the generation mix of France and the UK and are therefore less prone to the fluctuations of renewable energy when it comes to the loss of load. As this could be a result of nuclear power generation in the energy mix, this should not be a conclusion from the results. The nuclear power plants in both countries only run on average for 4200 hours in the year. A study from the World Nuclear Association (2008) has shown that a nuclear power plant should run on average 6000 hours in a year to become economically viable, while in this scenario it only runs for 4200 hours. Therefore, the results regarding nuclear power should not be compared to the reality as no costs studies regarding the start and shut down costs of nuclear energy have been done here. This does however explain the differences in loss of load between France and the UK compared to the other countries. As is stated in the study of Jenkins et al., (2018) that nuclear power does help with integrating renewable energy of wind an PV in reducing both curtailment and loss of load. So, the problems of reaching climate neutrality by integrating VRE can differ per country. This has the implications that the incentive to obtain new flexibility options can differ a lot between countries in the NWEU region. More research is necessary to indicate how these differences between the countries occur and what the role of nuclear power is when integrating wind and PV to reach the goal of climate neutrality.

Besides the difference in the countries of the NWEU, a large difference can be noticed between the energy regions as well. The curtailment in the north is very high with almost no loss of load, however the curtailment is much lower in the south, with a much higher loss of load. This difference can be explained by the imbalance of demand and supply at the specific locations' sites. As in the north a lot of wind and solar is installed compared to the south region, the demand in the north is also lower than in most other regions. As the oversupply of the wind and PV has to be curtailed locally and cannot be stored in the FLEX scenarios, the loss of load will be much greater in regions with lower installed capacity of wind and PV and higher demand. This due to the larger differences between the moments where demand is high and wind or PV generation is low. Another difference between the regions can be noticed between the regions with a high PV integration. The South of the Netherlands integrates much more PV then wind, resulting in the more loss of load compared to the other regions where wind is integrated more. This indicates that the need for flexibility differs a lot on the regional level as well. Therefore, solutions to flexibility issues have to be solved from a regional perspective as well.

Considering the Netherlands in both scales, a difference in loss of load and curtailment can be observed as well. As the loss of load is 3 TWh higher and the curtailment is 15 TWh higher in the Netherlands scale compared to the Netherlands in the NWEU scale. This can be explained through both the workings of the FlexTool and transmission capacities. In the NWEU scale the import and export of the Netherlands is just partially determined by its input data, because of the connection to its neighbouring countries. Therefore, the model is able to optimise the import and export as a variable to the other countries whereas in the Netherlands scale, this factor is solely determined by rigid input data over which the FlexTool cannot make any decisions. Thus, when the FlexTool is able to determine the import and export more as a variable, the curtailment and loss of load are reduced as well. This indicates the role of transmissions as a flexibility source as is studied in multiple studies (Lund et al., 2015; Child et al., 2019; Liebensteiner & Wrienz, 2019).

7.3.2. Sector coupling and batteries

Besides the increasing occurrence of curtailment and loss of load, the modelling results show that both issues can be solved with sector coupling options and battery storage. For the Netherlands and NWEU both the curtailment and more importantly the loss of load can be reduced to 0 through these options. It would be expected that the pure storage technologies, batteries and hydrogen would only decrease the loss of load and curtailment since they would only store the energy to provide back to the power system when it is needed again (Denholm, 2019). However, both batteries and hydrogen storage do not show this expected pattern, since hydrogen shows higher curtailment rates in its high level than medium in the NWEU and Netherlands. And batteries show a higher loss of load percentage in its high level than medium in the NWEU. This could be explained through the fact that not a full factorial analysis is performed but rather only a main effects design of experiments. Therefore, no relation between the different technologies is measured and the main effect on the objective can be altered due to another technology being set on a high or low level. And in this way reducing or increasing the curtailment or loss of load.

For the EVs and heat pumps, another pattern would be expected. Since both EVs and heat pumps add more demand to the energy system, there would be a trade-off between the added storage and added demand in providing flexibility. This trade-off occurs through the added peak demand at certain moments that cannot always be served, resulting in extra loss of load (Luca & Pregger, 2018). In the results the heat pumps show only an increase in loss of load for both scales indicating that a potential optimum could be lower than the levels chosen in this study. For the EVs the pattern regarding the loss of load only decreases for the NWEU scale, indicating a potential optimum higher than the chosen levels. For the Netherlands the pattern shows a potential optimum in the medium level. Since this study uses very broad levels to research the different options, the results presented here cannot say where this trade-off happens, since it possibly happens for some of the options outside of the levels chosen in the DOE. Therefore, more research towards the trade-off between the added demand and storage of EVs and heat pumps is necessary.

When comparing the options regarding the loss of load, a high integration of hydrogen storage in the power systems for both the Netherlands and the NWEU does reduce the loss of load to zero. The modelling results show that only when hydrogen is integrated on the high level, the loss of load can be brought back to zero. This can be explained through the fact that hydrogen is able to function as a bridge between the different seasons. Since salt cavern storage has a very low discharge rate it is able to store the power generated in the summer by PV and use this energy in the winter when much less PV generation is available. For the other options this is not the case because their discharge rate is much higher and are therefore not able to store the power for such long periods.

The modelling results show that the LCOE of hydrogen is the lowest in the Netherlands and the second lowest in North West Europe where battery storage is a much more economical choice due to the low LCOE compared to the other options. The result workbook of the IRENA FlexTool shows that the batteries in NWEU generate more power back to the power system proportionally to their OM costs compared to the Netherlands. This means that they produce relatively more power and therefore their LCOE is lower. This can be explained through the fact that Belgium does not contain any salt cavern storage. Therefore, when power is needed in Belgium, battery storage will be chosen above the use of hydrogen from other countries. This results in more use of battery storage then hydrogen in Belgium, increasing the average use of batteries in the NWEU. And thus, results in a lower LCOE compared to the Netherlands.

