Green hydrogen gas in the Netherlands

A system comparison between an electricity-based and a gas-based energy system

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SUMMARY

To reduce CO_2 emissions in the Netherlands, the government has decided to phase out the use of natural gas. Currently, natural gas is widely used in the country for different purposes, i.a. for electricity generation, heating of buildings and in industry. To enable a successful phase-out of natural gas, renewable alternatives must be found. One alternative energy carrier can be green hydrogen. Green hydrogen can be produced by electrolysis using electricity from renewable and non CO_2 emitting sources. The produced hydrogen can be used for different purposes. Hydrogen is suitable for long term and large volume energy storage. Additionally, hydrogen can be transported through gas pipelines, and it can be used as a fuel for heating and in industry. An other alternative for natural gas could be increased electrification of the energy system. For example, heating of buildings could be done using electric heat pumps, which are very efficient. With different options as alternative for natural gas, it is not obvious what would be the best energy system to aim for.

In this research, different scenarios are compared to find out what the technical possibilities are for the Netherlands to use hydrogen for energy storage, heat delivery and for industrial gas consumption. Two extreme systems are compared based on i.a. efficiency and storage requirements. In the electricity based scenario, heat demand is fulfilled using electric heat pumps. Only electricity surpluses are converted into hydrogen so that it can be stored. Using electric heat pumps to fulfil the heat demand leads to an increase in the overall electricity demand. Therefore, this system requires extension of the electricity grid. The other extreme system that was compared is the gas based scenario. In this scenario, all generated electricity is converted into hydrogen, to allow for easy transport and energy storage. Because energy is lost in the conversion from electricity to hydrogen, this system suffers from larger conversion losses. Heat demand is fulfilled using boilers running on hydrogen. These are low in efficiency compared to electric heat pumps. All electricity demand in this system is fulfilled using gas turbines running on hydrogen. Also, a third system was compared. In this scenario only electricity surpluses are converted into hydrogen, decreasing the conversion losses of the system. To fulfil the heat demand, boilers running on hydrogen are used. In this way, the need for electricity grid extension is avoided. This system is referred to as the combined scenario.

Using the Power Nodes method, a model is built in Excel that allows for comparison of the different scenarios. Required capacities for energy generation, energy storage and energy conversion technologies are compared to find out what scenario would be the most feasible. It was found that the electricity based scenario is the most efficient of the three systems. In this system all energy demand can be fulfilled using the lowest amount of installed wind turbine and solar PV capacity. Also, this system needs the lowest hydrogen storage capacity. The least efficient system is the gas based scenario. Here the highest capacities of installed wind turbines and solar PV are required. Also for the gas based scenario the most hydrogen storage capacity is necessary. For the combined scenario the required capacities for wind turbine and solar PV are in between the two extreme scenarios. For hydrogen storage, the required capacity is comparable to that of the gas based scenario.

According to this research, for all three scenarios it would be possible to create a balanced energy system in the Netherlands. To decide which of the scenarios seems most feasible, additional economic and environmental analysis are necessary. An economic analysis could point out which of the systems would be most affordable. Environmental analysis is needed to understand e.g. the impact of indirect emissions and the use of raw materials.

Chapter 1

INTRODUCTION

1.1 Background

To reduce greenhouse gas emissions, the Dutch government wants to phase out the use of natural gas [1]. The goal was set to stop using gas from the Groningen gas field by 2030, and to phase out the use of natural gas completely by 2050 [2]. To achieve this, alternatives must be found for the functions previously fulfilled by natural gas. Furthermore, to reduce greenhouse gas emissions, these alternatives must be renewable and low in greenhouse gas emissions.

Natural gas is used as an energy source and as an energy carrier. It can be used as a fuel for heating, cooking and in the transport sector, as a raw material in industry, and to generate electricity. If natural gas is to be phased out, new energy sources and energy carriers must be found, to replace natural gas. Renewable energy sources are often based on weather patterns, for example wind energy or solar energy. This leads to intermittent energy supply, that does not match the energy demand. This requires the possibility to store energy. Also, these renewable energy sources usually generate electricity. Electricity is not always an appropriate carrier to deliver the demanded energy. In some cases, conversion of electricity into another energy carrier, like gas, is more suitable for the intended purpose. Also, energy in the form of gas is easier to transport than electricity.

Hydrogen is an energy carrier that can be produced using electricity and water, in a process called electrolysis. In this way, hydrogen can be produced without the emission of greenhouse gases. Converting electricity into hydrogen allows for energy storage, transport through gas pipelines, and use for industrial purposes. Using hydrogen in this way has several advantages, but also some disadvantages. Hydrogen is suitable for storage in large volumes for long periods of time. Because of this, it can be used for seasonal storage. Energy surpluses during summer can be stored so that enough energy is available to fulfil increased energy demand during winter. To facilitate storage, empty salt caverns can be used. Subsurface salt layers that are required for creating such salt caverns exist in the Netherlands [3], offering a suitable solution to create large volume storage. Also, after some simple adjustments of gas pipelines, hydrogen gas can be transported via the existing gas network in the Netherlands [4]. This is an easier and cheaper way to transport energy compared to transport via electricity grids. Despite these advantages, a major disadvantage of using hydrogen in this way is the large energy loss associated with the energy conversion [5]. Currently, efficiencies of electrolysis plants are typically about 75% [6]. For storage, another 10% is lost due to necessary compression [6, 7]. For generating electricity based on hydrogen, combined cycle gas turbines (CCGTs) can be used, that run at about 60% [6]. This leads to a round trip energy loss of almost 60%. At this moment, not many suitable alternatives exist for seasonal energy storage. Hydro storage has limited potential due geographical requirements and low volumetric energy density, and battery storage is more suitable for day-night storage and less for seasonal storage [8]. Because of this lack of alternatives, hydrogen is still an interesting option, despite the low efficiency.

Also, the fact that hydrogen can be used for other purposes makes hydrogen more interesting as an energy carrier. Existing literature already covers many aspects of research in the field of hydrogen applications. For example, hydrogen cars outperform electric vehicles in terms of driving range and recharging time [9]. For heating purposes boilers, combined heat and power (CHP) systems or gas driven heat pumps can run on hydrogen [10, 11]. Also existing gas turbines can be modified so that they can run on hydrogen gas [12]. Staffel et al. give a broad overview of applications of hydrogen gas and fuel cells for energy storage, distribution and supply [13]. CE Delft has developed different scenarios to better understand possible future developments, where technical and financial aspects are weighed against political and social aspects of the different scenarios [14]. The study shows that a climate-neutral energy system can be realized in different ways, and that hydrogen will have an essential role in all scenarios. An extensive study by TenneT and Gasunie used these scenarios for the outlining of a plausible future energy system for Germany and the Netherlands [15]. This study explores how to match future demand and supply, and looks into possible interaction between gas and electricity infrastructure. An analysis of economic factors affecting the outlook for a hydrogen market in the Netherlands, was carried out by Mulder et al. [16]. They discuss factors that determine alternative options to make hydrogen, the quantitative outlook of hydrogen markets, and the need for regulatory measures to promote the hydrogen market. In a study by KIVI, an energy plan is designed, in which solar and wind energy sources can supply the Netherlands with enough energy in combination with battery and hydrogen energy storage [17].

1.2 Research aim

Despite all the research that has been executed, it is not obvious what would be the best way to implement hydrogen in energy systems. Converting all generated electricity into hydrogen has the advantage of relatively easy transport and storage, but the low round trip efficiency may be so disadvantageous that it is simply not feasible to realize such a system. Higher production capacities would be necessary, which would also increase spatial requirements. Additionally, it is not known whether the storage capacity in the Netherlands would be sufficient to substantiate such a system. If it would be decided that hydrogen is not the way to go, electrification of the energy system seems to be a likely alternative. However, this would require expensive extension of the electricity grid, and leaves the storage problem unsolved. To the author's knowledge, an explicit comparison has never been made for different energy systems that are completely based on renewable and green energy sources with hydrogen fulfilling different roles. If in the future, completely sustainable and renewable energy systems are to be designed, it is important to understand what kind of system to aim for. By making an explicit comparison on the role of hydrogen within a sustainable energy system, it can be learned what would be the best way to implement hydrogen.

This research will look at the case of the Netherlands. The Dutch energy demand is considered and for different scenarios, the required capacities of renewable energy sources, energy conversion technologies and hydrogen storage are compared.

1.3 Research questions

To be able to achieve the aim of this research, and to execute the research in a structured manner, research questions were formulated. The main research question that should be answered in the end of this research is formulated as follows:

"How do renewable energy systems with hydrogen fulfilling different roles, compare to each other based on efficiency and system reliability?"

With this question, the focus will be on comparing a system based on electrification of the energy demand, to a system where green hydrogen gas is used in gas form, as a substitute of natural gas in the current Dutch energy system. To find the answer to this question, the research will be executed in different steps. The following sub-questions will enable us to gather the information necessary to answer the main question.

a. What could the future hourly demand for hydrogen and electricity look like?
    1. In an electricity based system?
    2. In a partly hydrogen powered system?
b. What are the renewable electricity and green hydrogen production potential for the Netherlands?
c. What would be the renewable electricity and green hydrogen production on an hourly basis for the Netherlands in different scenarios?
d. What is the mismatch between hourly energy demand and supply from renewable energy sources in different scenarios?
e. What hydrogen storage capacity is needed to match hourly electricity and gas demand and supply?
f. Is the needed hydrogen storage capacity available in the Netherlands?

Chapter 2

METHODS

2.1 System boundaries

To specify the scope of the research, system boundaries are defined. These boundaries indicate which elements of the Dutch energy system are included in the research, and which elements are excluded. Figure 2.1 shows a schematic overview of the system boundaries. This research is focused on using hydrogen as an alternative for natural gas. From that perspective, we focus on the functions that natural gas fulfils in the Dutch energy system. The main functions of natural gas, that are included in this research are the balancing of the electricity grid, the domestic use for heating and cooking, and the gas demand from industry for high temperature heating and as raw material. In the Netherlands also a small fraction of natural gas is used in the mobility sector [18]. However, for this research the mobility sector has been excluded, since including this sector would bring a lot of additional complexity to the system, and the actual share of natural gas used in this sector is very small.

The aim of this research is investigating the possibilities to replace natural gas completely by renewable energy sources. The renewable energy sources that were included are offshore wind, onshore wind, and solar energy. These energy sources were chosen because wind turbines and solar photovoltaics are both developed technologies that are already widely used. Additionally, these technologies offer large potential capacity in the Netherlands [14][19].

This research is based on hourly data. The energy demand, supply, storage and production, need to be matched on an hourly basis to give an indication of how well the overall energy system is functioning. Hourly demand and supply data are available online, and working with hourly data allows for a more detailed understanding, than looking at demand and supply data on a yearly basis. Also, the number of data points necessary to simulate a year is still workable in Microsoft Excel.

In this research, the focus is on the technical capacity of the energy system. However, the distribution of energy via electricity grids and gas grids was not taken into account. Throughout the research it was assumed that energy in any form can always be transported from one location to another location instantly and with unlimited capacity. Also the economic, environmental, and social aspects of creating an energy system like this, are outside the scope of this research. Although the ultimate goal would be to create an affordable energy system, with the lowest possible environmental impact that is socially acceptable, this scope is too wide for one research project. By focusing on the technical aspect of matching supply and demand, the goal is to find out what possibilities are in the Netherlands for building a reliable energy system. Shedding more light on the economic, environmental and social aspects of realising such a system was left for future research.