Relating back to the knowledge gap regarding the comparison of battery storage and the sector coupling options. The modelling results show that EVs and Heat pumps can provide extra flexibility to the power system, but are dependent on their demand. This will create a trade-off when EVs and Heat pumps will add too much demand resulting in no extra flexibility benefits. Hydrogen and battery storage as used in this research do not have this characteristic and only provide storage to the power system. Batteries diminish the loss of load to a certain extend by using the curtailment of renewable energy. However, only hydrogen is able to completely reduce the loss of load because of the possibility to store energy over seasons. The explanation of the LCOE difference of battery storage in the Netherlands and NWEU shows that when the relative percentage of battery storage is higher, the LCOE decrease. The LCOE resulting from the modelling approach are compared to other studies, ranging in the higher LCOE of the technology (IEA, 2019). This could be explained by the DOE where all the options are included in each run, resulting in non-optimal use of the stored energy for each option, increasing the LCOE of the technology. Future research is needed to study the interaction between the different options. This could provide useful results on how to efficiently allocate and use the different options when they are used in combination with each other.

The academic contribution of this research exists of two parts. The study showed that the IRENA FlexTool is better suited to model smaller energy systems to gain a quick insight into the flexibility issues of loss of load and curtailment, instead of modelling larger complex energy systems. And the study showed a comparison of battery storage, power-to-heat, power-to-hydrogen and vehicle-to-grid for the Netherlands and North West Europe. Where power-to-hydrogen showed to be to most viable option for the Netherlands, and power-to-hydrogen and battery storage for North West Europe.

7.4. Policy recommendations

One of the main issues that is relevant for policy makers from this study is the fact that as long as natural gas is a part of the generation mix, flexibility does not really become a problem. With the goal of the EU in mind, the flexibility options are eventually necessary when natural gas needs to be phased out due to its CO2 emissions, in order to avoid loss of load. Therefore, investments in R&D on a European level need to be made regarding flexibility options for the power system. As the Netherlands is already phasing out natural gas, hydrogen does seem to provide the best alternative in providing flexibility. However, assumption of cost reduction to 2050 are made in this research and therefore a lot of investments in R&D is necessary for electrolysers and fuel cells in order to reach these projected costs.

This research showed that on the regional level the flexibility issues can differ a lot. Currently the policy makers in the RES focus mostly on where and how to integrate wind and PV into their regions (RES, 2020). However, policy makers on the regional level should also start to consider strategies to cope with the flexibility issues of these sources. This in order to avoid jeopardizing the bankability of the renewable energy projects if they eventually want to become climate neutral.

8. Conclusion

In order to answer the research question, first each sub question will be answered with the data provided by the earlier chapters of this research, followed by the conclusion on the main research question.

8.1. Answers to sub questions

The first sub question focussed on which reference scenario was suitable for this research and was formulated as: *Which reference scenario is mainly used in scientific literature as a reference scenario for a European energy system in 2050?* This sub question is answered in chapter 4 where a short literature review showed that the EU 2016 reference scenario as defined in Capros et al., (2016) was widely used in current literature. And is therefore chosen to form the base scenario in this study.

The second sub question focussed on the total amount of curtailed power when conventional power generation was substituted with renewable energy in the form of wind and PV and was formulated as: *How much power is lost through curtailment and loss of load occurs when the EU climate goals are met in 2050 by only integrating VRE for the Netherlands and North West Europe using the IRENA FlexTool?* This question was answered by running the two FLEX scenarios for 2030 and 2050 with the IRENA FlexTool of which the answers are described in chapter 6. The modelling results show that for the North West of Europe an amount of 21,7% of the power generated by renewables is curtailed when coal and oil are phased out and replaced by wind and PV. And 76,2% of the power generated by renewables is curtailed when natural gas is phased out and replaced by wind and PV. For the Netherlands an amount of 22,4% of the power generated by renewables is curtailed when coal and oil are phased out and replaced by wind and PV. And 146,2% of the power generated by renewables is curtailed when natural gas is phased out and replaced by wind and PV. Regarding the loss of load, for North West Europe 0,4% loss of load occurred in the FLEX 2030 scenario, and 5,7% in the FLEX 2050 scenario. For the Netherlands 0,14% loss of load occurred in the FLEX 2030 scenario and 18,3% in the FLEX 2050 scenario. These results indicate that when natural gas is still a part of the power system, flexibility will not be a very large issue. However, when the goal is climate neutrality and natural gas has to be phased out, flexibility becomes a much large issue. This increase in curtailment can lower the bankability of new renewable energy projects which can severely jeopardize the goal of climate neutrality of the European Union by 2050.

The third sub question focussed on the cost aspects of the different sector coupling technologies and batteries and was formulated as: *What are the levelized cost of energy of sector coupling and batteries in 2050 for the Netherlands and North West Europe using the IRENA FlexTool?* Figures 8.1 and 8.2 show that the answer on this question differs for the Netherlands and North West Europe.

Figure 8.1. LCOE Netherlands

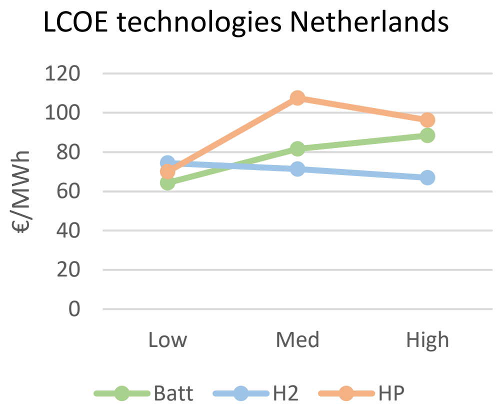
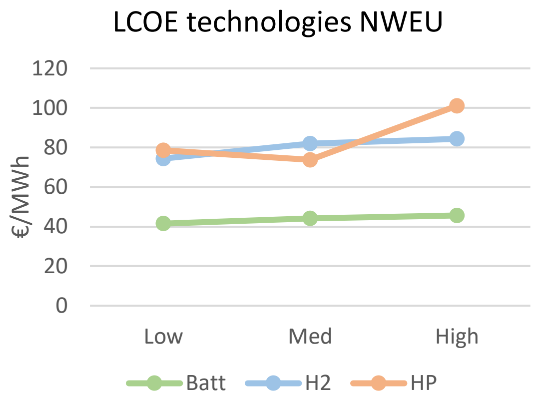


Figure 8.2. LCOE NWEU



As the LCOE for batteries is for all levels the lowest in North West Europe, ranging from €41,5/MWh to €45,6/MWh. However, in the Netherlands, batteries only have the lowest LCOE in the low level with €64/MWh. And hydrogen has the lowest LCOE ranging from €71,4/MWh in the medium level and €66,9/MWh in the high level. This can be explained by the fact that Belgium does not contain any salt cavern storage in the NWEU. This results in more use of battery storage then hydrogen in Belgium, increasing the average use of batteries in the NWEU. And thus, lowering the LCOE compared to the Netherlands.