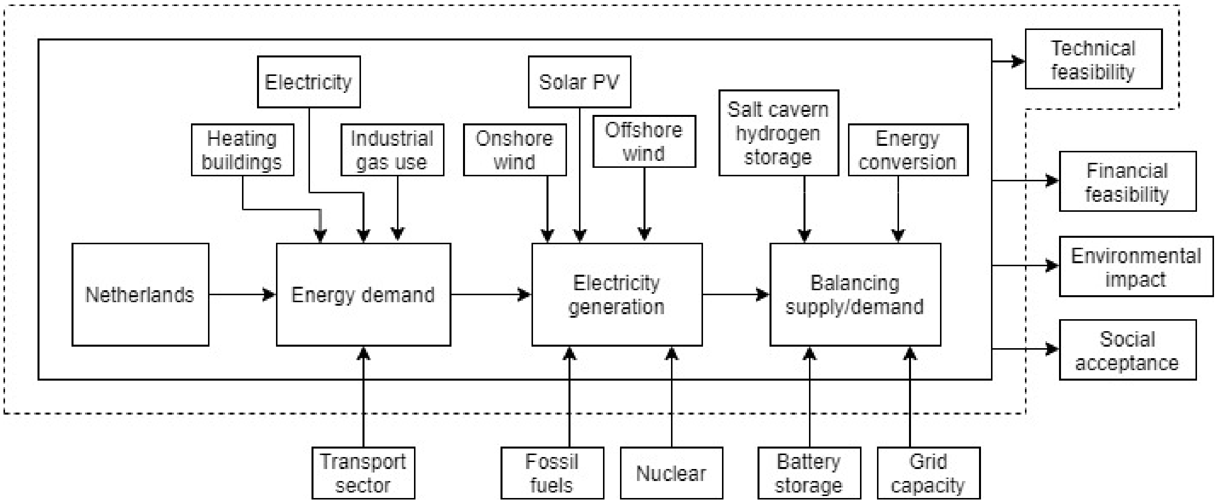


Figure 2.1: Schematic overview of the system boundaries. Items that are enclosed in the dashed line were included in the research. Items outside the dashed line are outside the scope of this research

2.2 Used methods

2.2.1 Literature research

To find answers to the indicated research questions, different methods are used. To start, a literature research is done. Since an abundant amount of research has already been done on the application of hydrogen in energy systems, a lot of knowledge is readily available. This existing knowledge can be collected and used. This is information about technologies, energy demand patterns, weather patterns and spatial requirements. Making use of existing knowledge is much more time efficient than investigating the same topics again. This speeds up the research process and leaves more time to acquire new knowledge.

2.2.2 Scenario studies

To be able to compare different energy systems, scenario studies are executed. By constructing scenarios, different developments in the Dutch energy system can be compared to each other. This gives insights in consequences of aiming for a specific type of energy system. The results of comparing the scenarios must give the information that is necessary to answer the main research question.

2.2.3 Power Nodes

To execute scenario studies, a lot of different methods are available. To decide what method would be most suitable to provide answers to the research questions, strengths and weaknesses of different models and methods were explored and compared. The following requirements for the model were determined. For input data, the model must be able to handle hourly data for electricity demand and gas demand, and weather patterns to generate renewable electricity. Also, there must be the possibility to include a hydrogen storage unit in the system. As output, the model must give some indication of national grid balance, like a load duration curve, net load signal, loss of load probability, or expected unserved energy. Additionally it would be an advantage if the model could give, or could be extended to give some indication of system cost and greenhouse gas emissions. Based on these criteria information was gathered on different models. Some existing models are already fully developed. The advantage of using model that is already fully developed, is that it is ready to use. After learning how to work with the model, one can start building scenarios right away, which is very time efficient. A drawback of using such a ready to use model, is that it can become a black box. This means that you put data in and you get data out, but it is not always understood what is happening inside the model. Also, the model was originally developed for a different purpose. Because of that, the model might not be the most efficient tool to answer the research questions specific for this research.

Considering these aspects, Power Nodes was chosen as the modeling method to be used [20]. This modeling method works based on hourly data. Power Nodes generates a so-called net load signal that represents energy shortages and surpluses per hour, to indicate the balance on the energy grid. The method is easy to work with, and a basic model in Microsoft Excel exists. This basic model can be used as a starting point and it can be adapted to the requirements of the research. Additionally, it is possible to add environmental and economic information to the model. This offers opportunities for future extension of the research.

2.2.4 Validation and verification

Before the outputs of a self-built model can be trusted as being reliable, the correctness and reliability of the model need to be confirmed. This is also called validation and verification. Different validation and verification techniques are used, based on methods described by Sargent [21] and methods described by Pierie et al. [22]. Validation is done by asking some critical questions about the application and usefulness of the model [22]. For verification, the methods that are considered useful and applicable to verify the Power Nodes method are the extreme condition test, data relationship correctness, event validity, and face validity [21].

2.2.5 Sensitivity analysis

Additionally, a sensitivity analysis is executed. A sensitivity analysis measures the impact of single input variables on the model outputs. This is important to become aware of input variables that are disproportionately represented in the model output.

2.2.6 Qualitative comparison

To be able to compare the results of different scenarios, a qualitative comparison is executed. Per topic, the different scenarios are compared, and labeled. The scenario with lowest capacity requirements is set to 0% and the scenario with the highest capacity requirements is set to 100%. For the scenario in between, the required capacity is scaled and labeled according to figure 2.2. In this way, an overview can be created of the overall performance of each scenario.

Least required capacity 0-20%	(green)
20-40%	(yellow)
40-60%	(light orange)
60-80%	(orange)
Most required capacity 80-100%	(red)

Figure 2.2: Scaling method for the qualitative comparison.

Chapter 3

MODEL

3.1 Power Nodes method

As described in subsection 2.2.3, the Power Nodes method, developed by Pierie et al. [20] was used to build the model used for this research. For this research, the model was built in Microsoft Excel. In this section, the Power Nodes method will be explained. First, the overall construction of a model will be described. Afterwards, the model outputs are explained and how these can be interpreted.

3.1.1 Explaining the conceptual model

Figure 3.1 shows an example of what a conceptual model according to the Power Nodes method looks like. This conceptual model shows the structure of the model. Every horizontal blue bar represents a flow of one type of energy. In this research, energy is used in the form of electricity, hydrogen, natural gas and heat.

Within every horizontal blue bar one finds the colored, circular shapes, also called nodes. The numbering was added for further explanation in section 3.2. Every node represents a sub-module of the model, that is one link in the complete energy system. A node is a small model by itself. In Excel, every node is built in a separate sheet. Within such a node, technology characteristics are specified. Based on these characteristics and node-inputs, hourly data are generated for one year. The colors indicate the type of the node. Demand nodes represent the demand for one type of energy, in this example electricity, heat or gas. For these nodes the color depends on the type of energy that is demanded. Production nodes (green) represent technologies that are used to generate electricity. Conversion nodes (purple) convert one type of energy to another type of energy. For example, an electrolyzer can convert incoming electricity to hydrogen. Storage nodes (black) can store energy. At moments of overproduction of energy, the energy can be stored in the storage unit. At moments of energy shortages, the storage unit can provide additional energy. The grid nodes (yellow) represent the electricity and gas grids that could connect the described system to any larger energy system. In case of energy surpluses, excess energy produced in the described system can be added to the grid. In case of energy shortages, electricity or gas can be withdrawn from the grid. However, for this research the goal is to create a system that can be balanced by itself, and the grid nodes are not used.

The nodes are connected in a merit order, that determines in what order the energy flows from one node to the other. The more left a node is located in the conceptual model, the higher it is in merit order. Nodes that are completely left are the first in merit order. The grid nodes on the right side of the conceptual model are last in merit order. The energy flow from one node to the other is called the Net Load Signal (NLS). An NLS exists of a set of 8760 data points, representing an energy value in kWh/h for every hour of the year. In figure 3.1, the NLS's are indicated by solid lines with arrows between the

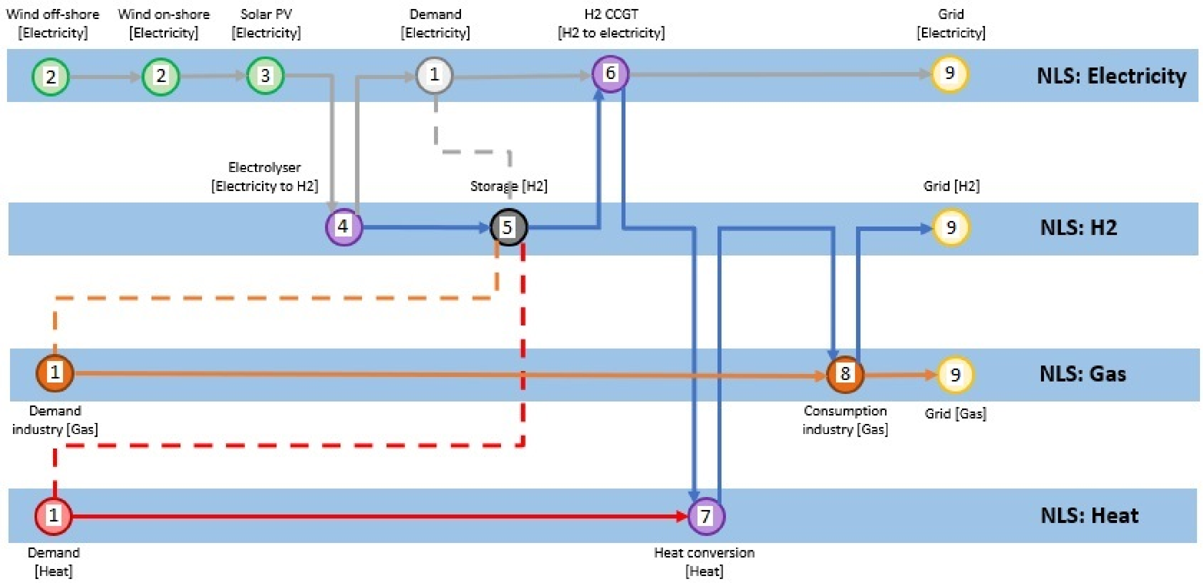


Figure 3.1: Example of a conceptual model according to the Power Nodes method.

nodes. Every node receives an input NLS from one or multiple preceding nodes that are connected. The first node at the start of the chain starts with an input NLS of zero. Within every node, calculations are made for every hour, based on the characteristics of that node and the input NLS it receives. These calculations result in an output NLS, that is send on to the next node. Next to the solid lines, figure 3.1 also shows some dashed lines that connect demand nodes to the hydrogen storage system. Dashed lines represent information flows. These information flows are not added to the NLS, but the information is used for calculations inside the node.

3.2 Sub modules

Using the before described method, a model was built to investigate the functioning of different energy systems that include a hydrogen storage unit. The different nodes that are used in the model, as shown in figure 3.1, are further explained here. In the figure, all nodes are labelled with a number. This number does not determine the merit order, but is simply to indicate which node is, or which nodes are being explained. Sometimes, multiple nodes are labeled with the same number. This means that the structure inside these nodes is the same. Even though multiple nodes can be labeled with the same number, the information calculated inside each node is different, due to different input data and a different position inside the model structure. For every type of node it is explained what the input and output NLS's are, what other input data are needed, what calculations happen inside the node, and what outputs the node will give. The explanation includes information from literature research. A detailed overview of all node inputs can be found in appendix C.

3.2.1 Demand nodes

The demand nodes are labeled with numbers 1 in figure 3.1. Demand nodes represent electricity demand, gas demand and heat demand.

Input NLS

Demand nodes receive one single input NLS. This NLS is zero if the demand node is the first node in the merit order.

Input variables

The input for demand nodes needs to be a data set of 8760 values for the energy demand during every hour of the year, in kWh/h. Which input data set is used is further explained in section 4.2. All data need to be negative in case of demand, or zero in case of no demand. An optional model input is a percentage of the energy demand that is left after energy saving measures have been implemented. In the scenarios that are modeled for this research, it is assumed that energy savings can lead to a decrease in electricity demand of 20%, a decrease in heat demand of 20% and a decrease in industry gas demand of 50%. These estimates are based on scenarios created by CE Delft [14].

The demand patterns that are given as input to the demand nodes are electricity and gas demand patterns. For the electricity demand node and for the industrial gas demand node, these represent the actual required electricity and gas. However, for the heat demand node, an extra conversion step is required. The demand pattern that is given as input, represents the gas demand that is sent to houses and buildings to provide heating. Because space and water heating is not a 100% efficient process, the demand for actual heat is lower than the demand for gas. To correct for this discrepancy, the heat demand node requires an additional input. This is the average conversion efficiency in the Netherlands at which natural gas is burned for domestic heating. This efficiency is 87.91% [23].

Table 3.1: Specification of the input variables and values for the demand nodes.

Variable	**Value**	**Unit**
Electricity demand		
Demand pattern	user specified	kWh/h
Demand after savings	80	%
Heat demand		
Demand pattern	user specified	kWh/h
Demand after savings	80	%
Average heating efficiency	87.91	%
Industry gas demand		
Demand pattern	user specified	kWh/h
Demand after savings	50	%

Node calculations and outputs

The demand node multiplies the savings- and efficiency percentages with the given demand pattern. The output NLS of a demand node is the hourly energy demand added to the input NLS. If the demand node is the first node in the merit order, this will be all negative values (or zero for hours with no energy demand).