The fourth sub question focussed on the modelling aspects of the IRENA FlexTool. This sub question was formulated as: *What do the modelling results show about the suitability of the IRENA FlexTool for modelling battery storage and sector coupling for the Netherlands and North West Europe?* This research addressed three short comings of the IRENA FlexTool. The first shortcoming relates to the disability of running the investment mode when sector coupling is used in the model. The second shortcoming relates to the modelling of the electricity prices, which fails to model the peak prices in the model validation. The third shortcoming relates to the number of nodes that the FlexTool is able to model, which causes to severely reduce the variety in the researched power system. The IRENA FlexTool could therefore be better suited to model smaller energy systems to gain a quick insight into the flexibility issues of loss of load and curtailment, and not the electricity price, instead of modelling larger complex energy systems.

8.2. Answer to main research question

With the answers found on the sub questions, the research question can be answered. The research question focussed on the utilization of the lost power through curtailment and avoiding loss of load. In order for a high integration of renewable energy in the form of wind and PV, without losing incentives for investments in these renewable energy sources due to too much lost power by means of the IRENA FlexTool. This problem was researched according to the following research question:

How can battery storage and sector coupling cost optimally utilize the power that is lost through variable renewable energy curtailment and avoid loss of load for the Netherlands and North West Europe in 2050, using the IRENA FlexTool as modelling approach?

The answer on this question is provided in the results of chapter 6. Where the modelling results of the IRENA FlexTool show that the costs for utilizing the lost power of curtailment and avoiding loss of load differs for the Netherlands and North West Europe. For North West Europe, batteries have the lowest LCOE when almost all lost power trough curtailment is used and hydrogen provides a good solution for the loss of load. Therefore, both battery storage and hydrogen could be a good substitution for natural gas in NWEU. For the Netherlands hydrogen storage is the option with the lowest LCOE when all lost power through curtailment is used and loss of load is avoided. Therefore, hydrogen could provide a good substitution for natural gas in the Netherlands. The difference in LCOE can be explained through the allocation of the power use of batteries and sector coupling, since this is not included in this study. Future research should focus on the interaction between the different options. This could provide useful results on how to efficiently allocate and use battery storage and sector coupling when they are used in combination with each other.

This research showed that the IRENA FlexTool is better suited to model smaller energy systems to gain a quick insight into the flexibility issues of loss of load and curtailment, instead of modelling larger complex energy systems. And the study showed a comparison of battery storage, power-to-heat, power-to-hydrogen and vehicle-to-grid for the Netherlands and North West Europe. Where power-to-hydrogen showed to be to most viable option for the Netherlands, and power-to-hydrogen and battery storage for North West Europe. However, in order to reach this, a lot of research and investments need to be made. Hence, a long road in both research, politics and business lie in front in order to reach the goal of the European Union of becoming a climate neutral continent in 2050.

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Appendix I input data scenarios North West Europe

The input data as used for the NWEU scale in the FlexTool for the EUCO scenarios and FLEX scenarios are presented here. The method used to determine the final input data is described in chapter 5 of this report. Tables I.1 to I.3 show the input data of the 3 EUCO scenarios. Tables I.4 to I.6 show the input data for the transmission capacity based on the TYNDP for the ENTSO-E. And tables I.7 and I.8 show the input data for the Flex scenarios

Table I.1. Input data EUCO 2020

EUCO 2020		Germany (DE)	France (FR)	United Kingdom (GB)	Netherlands (NL)	Belgium (BE)
Annual demand *(MWh)*		579825280	452232550	322232410	110519890	84015120
Import/export *(MWh)*		89879	-29181308	385853	441734	89879
Capacity *(MW)*	**Wind**	61832	22130	33421	10096	4558
	PV	52803	20535	11043	5586	3818
	Natural Gas	21891	9181	35332	14406	6270
	Coal	49170	3856	11149	5388	43
	Oil	1674	5008	1235	77	266
	Biomass	7100	2894	17238	2254	869
	Nuclear	6907	61327	8884	485	5055
	Geothermal	170	0	0	0	0
	Hydro ROR	5592	23635	1791	0	119
Storage *(MWh)*	**Pumped hydro**	8918,00	5020,00	0	0	1150,00

Table I.2. Input data EUCO 2030

EUCO 2030		Germany	France	United Kingdom	Netherlands	Belgium
Annual demand *(MWh)*		558984320	452232550	356168750	116311630	88981130
Import/export *(MWh)*		12490546	-28246530	305893	-3269240	114190
Capacity *(MW)*	**Wind**	67214	30771	33421	10096	6907
	PV	63959	25382	11043	5586	3818
	Natural Gas	26978	8344	35928	12289	10331
	Coal	36775	3780	501	4429	16
	Oil	1248	1679	1167	66	215
	Biomass	6894	3431	17244	2308	820
	Nuclear	0	59493	13107	485	0
	Geothermal	170	0	0	0	0
	Hydro ROR	5857	23635	1791	0	177
Storage *(MWh)*	**Pumped hydro**	8918,00	5020,00	0	0	1150,00

Table I.3. Input data EUCO 2050

EUCO 2050		Germany	France	United Kingdom	Netherlands	Belgium
Annual demand *(MWh)*		579825280	547505510	438009060	132837860	108135740
Import/export *(MWh)*		11812068	-12673704	135598	-3651243	92659
Capacity *(MW)*	**Wind**	86549	57569	41468	12806	9331
	PV	86141	45200	11255	5871	4722
	Natural Gas	41426	34924	46102	17788	14810
	Coal	24057	2892	448	3496	0
	Oil	674	625	339	58	2

	Biomass	6586	3636	18032	2644	1003
	Nuclear	0	32276	17302	0	0
	Geothermal	170	0	0	0	0
	Hydro ROR	7170	26559	1818	0	193
Storage *(MWh)*	**Pumped hydro**	8918,00	5020,00	0	0	1150,00

Table I.5. Input data transmission capacity 2020

TC 2020	=> (MW)	<= (MW)
BE-DE	1000	1000
BE-FR	1800	3300
BE-GB	1000	1000
BE-NL	2400	1400
DE-FR	2300	1800
DE-GB	0	0
DE-NL	4250	4250
FR-GB	2000	2000
GB-NL	1000	1000

Table I.6. Input data transmission capacity 2030

TC 2030	=> (MW)	<= (MW)
BE-DE	1000	1000
BE-FR	2800	4300
BE-GB	1000	1000
BE-NL	3400	3400
DE-FR	4500	4500
DE-GB	1400	1400
DE-NL	5000	5000
FR-GB	6900	6900
GB-NL	1000	1000

Table I.7. Input transmission capacity 2050

TC 2050	=> (MW)	<= (MW)
BE-DE	1000	1000
BE-FR	4300	5800
BE-GB	2500	2500
BE-NL	4900	4900
DE-FR	4800	4800
DE-GB	1400	1400
DE-NL	5000	5000
FR-GB	6900	6900
GB-NL	2500	2500

Table I.8. Input data FLEX 2030

FLEX 2030		Germany	France	United Kingdom	Netherlands	Belgium
Capacity *(MW)*	**Wind onshore**	331680	10609	1616	12396	10569
	Wind offshore	43175	23385	33570	X	1039
	PV	331680	54901	19706	38060	5445

Table I.9. Input data FLEX 2050

FLEX 2050		Germany	France	United Kingdom	Netherlands	Belgium
Capacity *(MW)*	**Wind onshore**	49033	37764	4727	23730	12023
	Wind offshore	57888	41116	86391	X	1941
	PV	551954	253068	254786	160056	109055

Appendix II Input data scenarios Netherlands

The input data as used for the Netherlands scale in the FlexTool for the EUCO scenarios and FLEX scenarios are presented here. The method used to determine the final input data is described in chapter 5 of this report. Tables II.1 to II.3 show the input data of the 3 EUCO scenarios. And tables II.4 and II.5 show the input data for the Flex scenarios

Table II.1. Input data EUCO 2020

EUCO 2020		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Annual demand *(MWh)*		12510835	18033810	27845996	25852048	26277199
Import/export *(MWh)*		588252	786247	-169026	-309963	0
Capacity *(MW)*	**Wind**	1870	555	725	2608	4337
	PV	1029	1265	1351	758	1179
	Natural Gas	4158	61	2711	3178	4297
	Coal	0	0	2091	2487	886
	Biomass	0	0	862	1025	365
	Nuclear	0	0	0	485	0

Table II.2. Input data EUCO 2030

EUCO 2030		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Annual demand *(MWh)*		13166489	18978863	29305251	27206812	27654242
Import/export *(MWh)*		2552162	1391727	-6473775	-4843535	0
Capacity *(MW)*	**Wind**	1870	555	724	2608	4338
	PV	1029	1265	1351	759	1179
	Natural Gas	3547	52	2313	2711	3665
	Coal	0	0	1720	2045	728
	Biomass	0	0	883	1050	374
	Nuclear	0	0	0	485	0

Table II.3. Input data EUCO 2050

EUCO 2050		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Annual demand *(MWh)*		15037226	21675490	33469111	31072513	31583517
Import/export *(MWh)*		2282454	1244652	-5789638	-4331678	0
Capacity *(MW)*	**Wind**	2373	704	919	3308	5502
	PV	1082	1330	1420	797	1239
	Natural Gas	5134	76	3347	3924	5305
	Coal	0	0	1360	1617	576
	Biomass	0	0	1012	1203	429
	Nuclear	0	0	0	0	0

Table II.4. Input data FLEX 2030

FLEX 2030		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Capacity *(MW)*	**Wind**	2833	1126	906	2824	4706
	PV	10911	8755	6367	4850	7173

Table II.5. Input data FLEX 2050

FLEX 2050		**Noord**	**Oost**	**Zuid**	**Zuid-West**	**Noord-West**
Capacity *(MW)*	**Wind**	6944	3417	1783	4332	7252
	PV	48001	36892	25234	20225	29700

Appendix III input data technologies

This appendix shows the input data for the different levels of the DOE for both the Netherlands and the NWEU. The method of obtaining these levels is described in chapter 5, and the resulting absolute levels are presented here. Tables III.1 to III.4 show the input data regarding hydrogen, batteries, heat pumps and EVs for the NWEU. Tables III.5 to III.8 show the input data regarding hydrogen, batteries, heat pumps and EVs for the Netherlands.

Table III.1. DOE levels NWEU hydrogen

Hydrogen (MW)	Low	Med	High
NL	2795,566234	5591,132	11182,26
BE	1871,278111	3742,556	7485,112
FR	5049,320787	10098,64	20197,28
UK	5261,608118	10523,22	21046,43
DE	10022,22675	20044,45	40088,91

Table III.2. DOE levels NWEU battery

Battery (MW)	Low	Med	High
NL	5241,68669	10483,37	20966,75
BE	3508,646459	7017,293	14034,59
FR	9467,476475	18934,95	37869,91
UK	9865,51522	19731,03	39462,06
DE	18791,67516	37583,35	75166,7