3.2.2 Wind production nodes

The wind production nodes are indicated by numbers 2 in figure 3.1. Wind production nodes can be either for onshore or offshore wind. Both nodes work the same way, so they are discussed together.

Input NLS

A wind production node receives one single input NLS. This can be either zeros if it is the first node in the merit order, negative values if it is preceded by a demand node, or positive values if it is preceded by another production node.

Input variables

The variables that are needed as input in the wind turbine sheets are shown in table 3.2. These inputs represent a wind speed pattern with hourly numbers for one year, the total installed wind capacity, the characteristics of the wind turbine, characteristics of the surrounding area where the wind turbine is placed, and the height at which the wind speed is measured. Wind turbine characteristics are based on different existing wind turbine models [24].

The electricity production of a wind turbine as a function of the wind speed is dependent on the type of wind turbine that is used. This relation is called the power curve of a wind turbine. The power curve is built-in in the model. This means that it cannot be changed as one of the model inputs. If a different power curve must be used, the model code must be changed. Related to this power curve are the start speed, rated speed and cut off speed of the turbine. These should only be changed in relation to the coded power curve.

Table 3.2: Specification of the input variables and values for the wind nodes.

Variable	**Value**	**Unit**
Onshore wind turbines		
Wind speed pattern	user specified	m/s
Total capacity	user specified	GW
Turbine output	5	MW
Hub height turbine	110	m
Height measurement location	user specified	m
Roughness location	0.05	m
Offshore wind turbines		
Wind speed pattern	user specified	m/s
Total capacity	user specified	GW
Turbine output	10	MW
Hub height turbine	130	m
Height measurement location	user specified	m
Roughness location	0.0002	m

Node calculations

The electricity production of wind turbines is calculated in several steps. First, the measured wind speed needs to be corrected. The height dependence of the wind speed is called the wind profile power law, and the relationship is shown in equation 3.2.2.

$$\frac{v_1}{v_2} = \frac{ln(\frac{z_1}{z_0})}{ln(\frac{z_2}{z_0})} \tag{3.1}$$

[25]

Here, v_1 and v_2 represent the wind speeds in m/s at height z_1 and z_2 in m respectively. The factor z_0

represents the roughness length of the location. This gives an indication of the surface roughness, and is expressed in m [25]. It is often a value between 0 and 1, but it can also be larger. A higher number indicates a rougher surface. The Dutch weather institute KNMI publishes data of measured wind speeds at different locations and heights [26][27]. Using the measured wind speed, the measurement height, the roughness length and the wind turbine height, the wind speed at turbine height can be calculated.

Once the corrected wind speed is calculated, the power curve that is built-in in the model is used to calculate the power output for the corrected wind speed during each hour. Further specification of how the used power curves for the offshore and onshore wind turbines were arrived at can be found in appendix A.

Output NLS

Depending on the input NLS the wind node receives, the produced electricity is split up into used wind and dump wind. Used wind is the part of the energy that can be directly used to fulfil the electricity demand. Dump wind is produced wind energy that is left after fulfilling the electricity demand. The output NLS is the sum of the input NLS and the total produced wind energy in that node.

3.2.3 Solar PV production node

The solar PV production node is indicated by number 3 in figure 3.1.

Input NLS

A solar PV production node receives one single input NLS. This can be either zero if it is the first node in the merit order, negative values if it is preceded by a demand node, or positive values if it is preceded by another production node.

Input variables

To specify the solar PV characteristics, input data are needed that are presented in table 3.3. These data include the total installed capacity, characteristics of the solar panels, and a solar irradiance pattern. The inverter efficiency follows a curve that is dependent on the power output of the solar panel. At higher power output, the inverter functions with higher efficiency [28]. However, in the model the inverter efficiency was assumed to be a constant.

Solar cells can be built using different materials, leading to different efficiencies and specifications. The most common types of solar panels for rooftop use are produced from silicon or thin-film materials (e.g. gallium arsenide, copper indium gallium selenide, cadmium telluride). Silicon panels are the most efficient type of solar panels, with efficiencies that can reach to almost 23%. However, the majority of the panels have an efficiency between 15% and 17%. Maximum power outputs of solar panels that are produced nowadays usually vary between 250 and 400 Wp [29]. The data that are used in the scenarios are based on existing high quality solar panel models [29–31]. This is the power output that the solar panel can produce under ideal sunlight and temperature test conditions.

Table 3.3: Specification of the input variables and values for the solar PV node.

Variable	Value	Unit
Solar PV		
Solar irradiance pattern	user specified	Wh/m^2
Total capacity	user specified	GW
Max. power output panel	375	Wp
Panel efficiency	21	%
Inverter efficiency	90	%
Surface area per panel	1.75	m^2

Node calculations

To calculate the hourly production of a solar PV node, most of the variables are multiplied, as shown in equation 3.2. Within the node, the number of panels is calculated using the total installed capacity and the capacity per panel. The shown equation is valid as long as *solar irradiance* · *panel surface area* · *panel efficiency* · *inverter efficiency* does not exceed the maximum power output. If it does, the solar panel will still produce at maximum power.

$$\textit{Power output} = \textit{irradiance} \cdot \textit{panel surface area} \cdot \textit{panel efficiency} \cdot \textit{inverter efficiency} \cdot \textit{number of panels} \tag{3.2}$$

Node outputs

Just like for wind production nodes, the produced electricity is split up into used solar and dump solar. The output NLS is the sum of the input NLS and the total produced solar energy in that node.

3.2.4 Electrolyzer node

The electrolyzer node is indicated by number 4 in figure 3.1.

Input NLS

The electrolyzer node interferes with two NLS's, namely the electricity NLS and the hydrogen NLS. In the scenarios used in this research, the electrolyzer node is the first node in the hydrogen flow bar. Therefore, the hydrogen input NLS is zero. The electricity NLS can contain both positive values for the hours with overproduction of electricity, and negative values for the hours with unfulfilled demand.

Input variables

Input data needed for the electrolyzer node are the total number of electrolysis plants, the maximum capacity of one plant, and the electrolyzer efficiency. Table 3.4 shows an overview of these numbers. For the number of plants, a high random number was chosen, so that for the modeling practices the electrolyzer capacity would be "unlimited".

For the production of green hydrogen, different types of electrolyzers can be used. Three known technologies are called alkaline electrolysis (AEL), polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolyte (SOE) electrolysis [32]. AEL and PEM are both commercially available, SOE is still in development phase. The technologies differ in type of electrolyte that is used, operation temperature, efficiency, start up time, suitability for large production volumes, lifetime, etc. At the moment AEL is the most common and mature technology. Since AEL is suitable for large plant size and costs are relatively low, this technology was assumed to be used in this research. Observed and expected efficiencies for this technology vary from 61% up to 86% [32–34].

Electrolyzers can be built for various capacities. Currently, a 10 MW hydrogen electrolysis plant is being built at the Rheinland refinery in Germany [35]. Also, smaller capacity modules can be stacked to reach plant capacities of over 20 MW [36].

Table 3.4: Specification of the input variables and values for the electrolyzer node.

Variable	Value	Unit
Electrolysis plant		
Number of plants	50,000	-
Maximum capacity plant	20	MW
Electrolyzer efficiency	75	%

Node calculations

Based on these numbers and on the input electricity, all positive electricity input will be converted to hydrogen with the indicated efficiency. All negative electricity input will remain unchanged. As described before, the number of plants was chosen so that this would not be a limiting factor.

Node outputs

The output NLS for electricity consists of the negative values for hours with left over electricity demand and zeros for hours where electricity surpluses are converted to hydrogen. The hydrogen output contains positive values for hours where the input electricity NLS was positive, and zeros for the hours with electricity shortage.

3.2.5 Hydrogen storage node

The hydrogen storage node is indicated by number 5 in figure 3.1.

Input NLS

The hydrogen storage only affects the hydrogen NLS. However, it also receives information from the NLS's of electricity, heat and gas. The storage node does not interfere with these NLS's, but it uses the information to give the right amount of hydrogen output.

Input variables

The input data that are needed for the storage node are shown in table 3.5. Based on these numbers, during every hour it is calculated what the charge state of the storage unit is, with how much hydrogen the storage is charged, and how much hydrogen is taken out of the storage.

Salt cavern hydrogen storage can be realized in areas where salt layers are naturally present in the subsurface. In the northern part of the Netherlands, these salt layers are present. In a research by Susan

[37], the potential hydrogen storage capacity for the Netherlands based on salt cavern storage was estimated. Based on the presence of salt pillars in this area, the storage capacity was found to be 34.6 TWh of hydrogen gas. This number is the sum of the capacity of salt caverns that are already present, and salt caverns that could potentially be realized, but are not yet formed. However, in the scenarios, the storage capacity was set to a higher number. This was chosen to analyse what the system behavior would be without storage limitations. The impact of the actual availability of storage is discussed in chapter 7.

Before hydrogen is stored in salt caverns, it needs to be compressed. Depending on the final pressure, this costs 7% up to 13% of the hydrogen energy content [38]. In the model, the variable "charge efficiency" represents this energy loss that is due to the compression. For filling salt caverns with hydrogen, and withdrawing hydrogen from the salt caverns, maximum fill and withdrawal rates must be taken into account. These are governed by maximum pressure change rates in the cavern and maximum flow rates in the bore holes. Generally, maximum withdrawal rates correspond to approximately 10% of the total storage capacity per day [39].

Table 3.5: Specification of the input variables and values for the hydrogen storage node.

Variable	Value	Unit
Salt cavern hydrogen storage		
Storage capacity	50,000	GWh
Max. charge power	0.10/24·storage capacity	MW
Max. discharge power	0.10/24·storage capacity	MW
Charge efficiency	90	%
Discharge efficiency	100	%
Self-discharge	0	%
Start stage	user specified	%

Node calculations

The calculations that happen within the hydrogen storage node are carried out in multiple steps. First the hydrogen that is coming in via the electrolyzer NLS is given as an input. As far as the charge capacity allows this, all incoming hydrogen is added to the storage, taking the compression loss into account. At the same time, depending on the demand NLS's, it is calculated how much hydrogen should be given as an output to fulfil the demand. This is the hydrogen that is discharged from the storage. Optional discharge losses as a percentage of the hydrogen discharged, and self-discharge as a percentage of the charge state are calculated. The charge state indicates the amount of hydrogen that is present in the storage during every hour. Next, the charge state is calculated. This is the charge state at the preceding hour raised by the incoming hydrogen and subtracted by discharge, discharge loss, and self-discharge.

Node outputs

The output NLS of the hydrogen storage is calculated by taking the input hydrogen NLS, subtracting the hydrogen that is added to the storage and the energy lost due to compression, and adding the amount of hydrogen that is taken out of the storage. In case the hydrogen storage is full or if the charge capacity reaches its limit, the incoming hydrogen NLS that cannot be stored is directly added to the output NLS.

3.2.6 Hydrogen Combined Cycle Gas Turbine

The CCGT is indicated by number 6 in figure 3.1.

Input NLS

The hydrogen CCGT interferes with both the electricity NLS and the hydrogen NLS, since it converts hydrogen into electricity. The electricity NLS consists of zeros for the hours where the demand has already been fulfilled, or negative values where there are still shortages. The hydrogen NLS consists of positive values, and is the output of the storage unit. The amount of hydrogen that is coming in to the CCGT every hour is matched to the hydrogen demand. This was calculated in the hydrogen storage node.

Input variables

The input data needed for the CCGT are the amount of gas turbines, the turbine capacity of one turbine, and the turbine efficiency. Table 3.6 shows an overview of the variables.

In combined cycle gas turbines (CCGT) by using a combination of a Brayton cycle (gas turbine) and a Rankine cycle (steam turbine), higher efficiencies can be reached compared to using a single-cycle turbine. For CCGT power plants, efficiencies up to 60% can be reached [40]. Gas turbine technology enhancement, use of advanced thermodynamic plant configurations or steam turbine optimization could even lead to higher efficiency levels up to 64-65% [41]. Most conventional CCGTs are fuelled by natural gas. However, it is also possible to build CCGTs fuelled by hydrogen [42], or to convert existing natural gas fuelled power plants into hydrogen fuelled power plants [43]. The CCGT technology used in this research is assumed to run on hydrogen.