Table III.3. DOE levels NWEU Heat pumps

Heat pumps				
NL	# Heat Pumps	MW	MWh	Demand (MWh)
Low	238333	8341,655	11916,65	2203303,5
Med	913609,8333	31976,34	45680,49	8445996,75
High	1588886,667	55611,03	79444,33	14688690
BE	# Heat Pumps	MW	MWh	Demand
Low	307028	10745,98	15351,4	818170,5
Med	1176940,667	41192,92	58847,03	3136320,25
High	2046853,333	71639,87	102342,7	5454470
FR	# Heat Pumps	MW	MWh	Demand
Low	4888000	171080	244400	3509061,75
Med	18737333,33	655806,7	936866,7	13451403,4
High	32586666,67	1140533	1629333	23393745
UK	# Heat Pumps	MW	MWh	Demand
Low	1170152	40955,32	58507,6	1140903
Med	4485582,667	156995,4	224279,1	4373461,5
High	7801013,333	273035,5	390050,7	7606020
DE	# Heat Pumps	MW	MWh	Demand
Low	2924000	102340	146200	8813214
Med	11208666,67	392303,3	560433,3	33783987
High	19493333,33	682266,7	974666,7	58754760

Table III.4. DOE levels NWEU EVs

Electric vehicles					EV chargers		
NL	#EVs	MW	MWh	Demand (MWh)	NL	# chargers	MW
Low	1382975,76	69148,79	82978,5455	6749671,927		1382976	22819,1
Med	4941181,51	247059,1	296470,89	24115646,22		4941182	81529,4948
High	8499387,25	424969,4	509963,235	41481620,51		8499387	140239,89
BE	#EVs	MW	MWh	Demand	BE	# chargers	MW
Low	900838,696	45041,93	54050,3217	4703228,78		900838,7	14863,8385
Med	3411676,51	170583,8	204700,591	17812173,52		3411677	56292,6624
High	5922514,33	296125,7	355350,86	30921118,26		5922514	97721,4864
FR	#EVs	MW	MWh	Demand	FR	# chargers	MW
Low	6146816	307340,8	368808,96	30577118,61		6146816	101422,464
Med	21458599,1	1072930	1287515,95	106745041,8		21458599	354066,886
High	36770382,3	1838519	2206222,94	182912965,1		36770382	606711,308
UK	#EVs	MW	MWh	Demand	UK	# chargers	MW
Low	8309933,84	415496,7	498596,03	39076834,01		8309934	137113,908
Med	20800754,9	1040038	1248045,3	97813973,37		20800755	343212,456
High	33291576	1664579	1997494,56	156551112,7		33291576	549311,004
DE	#EVs	MW	MWh	Demand	DE	# chargers	MW
Low	5647594,94	282379,7	338855,696	17364051,56		5647595	93185,3165
Med	30038706,7	1501935	1802322,4	92356774,57		30038707	495638,661
High	54429818,5	2721491	3265789,11	167349497,6		54429819	898092,006

Table III.5. DOE levels Netherlands Hydrogen

Hydrogen (MW)	Low	Med	High
Noord	824,06	1647,825	3295,651
Zuid	420,3823	840,6142	1681,228
Oost	604,5608	1208,905	2417,811
Nwest	560,6294	1121,058	2242,117
Zwest	386,3676	772,5969	1545,194

Table III.6. DOE levels Netherlands Battery

Battery (MW)	Low	Med	High
Noord	1544,67	3089,636	6179,271
Zuid	787,9912	1576,133	3152,266
Oost	1133,227	2266,67	4533,341
Nwest	1050,879	2101,959	4203,918
Zwest	724,2319	1448,602	2897,204

Table III.7. DOE levels Netherlands Heat Pumps

Heat Pumps				
Noord	# heat pumps	MW	MWh	Demand (MWh)
Low	23760,29	831,6103	1188,015	258094,95
Med	91081,13	3187,84	4554,056	989363,975
High	158402	5544,069	7920,098	1720633
Zuid	# heat pumps	MW	MWh	Demand (MWh)
Low	50460,39	1766,114	2523,02	551809,5
Med	193431,5	6770,102	9671,575	2115269,75
High	336402,6	11774,09	16820,13	3678730
Oost	# heat pumps	MW	MWh	Demand (MWh)
Low	45750,75	1601,276	2287,538	357203,025
Med	175377,9	6138,226	8768,895	1369278,263
High	305005	10675,18	15250,25	2381353,5
Nwest	# heat pumps	MW	MWh	Demand (MWh)
Low	62317,87	2181,125	3115,894	520400,025
Med	238885,2	8360,981	11944,26	1994866,763
High	415452,5	14540,84	20772,62	3469333,5
Zwest	# heat pumps	MW	MWh	Demand (MWh)
Low	56043,69	1961,529	2802,185	515795,85
Med	214834,1	7519,195	10741,71	1977217,425
High	373624,6	13076,86	18681,23	3438639

Table III.8. DOE levels Netherlands EVs

EV					EV charg		
Noord	**#EVs**	**MW**	**MWh**	**Demand (MWh)**	**Noord**	**#**	**MW**
Low	137873,9472	6893,697361	8272,436834	690728,835		137873,9	2274,92
Med	481668,8226	24083,44113	28900,12936	2413092,19		481668,8	7947,536
High	825463,698	41273,1849	49527,82188	4135455,54		825463,7	13620,15
Zuid	**#EVs**	**MW**	**MWh**	**Demand**	**Zuid**	**#**	**MW**
Low	292806,689	14640,33445	17568,40134	1466919,8		292806,7	4831,31
Med	1022933,31	51146,66549	61375,99858	5124750,16		1022933	16878,4
High	1753059,93	87652,99652	105183,5958	8782580,53		1753060	28925,49
Oost	**#EVs**	**MW**	**MWh**	**Demand**	**Oost**	**#**	**MW**
Low	265478,0658	13273,90329	15928,68395	1330007,29		265478,1	4380,388
Med	927459,5379	46372,97689	55647,57227	4646440,17		927459,5	15303,08
High	1589441,01	79472,0505	95366,4606	7962873,04		1589441	26225,78
Nwest	**#EVs**	**MW**	**MWh**	**Demand**	**Nwest**	**#**	**MW**
Low	361612,1335	18080,60668	21696,72801	1811625,28		361612,1	5966,6
Med	1263308,218	63165,41091	75798,49309	6328994,21		1263308	20844,59
High	2165004,303	108250,2151	129900,2582	10846363,2		2165004	35722,57
Zwest	**#EVs**	**MW**	**MWh**	**Demand**	**Zwest**	**#**	**MW**
Low	325204,922	16260,2461	19512,29532	1629230,33		325204,9	5365,881
Med	1136117,99	56805,89952	68167,07943	5691789,29		1136118	18745,95
High	1947031,059	97351,55295	116821,8635	9754348,25		1947031	32126,01

Appendix IV Results design of experiments

This appendix presents the results of the 9 runs with the FlexTool for the DOE. Table IV.1 shows the results for the North West of Europe. And table IV.2 shows the results for the Netherlands. The main effect plots on the loss of load and curtailment that are shown in chapter 6 are based on the data presented in these tables.

Table IV.1. Results DOE NWEU

# Run	Operational cost (million €)	Loss of load (% of annual demand)	Curtailment (% of VRE gen)
1	98097	0	0
2	88240	0,52	11,2
3	61934	0,19	18,11
4	80132	0,33	8,5
5	81446	0,075	3,1
6	83754	0,042	1,4
7	92985	0,12	1,6
8	64595	0,19	7,8
9	81973	0,16	0,34

Table IV.2. Results DOE Netherlands

#	Operational cost (million €)	Loss of load (% of annual demand)	Curtailment (% of VRE gen)
1	4273	0	0
2	3520	2,8	25,5
3	3124	0	18,7
4	3346	0,2	9,9
5	3109	0,5	0
6	3593	0	1,9
7	3820	0,7	1,8
8	3078	1,5	3,8
9	3549	2,5	0

Appendix V input data 30 and 17 region model Netherlands

In this appendix the input data from the test runs described in chapter 4 are resulted. Table V.1. shows the input data regarding the annual demand and generation capacity for all 30 energy regions retrieved from the Klimaatmonitor (2020), Tennet (2018), WindStats (2020) and CBS (2018). Table V.2. shows the combined energy regions and their abbreviations as used in the FlexTool. Table V.3. shows t the annual demand and generation capacities of the combined 17 regions of the Netherlands. Table V.4 to table V.7 conclude this appendix with the input data regarding battery storage, heat pumps, EVs and hydrogen storage used in the combined region test run.

Table V.1. Input data 30 energy regions Netherlands test run

Original energy regions:	Annual Demand (TWh)	Gas (MW)	Coal (MW)	Nuclear (MW)	Other (MW)	Biomass (MW)	Wind (MW)	PV (MW)
Goeree-Overlakkee	0,2	0	0	0	0	0	99	14
Achterhoek	1,5	0	0	0	0	0	30	93
Alblasserwaard	0,4	0	0	0	0	0	9	13
Amersfoort	1,1	0	0	0	0	0	0	36
Arnhem/Nijmegen	3,4	0	0	0	0	0	18	91
Cleantech regio	1,7	0	0	0	0	0	6	50
Drechtsteden	1,3	0	0	0	0	0	9	19
Drenthe	2,7	126	0	0	0	0	31	162
Flevoland	1,9	989	0	0	0	0	1144	127
Foodvalley	1,6	0	0	0	0	0	6	38
Friesland	2,9	144	0	0	0	0	195	170
Groningen	5,7	3770	0	0	0	0	469	184
Hart van Brabant	2,4	0	0	0	0	0	42	64
Hoeksche Waard	0,3	0	0	0	0	0	56	11
Holland Rijnland	2,1	83	25	0	0	0	30	59
Metropoolregio Eindhoven	5,5	0	0	0	0	0	24	134
Midden-Holland	1,1	0	0	0	0	0	13	25
Noord- en Midden Limburg	3,6	1570	249	0	510	0	21	152
Noord Holland Noord	3,0	0	0	0	0	0	333	133
Noord Holland Zuid	14,0	2609	650	0	182	0	102	193
Noord Veluwe	0,8	0	0	0	0	0	0	32
Noord-Oost Brabant	3,4	32	0	0	0	0	2	120
Rivierenland	1,5	0	0	0	0	0	79	58
Rotterdam-Den Haag	15,0	1685	1799	0	0	0	236	13
Twente	2,9	60	0	0	0	0	0	118
U10/U16	3,8	577	0	0	0	0	34	102
West Overijssel	2,9	0	0	0	0	0	67	154
West-Brabant	5,2	807	1285	0	0	0	180	96
Zeeland	3,0	1320	0	492	0	0	516	89
Zuid-Limburg	5,1	225	0	0	0	0	1	111

Table V.2. Abbreviations combined regions

Combined energy regions:	Abbreviation
Goeree-Overlakkee + Hoeksche Waard	Ge_Ho
Alblassenwaard + Midden-Holland	Al_M-Ho
Noord-Veluwe + Cleantech regio	N-Ve-Cl
Rivierenland + Foodvalley	Ri_Vo
Achterhoek + Twente	Ac_Tw
Drechtsteden + West-Brabant	Dr_W-Br
Amersfoort + Flevoland	Am_Fl
Zeeland	Ze
Hart van Brabant + Noord -oost Brabant	H-Br_NO-Br
Drenthe + West Overijssel	Dr_W-Ov
Noord midden limburg + zuid limburg	NMZ-Li
Holland Rijnland + U10/U16	Ho_U
Groningen + Friesland	Gr_Vr
Noord Holland noord + zuid	N-Ho
Arnhem/nijmegen	Ar_Ni
Metropoolregio Eindhoven	M-Ei
Rotterdam - Den Haag	Ro-DH

Table V.3. Input data 17 region rest run Netherlands

	Original data	Ge_Ho	Al_M-Ho	N-Ve_Cl	Ri_Fo	Ac_Tw	Dr_W-Br	Am_Fl	H-Br_NO-Br	Ze	Dr_W-Ov	Ho_U	NMZ-Li	Gr_Fr	N-Ho	Ar_Ni	M-Ei	Ro_DH
Annual Demand (TWh)		0,5	1,5	2,5	3,1	4,4	6,4	3,0	5,9	3,0	5,6	5,9	8,7	8,6	17,1	3,4	5,5	15,0
Current Conventional power plants (MW)	Gas	0	0	0	0	60	807	989	32	1320	126	660	1795	3914	2609	0	0	1685
	Coal	0	0	0	0	0	1285	0	0	0	0	25	249	0	650	0	0	1799
	Nuclear	0	0	0	0	0	0	0	0	492	0	0	0	0	0	0	0	0
	other	0	0	0	0	0	0	0	0	0	0	0	510	0	182	0	0	0
	Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Current Renewable power plants (MW)	Wind	155,91	21,68	6,2	85,48	29,8	189,66	1144,05	43,9	516,53	98,35	64,08	21,3	664,01	434,415	18,08	23,8	236,4
	Solar	25	38	82	96	211	115	163	184	89	316	161	263	354	326	91	134	150