Large turbines can generate electricity at capacities of 60 MW up to 1500 MW [40]. An example is the Vattenfall power plant at Eemshaven in the Netherlands. One of the units of this power plant is converted to run fully on hydrogen by 2023 [43]. This one unit has a 440 MW production capacity. In this research, the production capacity of one CCGT power plant was assumed to be 500 MW.

Just as for the electrolyzer node, also here for the number of plants a random high number was chosen, for “unlimited” capacity.

Table 3.6: Specification of the input variables and values for the CCGT node.

Variable	Value	Unit
CCGT plant		
Number of plants	50,000	-
Maximum capacity plant	500	MW
CCGT efficiency	user 60	%

Node calculations

Based on the turbine efficiency, the demanded electricity per hour and the input hydrogen received from the storage, the CCGT will convert hydrogen into electricity to fulfil the electricity demand. The CCGT receives a hydrogen input from the storage based on the demanded electricity. The energy content of this hydrogen multiplied by the efficiency determines the generated electricity output.

Node outputs

The output NLS for electricity will be only zeros if all electricity demand has been fulfilled. If there was not enough hydrogen in the storage, there will be negative values left in the electricity NLS. The output NLS of hydrogen will be the input hydrogen NLS, subtracted by the consumed hydrogen for electricity production. If enough hydrogen was present in the storage unit, these values will be positive to fulfil the industry gas demand, and the hydrogen boiler demand if applicable.

3.2.7 Heat pump node

Node number 7 in figure 3.1 refers to heat conversion. However, note that for a heat pump, the heat NLS would be connected to the electricity NLS, instead of to the hydrogen NLS.

Input NLS

The electricity based system contains a heat pump node. This node converts heat demand into electricity demand, and therefore receives input NLS's for both electricity and heat.

Input variables

The electric heat pump needs two numbers as input, namely the temperature of space heating water, and the correction factor. Additionally a weather pattern indicating the outside temperature at every hour is needed. The input values are shown in table 3.7.

For this research, the heat pump included in the model was assumed to be an air-to-water air source heat pump (ASHP). More information about this and other types of heat pump can be found in the review paper by Staffell et al. [44]. In the air-to-water ASHP, the outside air temperature is used as T_{cold}, and water is heated to a temperature of 40°C (T_{hot}) [44].

Table 3.7: Specification of the input variables and values for the heat pump node.

Variable	**Value**	**Unit**
Heat pump		
Temperature pattern	user specified	°C
Correction factor	0.2	-
Temperature space heating water	40	°C

Node calculations

The efficiency of heat pumps is expressed in the COP. This COP is theoretically determined by the outside (cold) and inside (hot) temperature. The COP is calculated in the model, according to the following formula:

$$COP_{theoretical} = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{3.3}$$

[45]

Here T_{hot} is the desired temperature of the water or the building that is heated. T_{cold} is the outside temperature that is used to heat the refrigerant liquid. Both temperatures need to be expressed in K. Inside the model, given temperatures in °C are converted to K. In practice, matters as friction and heat losses cause the actual COP to be lower than the theoretical COP. The relation between the actual and the theoretical COP is called the correction factor, as shown in the following equation:

$$\epsilon_{correction} = \frac{COP_{real}}{COP_{theoretical}} \tag{3.4}$$

[45]

This correction factor can vary from 0.3, for smaller heat pumps, up to 0.7, for large, very efficient systems [45]. In the analyzed scenarios, the number 0.2 was chosen. This number is lower than the numbers suggested by literature. This was done to compensate for the fact that not all building are suitable for heat pump heating. Some buildings require heating using other, less efficient technologies. Based on this, the correction factor 0.2 was chosen as an educated guess. Since the outside temperature varies depending on the weather, day-night fluctuations and seasons, the COP_{real} will vary as well. When the COP of a heat pump is specified in the product specifications, this is the COP_{real} under standard test conditions. Using the correction factor and the $COP_{theoretical}$, the COP_{real} is calculated. Based on this COP and the incoming heat demand, the heat production and corresponding electricity consumption are calculated.

Node outputs

The output heat NLS will be only zeros. All heat demand is converted into electricity demand. The output electricity NLS is the input electricity NLS subtracted by the calculated heat pump electricity consumption.

3.2.8 Hydrogen boiler node

Number 7 in figure 3.1 refers to heat conversion. This could be a hydrogen boiler node, as it is connected to the hydrogen NLS.

Input NLS

The gas based system and the combined system contain a hydrogen boiler node. This node converts hydrogen into heat, to fulfil the heat demand. The hydrogen boiler node receives input NLS's for both hydrogen and heat.

Input variables

For the hydrogen boiler the boiler efficiency must be given as input. Efficiencies of conventional boilers can vary between about 60% for older models up to a maximum of about 85% [46, 47]. Improvement of boiler systems has resulted in development of condensing boilers. This allows the overall efficiency to increase up to 88-95% [47]. Usually, boilers are running on fossil fuels. However, it is possible to build boilers fuelled by hydrogen. Giacomini, a producer of heating and cooling systems, has developed a 100% hydrogen-powered catalytic condensing boiler [48]. This boiler uses a catalyst to allow for flameless hydrogen combustion. The only reaction products of this boiler are heat and water. Other companies are working on the development of hydrogen boilers as well, but these models are still in the development state [49].

Table 3.8: Specification of the input variables and values for the hydrogen boiler node.

Variable	Value	Unit
Hydrogen boiler		
Boiler efficiency	90	%

Node calculations

Within the node, based on the demanded heat, hydrogen is converted into heat. The produced heat never exceeds the demanded heat. The heat is converted using the given efficiency.

Node outputs

As output NLS, the hydrogen boiler gives a heat NLS that is zero if the heat demand is fulfilled. If not enough hydrogen is present in the storage to fulfil the demanded heat, the NLS will also contain negative numbers. This indicates an imbalance in the system. The hydrogen output NLS should contain positive values if more nodes are following that consume hydrogen. Otherwise it should be zero for a balanced system.

3.2.9 Gas consumption industry node

The gas consumption industry node is labeled by number 8 in figure 3.1.

Input NLS

The gas consumption industry node connects the industry gas demand with the hydrogen output provided by the storage. It receives input NLS's for gas and hydrogen.

Input variables

The gas consumption for industry node does not need any inputs, next to the NLS it receives.

Node calculations

Within the node, the incoming hydrogen NLS with positive values is added to the demanded gas NLS with negative values.

Node output

If the amount of incoming hydrogen is sufficient, the incoming hydrogen supply and the gas demand cancel out. This results in NLS's with only zeros. If the hydrogen supply is not sufficient to fulfil all demand, all hydrogen will be consumed resulting in a hydrogen output NLS of only zeros. However, in this case some of the gas demand will remain unfulfilled, giving a gas output with negative numbers representing the unfulfilled demand.

3.2.10 Grid nodes

The nodes that are labeled with a number 9 in figure 3.1 are the grid nodes. These nodes allow for connection of the presented system to a larger system. If any energy surpluses would be left, these could be fed to the grid. In case any energy shortages would be left, energy could be withdrawn from the grid to fulfil this remaining energy demand. In this research, the modeled energy system is a representation of the Netherlands. Energy exchange via the grid nodes would represent the import and export of energy. Since energy import and export are outside the system boundaries, the grid nodes are not used in this research. However, the presence of these nodes in the conceptual model leaves the option open to include this in future research.

3.3 Model outputs

To compare the results for the different scenarios, the required capacities of offshore wind turbines, onshore wind turbines, solar PV, hydrogen storage, gas turbines, and electrolyzers are compared. Systems with higher required capacities are more expensive and more difficult to realize.

The required capacities of wind turbines and solar PV are found by a trial and error process. The model outputs show what part of the energy demand is fulfilled. Different capacities of installed wind turbines and solar PV are given as input. The ratio of offshore wind, onshore wind and solar PV is kept constant. For every set of input capacities, the outputs are monitored. The input capacities are adapted so that just enough electricity is generated to fulfil all energy demand. Via this process, the required capacities for offshore wind, onshore wind and solar PV are determined.

After an input scenario has been constructed in this way, the resulting required capacities can be found for hydrogen storage, gas turbines and electrolyzers. For the hydrogen storage, the maximum amount of hydrogen present inside the storage during the year, expressed in TWh, can be found from the storage sub module. This indicates the maximum storage capacity needed. The maximum hourly production for the electrolyzer and gas turbine that is reached within the analyzed year can be found in the respective sub module for the each technology. This indicates the required capacity in kWh/h. It was assumed that this capacity in kWh/h is equal to the capacity in kW.

3.3.1 Additional possibilities Power Nodes method

The Power Nodes method offers the possibility to include economic and environmental analyses. In every node, economic and environmental inputs can be added, to calculate technology cost and the environmental impact of realizing such a system. In this research this function was not used, but it could offer the option to extend the research in the future, and include economic and environmental aspects.

3.4 Validation and verification

As described in section 2.2 in chapter 2, it is important to validate and verify a newly built model, before its outputs can be trusted. It must be confirmed that the model is suitable for answering the research questions, and that the model is making the right calculations to generate correct data.

3.4.1 Model validation steps

To validate whether the model is suitable for the intended research, Pierie et al. set up a set of questions the model must comply with [22]:

1. Does the model add to scientific understanding or add to societal benefit?
2. Does the model refer to clear answers which can be provided through modeling?
3. Is the model reviewed and verified by experts in the field?

To add to scientific understanding, the model presents the electricity and hydrogen interaction from a system perspective. Positive and negative energy flows from different sub systems are connected. This allows for generation of data that represent the interaction between the different sub systems on an hourly basis. Hours with energy shortages or surpluses in the total system can be discovered. Based on this information, the system can be adapted and improved to create a balanced energy system. The model design leaves the option to include environmental and economic aspects in future research. In this way, the model allows for addition to scientific understanding.

The model provides answers in the form of hourly data about yearly energy demand, energy generation, conversion, and storage. These data are presented in summarizing numbers and plots that give an overview of the production of technologies and the balance at the end of the energy flow. Additionally, information can be derived about the extent to which technologies are used, and what capacities would be useful in the concerned scenario.

The review by experts was done during a walk-through session. This resulted in positive feedback and expert validation. The walk-through is also discussed in the verification section.

Based on these validation steps, the validity of the model is confirmed. The model is deemed suitable for adding understanding to the intended research.

3.4.2 Model verification steps

For the verification of the model, multiple techniques can be found in literature. Sargent [21] presents a list with different techniques, from which some were selected to test the model that was built for this research.

First, an extreme condition test was executed. In an extreme condition test, extreme and unlikely scenarios are used to test whether the model outputs are still plausible. To test this, individual inputs and individual sub modules were set to zero, to compare the effect this has on the model output. This leads to a better understanding of the links between data within the model, and allows for correcting any possible mistakes that are found. A more detailed description of the different steps taken in the extreme condition test can be found in appendix B.

Another technique described by Sargent is data relationship correctness. With this method, values of input data are compared to values of related data. The different types of data should relate to each other in a sensible way. This was done by changing the values of different inputs, and seeing how this affects data in the model. For example, the produced electricity by wind turbines should be linearly dependent on the amount of wind turbines installed. By changing the number of installed wind turbines in steps, and comparing the produced electricity, such a relation can be confirmed. Appendix B also gives a more elaborate description of the data relationship correctness analysis.

Event validity means comparing the simulated system to a real life situation. For the complete system this cannot be done, but for several sub modules this can be executed. For the heat pump node, the heat pump efficiency of the model is compared to the theoretical efficiency, and the energy consumption is compared to real life energy consumption patterns. To test the wind turbine nodes, real life data were compared to modeled data. From literature, information was found on the amount of installed wind capacity and the total electricity generated by wind turbines over one year. The amount of installed wind capacity was given as input for the wind power node and the output generated electricity was compared to the real life number. The same approach was used to compare the production of solar PV modules to reality. Both analyses found model outputs relatively close to the real life numbers. More information about the executed event validity test can be found in appendix B.

The next verification method is face validity. Face validity means that individuals that are familiar with the system are asked whether the model and its behavior seem reasonable. One can for example look at the conceptual model and the model's input-output relationships. Face validity was carried out during different discussions sessions when the model was under construction. The progress of the model construction and the functioning of different sub modules were discussed with other individuals that are familiar with the Power Nodes modelling method. Ideas were exchanged on what should and what should not be included in the model, how detailed sub modules should be, and what the model lay out should look like. Additionally, when the model construction process was close to finished, a structured walk-through was done. Together with the same individuals involved before, plus one individual experienced with modelling but not specifically with this modelling method, every sub module of the model, the dynamics between the different sub modules, and the model outputs were explained.