Heat pumps

Table V.4. Input data heat pumps 17 region rest run Netherlands

Ge_Ho	#	MW	MWh	Demand (MWh)
Low	1878,2281	65,73798352	93,91141	720125,329
Med	7199,874385	251,9956035	359,9937	738507,992
High	12521,52067	438,2532234	626,076	756890,655
Al_M-Ho	#	MW	MWh	Demand
Low	4346,056656	152,111983	217,3028	1967196,98
Med	16659,88385	583,0959347	832,9942	2028254,54
High	28973,71104	1014,079886	1448,686	2089312,1
N-Ve_Cl	#	#MW	#MWh	Demand
Low	7242,164278	253,4757497	362,1082	3376448,57
Med	27761,62973	971,6570406	1388,081	3476213,39
High	48281,09519	1689,838332	2414,055	3575978,22
Ri_Fo	#	#MW	#MWh	Demand
Low	8272,476463	289,5366762	413,6238	4157507,59
Med	31711,15977	1109,890592	1585,558	4271886,83
High	55149,84309	1930,244508	2757,492	4386266,07
Ac_Tw	#	#MW	#MWh	Demand
Low	12792,02529	447,720885	639,6013	5899966,05
Med	49036,09693	1716,263393	2451,805	6080622,57
High	85280,16857	2984,8059	4264,008	6261279,09
Dr_W-Br	#	#MW	#MWh	Demand
Low	13855,11449	484,9290072	692,7557	8603682,46
Med	53111,27222	1858,894528	2655,564	8861167,35
High	92367,42995	3232,860048	4618,371	9118652,24
Am_Fl	#	#MW	#MWh	Demand
Low	9892,072084	346,2225229	494,6036	4061966,52
Med	37919,60966	1327,186338	1895,98	4298140,44
High	65947,14723	2308,150153	3297,357	4534314,37
H-Br_NO-Br	#	#MW	#MWh	Demand
Low	14681,99688	513,8698907	734,0998	7857403,67
Med	56280,98803	1969,834581	2814,049	8035974,69
High	97879,97918	3425,799271	4893,999	8214545,72
Ze	#	#MW	#MWh	Demand
Low	5279,49882	184,7824587	263,9749	4079957,68
Med	20238,07881	708,3327584	1011,904	4264807,52
High	35196,6588	1231,883058	1759,833	4449657,35

Dr_W-Ov	#	#MW	#MWh	Demand	
Low	14049,65397	491,7378891	702,4827		7523312,79
Med	53857,0069	1884,995241	2692,85		7709388,41
High	93664,35982	3278,252594	4683,218		7895464,03
Ho_U	#	#MW	#MWh	Demand	
Low	20909,53453	731,8337084	1045,477		7914245,87
Med	80153,21568	2805,362549	4007,661		8100421,17
High	139396,8968	4878,891389	6969,845		8286596,48
NMZ-Li	#	#MW	#MWh	Demand	
Low	15384,20804	538,4472815	769,2104		11682373,6
Med	58972,7975	2064,047912	2948,64		12115625,1
High	102561,387	3589,648543	5128,069		12548876,5
Gr_Fr	#	#MW	#MWh	Demand	
Low	16976,54002	594,1789006	848,827		11569416,6
Med	65076,73674	2277,685786	3253,837		11896616
High	113176,9335	3961,192671	5658,847		12223815,4
N-Ho	#	#MW	#MWh	Demand	
Low	39329,10429	1376,51865	1966,455		22797408,7
Med	150761,5664	5276,654826	7538,078		23296567,8
High	262194,0286	9176,791001	13109,7		23795726,9
Ar_Ni	#	#MW	#MWh	Demand	
Low	10178,18874	356,236606	508,9094		4547401,84
Med	39016,39019	1365,573656	1950,82		4663112,93
High	67854,59163	2374,910707	3392,73		4778824,02
M-Ei	#	#MW	#MWh	Demand	
Low	10657,39762	373,0089168	532,8699		7341272,78
Med	40853,35756	1429,867514	2042,668		7472958,05
High	71049,31749	2486,726112	3552,466		7604643,31
Ro_DH	#	#MW	#MWh	Demand	
Low	32608,73972	1141,30589	1630,437		20201258,8
Med	125000,1689	4375,005913	6250,008		21136091
High	217391,5982	7608,705936	10869,58		22070923,2

Table V.5. Input data batteries 17 region rest run Netherlands

Batteries	Low (MW)	Med (MW)	High (MW)
Ge_Ho	95,98060991	191,9795	383,9591
Al_M-Ho	113,2787868	226,5792	453,1584
N-Ve_Cl	146,7631406	293,5543	587,1086
Ri_Fo	180,151242	360,3369	720,6737

Ac_Tw	361,8125289	723,6941	1447,388
Dr_W-Br	246,6422079	493,3315	986,663
Am_Fl	360,853707	721,7763	1443,553
H-Br_NO-Br	209,1431187	418,3261	836,6523
Ze	298,7230507	597,5031	1195,006
Dr_W-Ov	709,9718474	1420,079	2840,158
Ho_U	213,002771	426,0462	852,0924
NMZ-Li	244,5543631	489,1554	978,3108
Gr_Fr	1133,04629	2266,309	4532,618
N-Ho	490,2950672	980,6837	1961,367
Ar_Ni	110,7667937	221,5547	443,1094
M-Ei	130,7645946	261,5541	523,1083
Ro_DH	195,2555278	390,5483	781,0966