Executing the model verification and validation steps allowed for improvement and correction of errors in the model. After carrying out the correction and improvement of the model, the structured walk-through was done. The validity of the model was confirmed and the model was deemed suitable for further carrying out the research.

3.5 Sensitivity analysis

By carrying out a sensitivity analysis, the impact of varying one single variable was measured with relation to the most important outputs of the model. The sensitivity analysis was carried out separately for the electricity based scenarios and for the gas based scenarios, because these two systems represent the more extreme scenarios. All the model variables were increased and decreased by 10% one by one. To measure the effect, the relative change in output was listed for the electricity not delivered in GWh, the number of hours with electricity shortage, the heat not delivered in GWh, the number of hours with heat shortage, the hydrogen for industry not delivered in GWh, and the number of hours with hydrogen shortage. All the numbers can be found in appendix D. For both system scenarios, the influence of the wind pattern for offshore wind, the installed capacity of offshore wind, and the demand patterns have a relatively large impact of close to or over 15% on some of the outputs. This must be kept in mind when collecting data for construction of sub scenarios. The importance of getting correct data for these variables is extra relevant, for getting reliable model outputs. For the gas based system, also the electrolyser- and storage efficiency have a large impact of close to or over 15% on the model outputs. In the gas based system, the influence of the electrolyser- and storage efficiency is larger because all generated electricity is converted into hydrogen and therefore affected by these efficiencies. In the electricity based system the efficiencies have less impact, because only electricity surpluses are affected by these efficiencies.

Chapter 4

CASE NETHERLANDS

The model as described in the preceding chapter is used to analyze a case study of the Netherlands. This chapter further specifies this case study. For the energy generation, wind patterns are used. For energy demand, demand patterns are used. This chapter explains which weather patterns and energy demand patterns are used and how these are arrived at.

4.1 Weather patterns

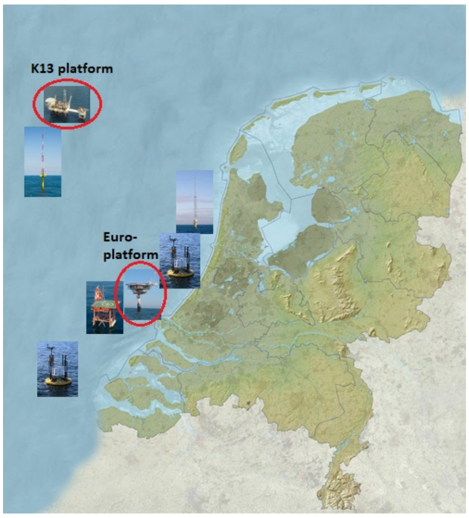
Since the used demand patterns are based on the weather patterns, the weather patterns are discussed first.

4.1.1 Wind patterns

As input for the wind turbine nodes, wind patterns are needed that indicate the wind speed for every hour during a year. The Dutch weather institute KNMI publishes hourly weather patterns measured from different measurement stations scattered throughout the country [26]. In reality, every wind turbine can experience a slightly different wind speed, depending on its location and surroundings. However, the model would become too extensive and the calculations become too complex to use a different wind pattern for every wind turbine, or even for every wind park. For this research it was decided to only use two different wind patterns for onshore wind, and two different wind patterns for offshore wind. In this way, the electricity generation is not dependent on one single wind pattern. If the wind speed is too low or too high for electricity generation in one location, electricity may still be generated from the wind pattern at the second location. To determine what year would be used to take the data from, average wind speeds from 2014 to 2019 were compared for different locations. The locations that are used can be found in figure 4.1. For onshore wind, four measurement stations are selected that are spread throughout the country. These measurement stations are De Kooy, De Bilt, Hoogeveen and Maastricht. For offshore wind, the two measurement stations were picked for which measurement data were available. These measurement stations are the K13 platform and the Europlatform. For all measurement stations, the yearly average wind speed was calculated. Based on these averages, a year average is calculated for every year, and a multiple-year average is calculated for all analyzed years. These data are plotted in figure 4.2. From this analysis it was found that in 2014, the year average was closest to the multiple-year average. Based on this, it was decided that wind speed data from 2014 would be used.

For offshore wind generation, the data are used from both measurement platforms from which data were available. For onshore wind generation, two locations need to be selected to give a proper representation of onshore wind park locations. In the Netherlands, most wind parks are located close to the shore [50, 51]. Here wind speeds are higher and energy generation per turbine is higher. Based on this, it is decided to use wind patterns from De Kooy and De Bilt. De Kooy is located close to the shore, in an area where a lot of wind turbines are located [51]. De Bilt is located a bit more land inward, in a central location that is relatively close to multiple wind turbines as well [51].

(a) Onshore stations [52]



(b) Offshore stations [53]

Figure 4.1: KNMI measurement stations in the Netherlands. Figure a) shows the onshore measurement stations. The locations used in the analysis are red underlined. Figure b) shows the offshore measurement stations. The location used in the analysis are encircled.

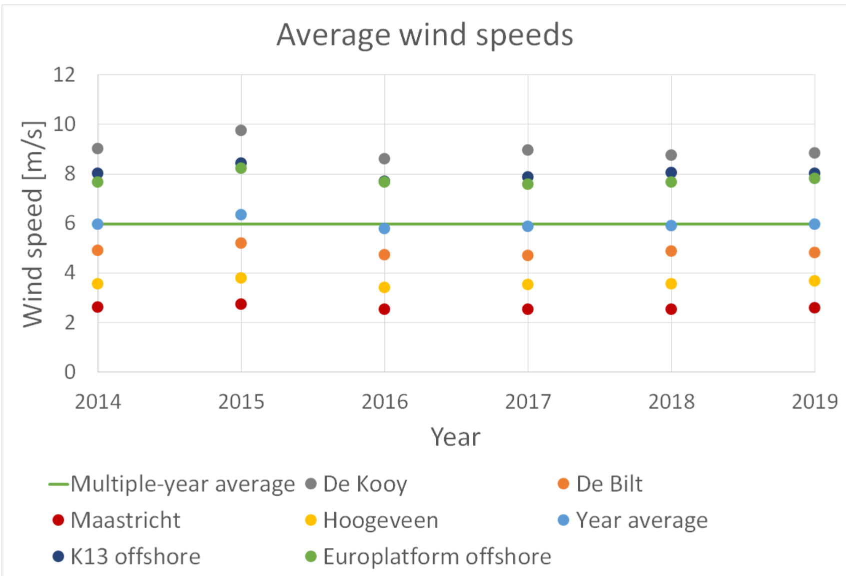


Figure 4.2: The average wind speeds were compared for 6 locations in the Netherlands, onshore and offshore, for 6 different years.

4.1.2 Solar irradiance patterns

As input for the Solar PV production nodes, solar irradiance patterns are needed. These data can be found in the same KNMI weather pattern files as for the wind data [26]. The average solar irradiance at the different locations during different years was compared. Again, data from measurement stations at De Bilt, De Kooy, Maastricht, and Hoogeveen were used, and the average solar irradiance was calculated for each location and for each year. The year-average solar irradiance is closest to the multiple-year-average in 2015 (fig. 4.3). It was decided to use the data from De Bilt and from Maastricht. In these two locations, the average incoming solar irradiance in 2015 is the closest to the year average. With this approach, the used irradiance patterns should give a representative pattern for incoming solar irradiance in the Netherlands.

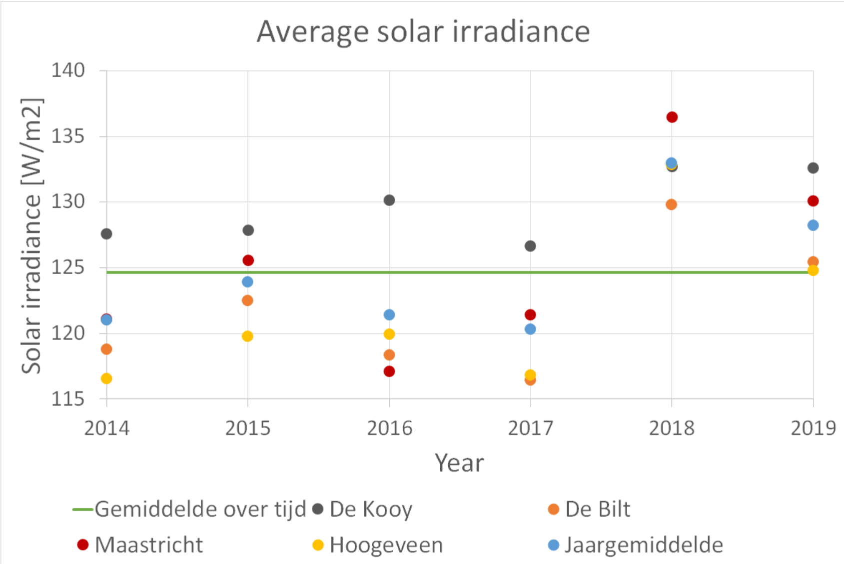


Figure 4.3: The average solar irradiance at different locations in the Netherlands was compared, for 6 different years.

4.1.3 Temperature pattern

For the heat pump node, an hourly temperature pattern is needed as input. The outside temperature determines at what COP the heat pump can function, as was explained in section 3.2.7. For simplicity it was decided to use one temperature pattern for this node. When looking at different maps indicating the temperature in the Netherlands, there is often a gradient found from north to south and from west to east. Land that is closer to the North Sea has a more moderate temperature compared to more inland areas. To pick a location with an average temperature, it was decided to use data from De Bilt, since this is located in the middle of the country. The year average of the temperature at De Bilt as presented by KNMI [54], was compared for the years 2011 up until 2019. The temperature was closest to average in the years 2011, 2015 and 2017. It was chosen to use the temperature pattern from 2015, since the weather pattern of this year was also used as input for the solar PV nodes.

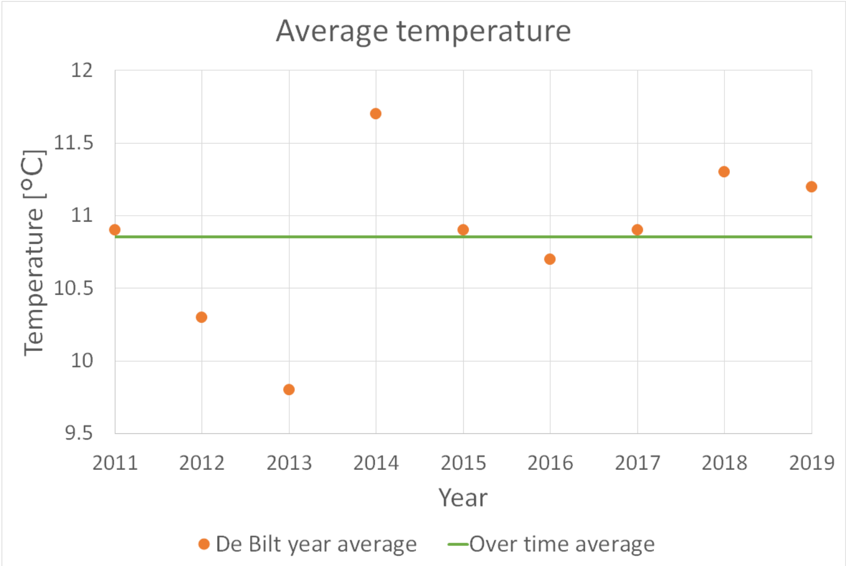


Figure 4.4: The year average of the temperature at De Bilt as measured by the KNMI [54] for the years 2011 - 2019.

4.2 Demand patterns

4.2.1 Demand pattern year

For the energy demand in the Dutch energy system, three different demand patterns were used, namely electricity demand, gas demand for heating, and gas demand for industrial use. The use of gas for heating houses is dependent on the outside temperature. Houses need more heating if the temperatures are low, and less heating if temperatures are high. Because of this dependence, it was decided to use demand patterns from the same year as the temperature pattern and the solar irradiance pattern. For temperature and solar irradiance, data from 2015 were used. Based on this, for the demand patterns, also data from 2015 were used.