Table V.6. Input data Hydrogen storage 17 region rest run Netherlands

Hydrogen storage	**Low (MW)**	**Med (MW)**	**High (MW)**
Ge_Ho	95,98060991	102,3903	204,7806
Al_M-Ho	113,2787868	120,8437	241,6873
N-Ve_Cl	78,2960773	156,5642	313,1283
Ri_Fo	96,10816114	192,1819	384,3639
Ac_Tw	193,0219101	385,9748	771,9496
Dr_W-Br	131,580159	263,1133	526,2265
Am_Fl	192,5103921	384,9519	769,9039
H-Br_NO-Br	111,5749208	223,1099	446,2199
Ze	159,3645583	318,6721	637,3442
Dr_W-Ov	378,7600239	757,3846	1514,769
Ho_U	113,6339912	227,2273	454,4547
NMZ-Li	130,4663231	260,886	521,772
Gr_Fr	604,4643056	1208,712	2417,425
N-Ho	261,5655424	523,0375	1046,075
Ar_Ni	59,09253102	118,1639	236,3279
M-Ei	69,76107736	139,4972	278,9944
Ro_DH	104,1660858	208,2949	416,5898

Table V.7. Input data EVs 17 region rest run Netherlands

EV					**EV charger**	
Ge_Ho	#	#MW	#MWh	Demand	#	#MW
Low	**10898,8**	**544,9401**	**653,9282**	**54601,45**	**10898,8**	**179,8302**
Med	38075,45	1903,773	2284,527	190752,6	38075,45	628,2449
High	65252,1	3262,605	3915,126	326903,7	65252,1	1076,66
Al_M-Ho	#	#MW	#MWh	Demand	#	#MW
Low	25218,88	1260,944	1513,133	126343	25218,88	416,1116
Med	88103,29	4405,164	5286,197	441384,9	88103,29	1453,704
High	150987,7	7549,384	9059,261	756426,8	150987,7	2491,297
N-Ve_Cl	#	#MW	#MWh	Demand	#	#MW

Low	42024,14	2101,207	2521,448	210535	42024,14	693,3983
Med	146813,2	7340,66	8808,792	735513,2	146813,2	2422,418
High	251602,3	12580,11	15096,14	1260491	251602,3	4151,437
Ri_Fo	#	#MW	#MWh	Demand	#	#MW
Low	48002,74	2400,137	2880,164	240486,9	48002,74	792,0452
Med	167699,7	8384,985	10061,98	840151,6	167699,7	2767,045
High	287396,6	14369,83	17243,8	1439816	287396,6	4742,045
Ac_Tw	#	#MW	#MWh	Demand	#	#MW
Low	74228,34	3711,417	4453,701	371873,4	74228,34	1224,768
Med	259320	12966	15559,2	1299156	259320	4278,78
High	444411,7	22220,58	26664,7	2226439	444411,7	7332,793
Dr_W-Br	#	#MW	#MWh	Demand		
Low	80397,14	4019,857	4823,828	436251,3	80397,14	1326,553
Med	262404,4	13120,22	15744,26	1423860	262404,4	4329,673
High	444411,7	22220,58	26664,7	2411469	444411,7	7332,793
Am_Fl	#	#MW	#MWh	Demand		
Low	57400,77	2870,039	3444,046	287569,7	57400,77	947,1127
Med	200532,1	10026,61	12031,93	1004637	200532,1	3308,78
High	343663,5	17183,18	20619,81	1721705	343663,5	5670,448
H-Br_NO-Br	#	#MW	#MWh	Demand		
Low	85195,29	4259,765	5111,717	426816,3	85195,29	1405,722
Med	297633,5	14881,68	17858,01	1491102	297633,5	4910,953
High	510071,8	25503,59	30604,31	2555387	510071,8	8416,184
Ze	#	#MW	#MWh	Demand		
Low	30635,37	1531,769	1838,122	153478,8	30635,37	505,4836
Med	107026	5351,302	6421,562	536185,2	107026	1765,93
High	183416,7	9170,835	11005	918891,5	183416,7	3026,375
Dr_W-Ov	#	#MW	#MWh	Demand		
Low	81525,99	4076,3	4891,56	408433,6	81525,99	1345,179
Med	284814,7	14240,73	17088,88	1426881	284814,7	4699,442
High	488103,3	24405,17	29286,2	2445328	488103,3	8053,705
Ho_U	#	#MW	#MWh	Demand		
Low	121331,9	6066,593	7279,911	607855,3	121331,9	2001,976
Med	423878,2	21193,91	25432,69	2123569	423878,2	6993,99

High	726424,6	36321,23	43585,47	3639284	726424,6	11986,01
NMZ-Li	#	#MW	#MWh	Demand		
Low	89270,02	4463,501	5356,201	447230,1	89270,02	1472,955
Med	311868,8	15593,44	18712,13	1562418	311868,8	5145,834
High	534467,5	26723,37	32068,05	2677606	534467,5	8818,714
Gr_Fr	#	#MW	#MWh	Demand		
Low	98509,85	4925,492	5910,591	493520,3	98509,85	1625,412
Med	344148,5	17207,43	20648,91	1724135	344148,5	5678,451
High	589787,2	29489,36	35387,23	2954750	589787,2	9731,489
N-Ho	#	#MW	#MWh	Demand		
Low	228215,2	11410,76	13692,91	1143326	228215,2	3765,55
Med	797279,8	39863,99	47836,79	3994258	797279,8	13155,12
High	1366344	68317,22	81980,67	6845191	1366344	22544,68
Ar_Ni	#	#MW	#MWh	Demand		
Low	59061,02	2953,051	3543,661	295887,3	59061,02	974,5069
Med	206332,3	10316,62	12379,94	1033695	206332,3	3404,483
High	353603,6	17680,18	21216,21	1771504	353603,6	5834,459
M-Ei	#	#MW	#MWh	Demand		
Low	61841,73	3092,087	3710,504	309818,3	61841,73	1020,389
Med	216046,8	10802,34	12962,81	1082364	216046,8	3564,773
High	370251,9	18512,6	22215,12	1854909	370251,9	6109,157
Ro_DH	#	#MW	#MWh	Demand		
Low	189218,9	9460,944	11353,13	947959,6	189218,9	3122,112
Med	661044,6	33052,23	39662,67	3311739	661044,6	10907,24
High	1132870	56643,51	67972,21	5675518	1132870	18692,36