4.2.2 Electricity demand

As described in section 4.2.1, for the initial electricity demand, the demand pattern for 2015 was used. In reality, the electricity demand pattern changes every year. On one hand, development of technology may lead to increased efficiency and a decreased electricity consumption per used device. On the other hand, people start using more different types of electric devices at their houses, increasing the electricity demand. These effects of increasing and decreasing electricity demand were not included in the research, so it was assumed that the initial electricity demand pattern remains unchanged with respect to the 2015 demand pattern.

4.2.3 Heat demand

The heat demand in the model is based on the gas demand in the section “distribution”. Gasunie, the company that manages the Dutch gas network, publishes its data in different categories. Distribution is the category that includes domestic gas consumption and consumption for small industry, for example for heating buildings. For simplicity it was assumed that all gas in this category is used for heat production at houses. According to Autoriteit Consument & Markt, in 2019, 79% of domestic gas consumption is used for space heating, and 21% of domestic gas consumption is used for water heating [23]. Additionally, they state that space heating happens at an average efficiency of 94%, and water heating happens at an average efficiency of 65%. With these numbers, it was calculated that the energy content of the final heat demand is 87.91% of the energy content of the consumed gas. This assumption was used for arriving at the heat demand pattern.

4.2.4 Industry gas demand

The gas demand for industry in the model is based on the category "industry" in the Gasunie publication of gas data. This category includes gas that is consumed for different purposes in industry. This could be final use, non-energetic use, production of other energy carriers, or refinery consumption [55]. In the current energy system, this gas demand is fulfilled in the form of natural gas. In the industry, natural gas is used for different purposes. Part of the natural gas is used to produce hydrogen. If hydrogen is directly delivered to industry, instead of natural gas, this conversion from natural gas to hydrogen does not have to be done at the industry itself. The production of hydrogen was already done at national level. This will save energy conversion losses in the industry. However, in other cases, natural gas itself might be needed. In this case, hydrogen needs to be converted into natural gas via methanation, which adds new conversion losses. These processes are not included in this research. It was assumed that natural gas demand for industry can be directly replaced by hydrogen with the same energy content.

4.2.5 Demand savings

A part of the Dutch climate policy is introducing energy saving measures [56]. Gasunie and TenneT executed a research where they came up with different scenarios that include energy savings [15]. Based on the energy savings suggested in the Gasunie and TenneT scenarios, energy savings are also included in the studied case in this research. The energy savings are expressed as a percentage of the original energy demand. For electricity, it is assumed that the electricity demand can be reduced by 20%. The low temperature heat demand is expected to be reduced by 20%, and the industrial gas consumption is expected to be reduced by 50%. The hourly pattern of the demand is contained. During every hour, the energy demand with savings is a certain percentage of the original demand without savings.

4.2.6 Dutch energy system

For this research, a basic energy system is designed. This section describes the basic overview of this energy system. This overview is based on the conceptual model as explained in chapter 3. In the next chapter, three variations to the energy system are described in more detail. These variations are called the system scenarios.

The analysed energy system contains four types of energy flows, namely electricity, hydrogen, gas, and heat. The system contains three demand nodes, namely electricity demand, heat demand and gas demand. Hydrogen only functions as an energy carrier for storage and transport, without a direct hydrogen demand node in the hydrogen flow bar. Next to the demand nodes, there are three production nodes, representing offshore wind, onshore wind, and solar PV. These technologies generate electricity, therefore the nodes are placed in the electricity flow bar. The model contains three conversion nodes. One node converts the heat demand into an electricity or hydrogen demand, depending on the system scenario. An electrolyzer node converts electricity into hydrogen, and a CCGT node converts hydrogen into electricity. In between the electrolyzer and CCGT node is a hydrogen storage unit. This node stores excess energy in the form of hydrogen, and provides hydrogen output to the CCGT, hydrogen boilers and industry sector. The grid nodes could potentially be used to connect the analyzed system to the network of a larger system. However, no actual energy exchange with grids is included in this model.

Chapter 5

SCENARIOS

To compare the different energy systems, scenarios are constructed. This chapter elaborates further on how these scenarios are built. First, the three system scenarios will be described. These system scenarios show which technologies are used and how all different technologies are connected within the energy system. Per system scenario, different production scenarios are created. These production scenarios are tailored to each system scenario. Analysis of these production scenarios allows for comparison between the system scenarios under different circumstances.

Figure 5.1 shows an overview of the structure of the different scenarios that are used. Every analysed scenario is a combination of one of the system scenarios together with one of the production scenarios.

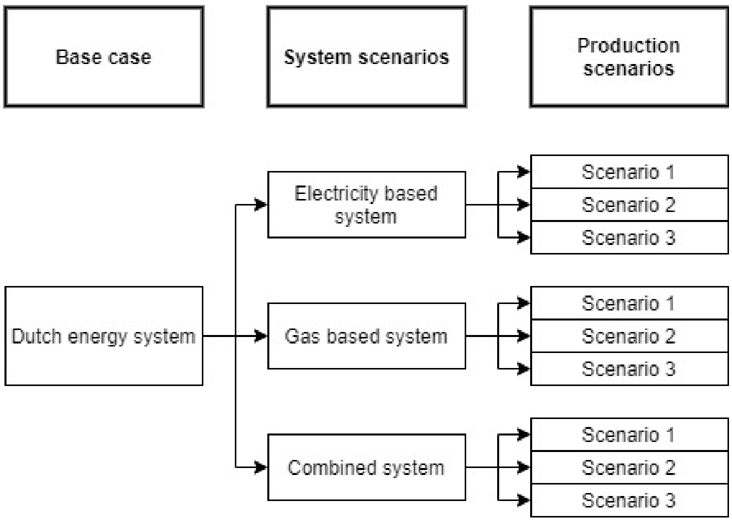


Figure 5.1: Overview of the structure of the system scenarios together with the production scenarios.

5.1 System scenarios

The three system scenarios that are designed are referred to as the electricity based scenario, the gas based scenario and the combined scenario. The following sections describe each system scenario in more detail.

5.1.1 Electricity based scenario

The main characteristics that specify the electricity based scenario are the presence of the electric heat pump for heat supply, and place of the electricity demand first in the merit order. The electric heat pump is high in efficiency and converts the heat demand into an electricity demand. The electricity demand first in merit order allows for direct delivery of electricity without conversion losses. Figure 5.2 shows the conceptual model for the electricity based scenario. The following description explains the function of each node, and the connection between the different nodes. In the bottom left, heat demand is converted to electricity demand via the heat pump. This heat demand is added to the initial electricity demand. This new electricity demand signal passes through the production nodes in the electricity flow bar. After the demand and production signals are added, any excess electricity is converted to hydrogen and stored in the storage unit. The storage unit receives information from the industry gas demand node and from the electricity demand that is left for hours of underproduction. The storage delivers a hydrogen output that matches the gas demand and the left over electricity demand. Hereby, the efficiency of the hydrogen CCGT is taken into account. The hydrogen CCGT converts hydrogen back to electricity to fulfil the left over electricity demand. At the industry consumption node, industry consumes the gas delivered from the storage.

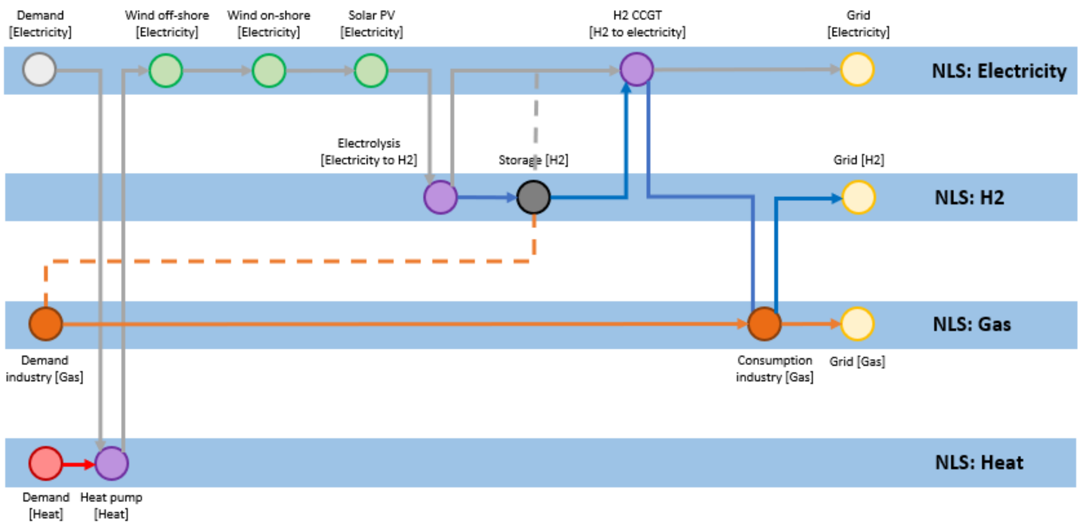


Figure 5.2: Conceptual model for the electricity based scenario.

5.1.2 Gas based scenario

The main characteristics that specify the gas based scenario are the use of the hydrogen boiler to fulfil the heat demand, and the place of the electricity demand in the merit order, after the electrolyzer. Both the place of the electricity demand in the merit order and the use of the hydrogen boiler allow for energy transport in the form of hydrogen through the gas grid. Figure 5.3 shows the conceptual model for the gas based scenario. Here, in the electricity flow bar, the NLS starts with electricity production. All produced electricity is converted to hydrogen and passed on to the storage unit. The storage unit receives information from the electricity demand node, the industry gas demand node, and the heat demand node. Based on this information, the storage delivers a hydrogen output that matches the electricity demand (taking into account the efficiency of the hydrogen CCGT), the industry gas demand, and the heat demand (taking into account the efficiency of the hydrogen boiler). The hydrogen CCGT converts hydrogen back to electricity to fulfil the electricity demand. The hydrogen boiler converts hydrogen to heat to fulfil the heat demand. At the industry consumption node, industry consumes the gas delivered from the storage.

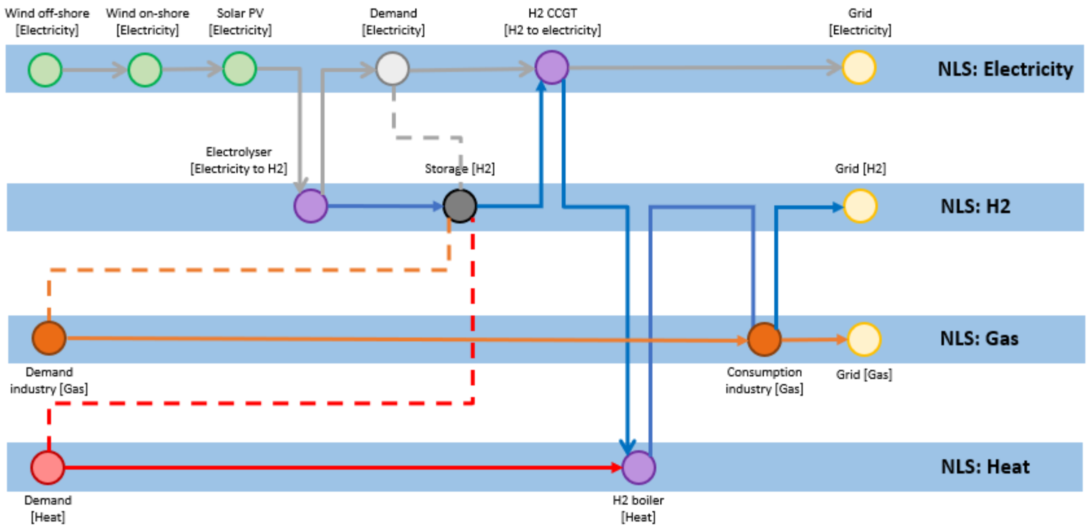


Figure 5.3: Conceptual model for the gas based scenario.

5.1.3 Combined scenario

The main characteristics that specify the combined scenario are the use of the hydrogen boiler, just like in the gas based scenario, and the place of the electricity demand first in the merit order, like in the electricity based scenario. The use of the hydrogen boilers allows for distribution of energy to buildings in the form of gas through gas pipelines. The place of the electricity demand in the merit order allows for more efficient electricity supply, reducing conversion losses. Figure 5.4 shows the conceptual model for the combined scenario. The electricity demand NLS is passed on to the production nodes, so that the produced electricity is added. Excess electricity is converted to hydrogen and stored in the storage unit. The storage unit receives information from the industry gas demand node, the heat demand node, and the electricity demand that is left at hours of low production. Based on this information, the storage delivers a hydrogen output that matches the electricity demand (taking into account the efficiency of the hydrogen CCGT), the industry gas demand, and the heat demand (taking into account the efficiency of the hydrogen boiler). The hydrogen CCGT converts hydrogen back to electricity to fulfil the remaining electricity demand. The hydrogen boiler converts hydrogen to heat to fulfil the heat demand. At the industry consumption node, industry consumes the gas delivered from the storage.

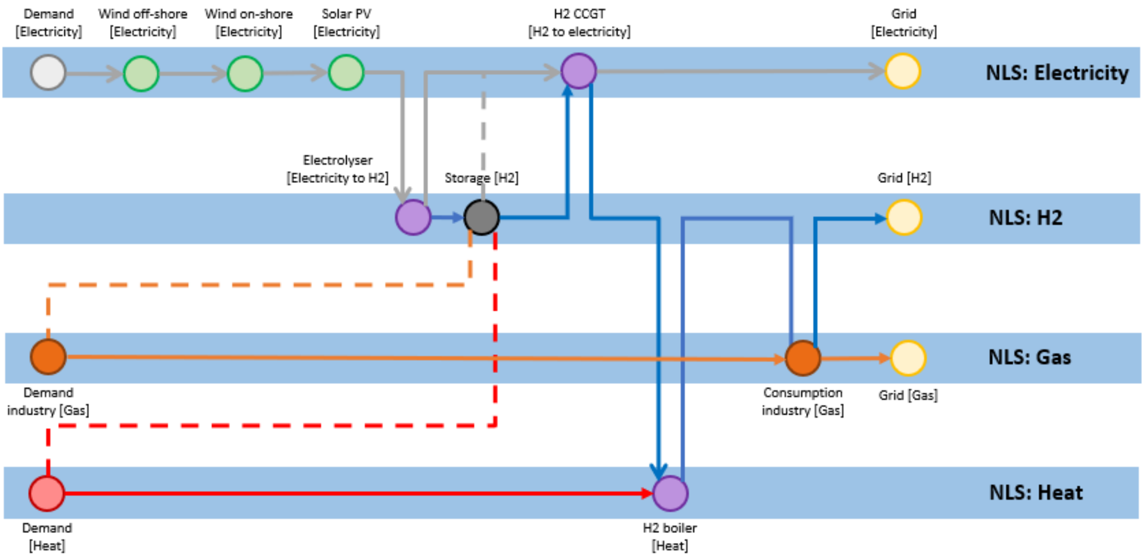


Figure 5.4: Conceptual model for the combined scenario.

5.2 Production scenarios

Within each system scenario, different production scenarios are given as input. By comparing the different production scenarios, one can see how external factors affect the system requirements. The aspects that are changed between the production scenarios are the total production capacities of offshore wind, onshore wind and solar PV, the ratio between offshore wind, onshore wind and solar PV, and wind speed patterns.

5.2.1 Production scenario 1

The basis for the first production scenario is the ratio between installed offshore wind, onshore wind and solar PV capacities. To determine what these ratios should be, existing scenario studies for the Netherlands were used. For offshore wind, in a scenario by Ros et al. 80 GW capacity was used [57]. For onshore wind, in a scenario created by CE Delft, 16 GW capacity was used [14]. For solar PV, the same scenario by CE Delft [14] assumed a potential capacity of 84 GW. These capacities are used as a starting point, resulting in a system with 44% offshore wind, 9% onshore wind and 47% solar PV. For the weather and demand patterns, the data are used as described in chapter 4. From here, for each system scenario the required production capacities are found. With these production capacities, just enough electricity is generated to fulfil the yearly energy demand.

5.2.2 Production scenario 2

The second production scenario was created after analyzing the results for scenario 1 (chapter 6). It was found that the amount of hydrogen in the storage shows a strong seasonal pattern. During summer months the amount of hydrogen in the storage strongly increases. During winter months the amount of hydrogen in the storage strongly decreases. To bridge this gap between energy supply and demand, a high storage capacity is required. During summer months, incoming solar irradiance is stronger and days last longer, leading to higher solar PV production. In production scenario 1, solar PV accounts for 47% of the installed generation capacity. It is expected that lowering the ratio of solar PV reduces this seasonal effect. Based on this expectation, a second production scenario was created. In this scenario, the ratios are set to 35% of solar PV, 10% of onshore wind and 55% of offshore wind. Again, for each system scenario, production capacities are found that generate just enough electricity to fulfil all energy demand.

5.2.3 Production scenario 3

For the third production scenario, the results of the sensitivity analysis are taken into account. As explained in section 3.5 of chapter 3, the impact of a different offshore wind pattern on the results is relatively high. However, in reality wind patterns vary every year. Production scenarios 1 and 2 are based on wind patterns of a year with an average wind speed. To analyse the impact of a different wind pattern, a new production scenario is created. Instead of using offshore and onshore wind patterns of 2014, wind patterns of 2015 are used. Data from 2015 are chosen because the average wind speed in this year differs the most from other years. This can be seen in figure 4.2 in chapter 4. For this production scenario, the installed electricity generation capacities are kept equal to the capacities in scenario 2.

Chapter 6

RESULTS

6.1 Scenario 1

This chapter shows and explains the results for each of the three production scenarios. For every production scenario, the system scenarios are compared to each other. Differences between the system scenarios are pointed out, and also the main differences between results for the production scenarios are pointed out. In scenario 1, offshore wind, onshore wind, and solar PV are installed as 44%, 9% and 47% of the total production capacity respectively. Wind speed patterns of 2014 are used.

6.1.1 Production capacity

Based on the trial and error process as described in section 3.3, the required capacities of offshore wind, onshore wind and solar PV were determined for the three system scenarios. Figure 6.1 shows the resulting required capacities.

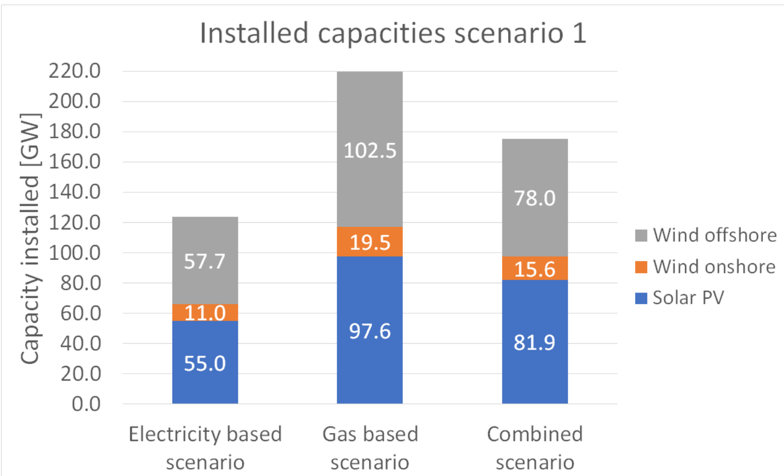


Figure 6.1: Installed offshore wind, onshore wind and solar PV capacities for the three system scenarios for the first production scenario.

The required total installed capacities are 123.7 GW for the electricity based scenario, 219.6 GW for the gas based scenario, and 175.5 GW for the combined scenario. When comparing the electricity based and the gas based scenarios, the electricity based scenario requires 44% less generation capacity. This is a large difference and this will have a major effect on aspects like cost, social acceptance and indirect environmental impact as well. When looking at generation capacity, the combined system is in the middle of the two extremes. Compared to the gas based system, this will still require 20% less generation capacity, which is already a big difference. The difference in required generation capacity can be understood by looking at required electricity to hydrogen conversion.

In the electricity based system, the generated electricity is directly used to fulfil the electricity demand as much as possible, without any conversion losses. Only surplus electricity is converted into hydrogen. This has a large effect on reducing losses in the system. Additionally, by using electric heat pumps, the overall heat demand is reduced due to the high heat pump efficiency. Furthermore, because the heat pumps can run on electricity, this also reduces the need for conversion to hydrogen. Together, this makes the electricity based scenario very energy efficient.

In the gas based system, all electricity that is generated is converted into hydrogen. With the assumed electrolyzer efficiency of 75%, this means a direct loss of 25% of all generated electricity. To fulfil the electricity and heat demand, this hydrogen will need to be converted again into electricity using CCGTs and into heat using boilers. These conversion steps lead to additional losses in the energy system. Overall, this system is associated with high conversion losses and low energy efficiency.

In the combined system, by directly using generated electricity to fulfil the electricity demand, losses are greatly reduced compared to the gas based system. The need for conversion steps, to hydrogen and back to electricity, are significantly reduced. However, the hydrogen demand is still relatively high, due to the use of hydrogen boilers for heating. With this combination, the overall efficiency ends up in the middle between the two extreme scenarios.

6.1.2 Hydrogen storage

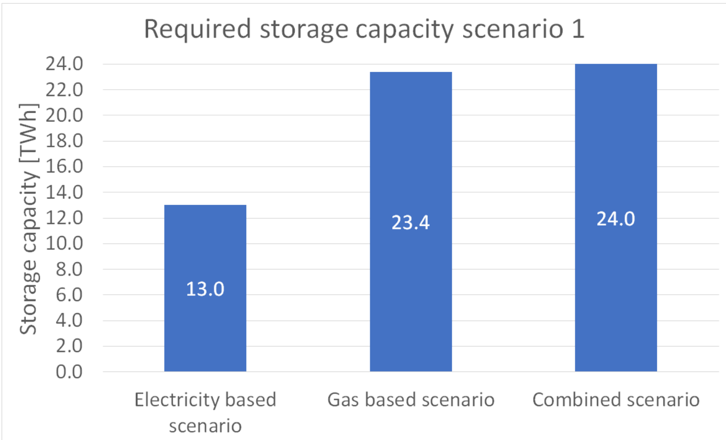


Figure 6.2: Required storage capacity for the first production scenario in the electricity based scenario, gas based scenario and combined scenario.

When looking at required storage capacity (fig. 6.2), the electricity based scenario requires lower capacity compared to the other two systems. For the electricity based scenario, 13.0 TWh of hydrogen storage is sufficient to support the energy system. For the gas based scenario, 23.4 TWh of storage is required, and for the combined scenario, 24.0 TWh of storage is needed. In the electricity based scenario, the hydrogen storage only functions as storage for electricity use, and to supply the gas for industry. In the gas based scenario and the combined scenario, additionally, gas is used to fulfil the heat demand. Since the heat demand shows strong seasonal fluctuations, this increases the storage capacity requirements. Furthermore, in the gas based system, hydrogen is used to generate electricity to fulfil the complete electricity demand using CCGTs. In the combined system, only electricity shortages are fulfilled using CCGTs. However, because the electricity demand is relatively constant throughout the year, this does not result in a big difference in storage requirements between the gas based and combined scenario.

In production scenario 1, the combined scenario requires a bit more storage capacity than the gas based scenario. This can be explained by incidental differences in demand and supply fluctuations rather than fundamental differences between the scenarios. Further illustration of this difference can be found in appendix E.

Next to the required storage capacity, the behavior of the hydrogen storage is monitored. Looking at this gives more insight in the role of the hydrogen storage throughout the year. Figure 6.3 shows the charge state of the hydrogen storage for the three system scenarios. The charge state indicates the amount of hydrogen that is stored in the storage during every hour of the year.

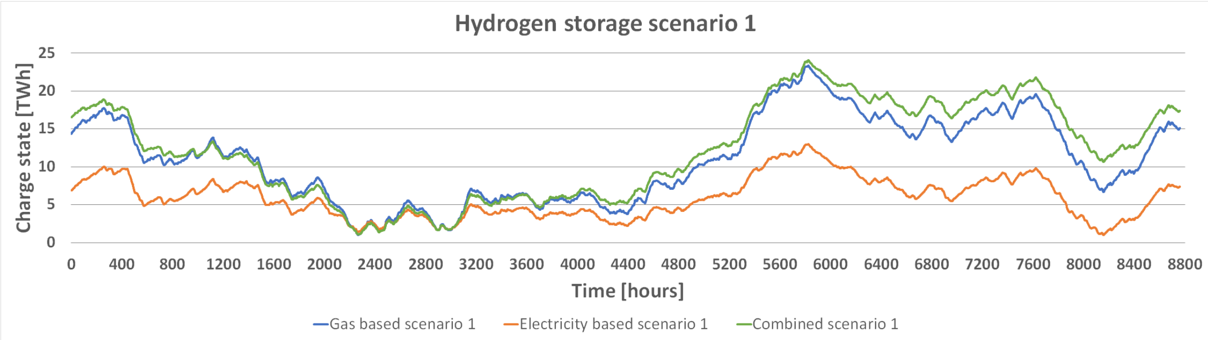


Figure 6.3: The charge state for the gas based scenario with the first production scenario, indicating the amount of hydrogen that is stored in the storage during every hour of the year.

The fluctuations in the amount of hydrogen stored in the storage, show a quite strong seasonal pattern. During the summer months (approximately hours 4400-6600), the level of hydrogen stored increases strongly, and during the winter months (approximately hours 0-2200), the level of stored hydrogen decreases. This can be explained by the seasonal fluctuations in energy supply and the inverse seasonal fluctuation in energy demand. During summer months, the length of days and the intensity of solar irradiance increase, leading to higher electricity production by solar PV. On the other hand, during winter months, the demand for heat is higher, due to colder outside temperatures. This mismatch results in high amounts of stored hydrogen by the end of summer, and low amounts of stored hydrogen by the end of winter. As already explained in section 5.2.2, the second production scenario is adapted to decrease this seasonal fluctuation. The results of this scenario are further discussed in section 6.2.

6.1.3 CCGT capacity

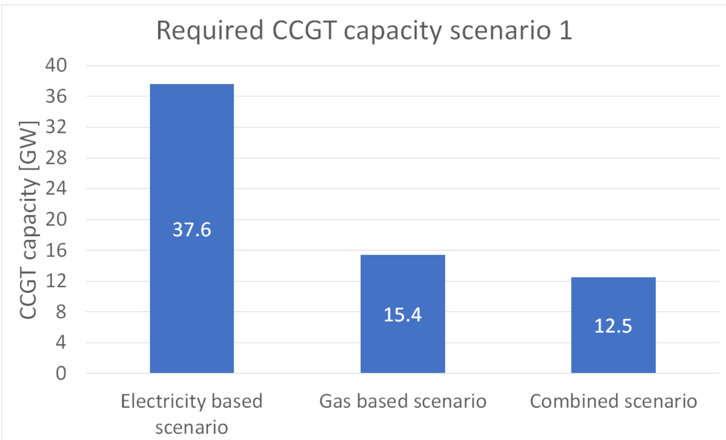


Figure 6.4: Required CCGT capacity for the first production scenario in the electricity based scenario, gas based scenario and combined scenario.

For the CCGTs in scenario 1 (fig. 6.4), the required capacity for the electricity based system is the highest, with 37.6 GW. This can be explained by the fact that the heat demand is added to the electricity demand pattern. During hours with low electricity generation, still all electricity demand and heat demand need to be fulfilled by electricity. Hydrogen in the storage is then converted into electricity by CCGTs, to fulfil this demand. In the gas based scenario, the required capacity is 15.4 GW. This is a lot lower than for the electricity based scenario. Electricity is only required to fulfil the electricity demand, and the heat demand is not added to this. This reduces the peak CCGT load significantly. For the combined scenario, the least CCGT capacity is required. During the hours with peak electricity demand, a part of the demand is already fulfilled by the electricity that could be directly delivered from solar and wind production. This leaves a required CCGT capacity of 12.5 GW.

6.1.4 Electrolyzer capacity

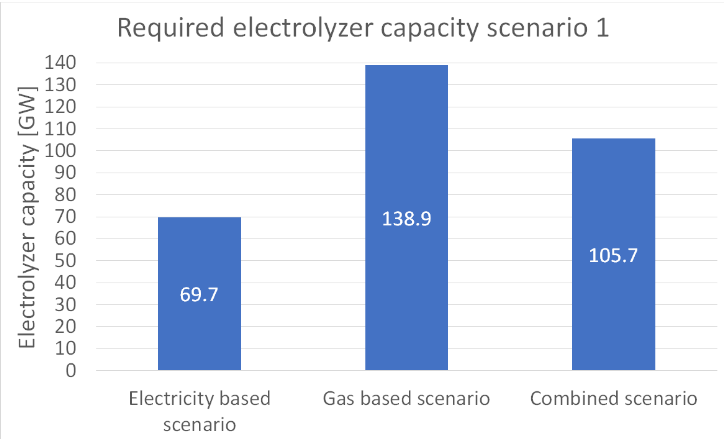


Figure 6.5: Required electrolyzer capacity for the first production scenario in the electricity based scenario, gas based scenario and combined scenario.

When looking at electrolyzer capacity (fig. 6.5), least capacity is required for the electricity based scenario, most capacity is required for the gas based scenario, and the combined scenario requires a capacity that is in between the two extremes. In the electricity based scenario, 69.7 GW of electrolyzer capacity is required. The eventual demand for hydrogen is lower than for the other two systems, reducing the amount of hydrogen that needs to be produced. In the gas based system, all electricity generated needs to be converted into hydrogen, requiring 138.9 GW of electrolyzer capacity. The combined system requires 105.7 GW of electrolyzer capacity in this scenario. This is a lot less compared to the gas based system because a lot of the generated electricity can directly be used to fulfil the electricity demand, and does therefore not need to be converted into hydrogen. This also reduces the final hydrogen demand for CCGTs. Still, there is a high hydrogen demand that needs to be fulfilled, because the heat demand is fulfilled using hydrogen boilers. Due to this, the electrolyzer capacity is high compared to the electricity based system.

6.2 Scenario 2

In scenario 1, offshore wind, onshore wind, and solar PV are installed as 55%, 10% and 35% of the total production capacity respectively. Wind speed patterns of 2014 are used.

6.2.1 Production capacity

With the new capacity ratios, a new production scenario is created for each system scenario. The resulting required capacities of offshore wind, onshore wind and solar PV are shown in figure 6.6.

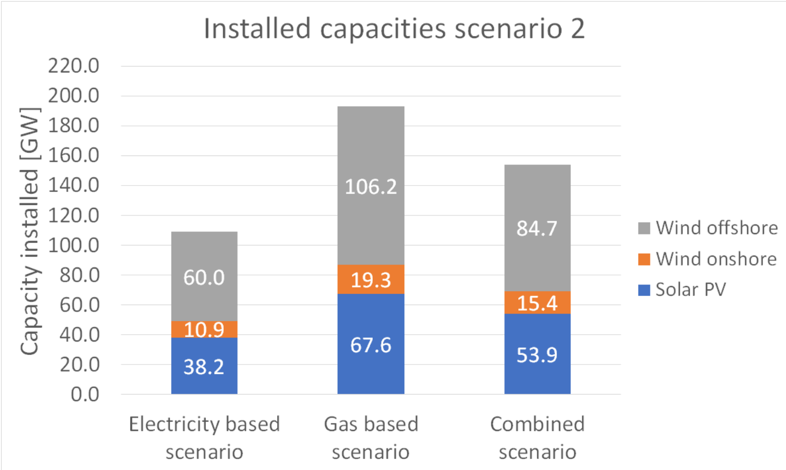


Figure 6.6: Installed offshore wind, onshore wind and solar PV capacities for the three system scenarios for the second production scenario.

In the second production scenario, the ratios between offshore wind, onshore wind and solar PV capacities were changed to 55%, 10% and 35% respectively. The goal of this change in ratios was to decrease the required storage capacity, by decreasing seasonal fluctuations in electricity generation. When looking at the required production capacities in this scenario, also a decrease in total required production capacity is found, compared to production scenario 1. For the electricity based scenario, the total required production capacity decreased from 123.7 GW in scenario 1 to 109.0 GW in scenario 2. For the gas based scenario, the necessary production capacity decreased from 219.6 GW in scenario 1 to 193.0 GW in scenario 2. For the combined system, the required production capacity decreased from 175.5 GW in scenario 1, to 154.0 GW in scenario 2. For all three system scenarios this comes down to a decrease in required capacity of about 88%. From this, we can learn that in the Netherlands wind energy is more efficient than solar PV when looking at required installed capacity. Solar PV production is restricted to periods of daylight. This means that during the night, solar PV will not produce any electricity. In the Netherlands, during the winter, the number of hours with daylight decreases. This limits the electricity generation of solar PV even more. Wind turbines are not affected by this daylight restrictions and can also produce electricity during night time. Due to this, the required installed production capacities reduce for a system that is more relying on wind turbine production.

For production scenario 2, the relations between the electricity based, gas based and combined scenario did not change compared to production scenario 1. Still, the electricity based scenario is most efficient, the gas based scenario is the least efficient, and the combined scenario is in between the two extremes. The same explanation holds for this as in production scenario 1.

6.2.2 Hydrogen storage

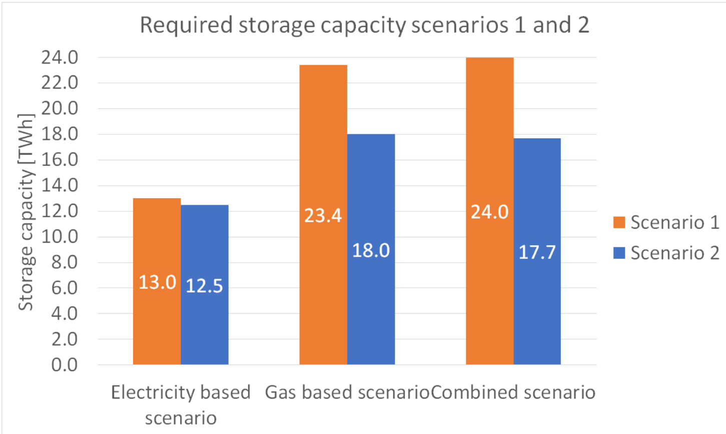


Figure 6.7: Required storage capacity for the first and second production scenarios in the electricity based scenario, gas based scenario and combined scenario.

The goal for changing the ratios of offshore wind, onshore wind and solar capacities was to decrease the required storage capacity. Figure 6.7 shows how the required storage capacities for scenarios 1 and 2 compare. Indeed, a decrease in required storage capacity is found for all three system scenarios.

Figure 6.8 shows the charge state of the hydrogen storage throughout the year for production scenarios 1 and 2 for the gas based scenario. This is shown as an example, to illustrate how the changed production scenario leads to a reduction in required storage capacity. Especially around hour 5800 it can be seen that the peak in stored hydrogen is reduced. The graphs for the electricity based scenario and the combined scenario can be found in appendix E.

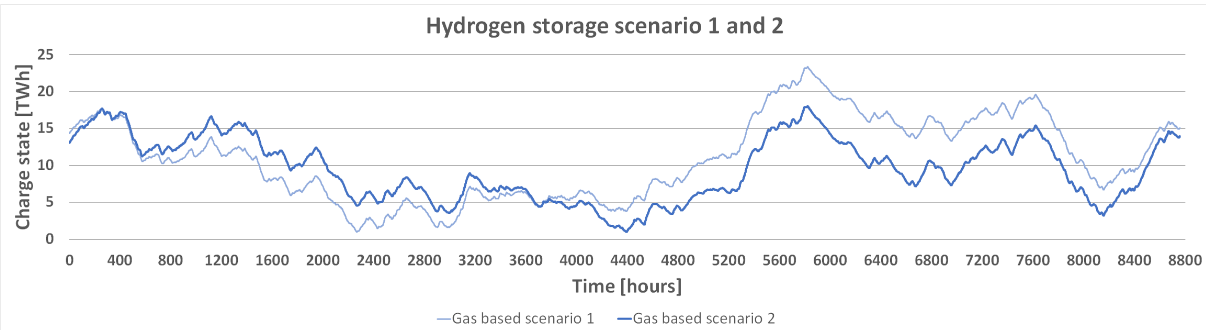


Figure 6.8: The charge state for the gas based scenario with the first and second production scenario, indicating the amount of hydrogen that is stored in the storage during every hour of the year.

For the electricity based scenario, the difference in required storage capacity is very small (fig. 6.7). 13.0 TWh of required storage capacity in production scenario 1 decreases to 12.5 TWh of required storage capacity in production scenario 2. In the electricity based scenario, the seasonal fluctuation in production scenario 1 is less strong compared to the gas based and the combined system. This can be seen in figure 6.3. This is caused by the high efficiency of the electric heat pumps, decreasing the impact of the heat demand. Because the seasonal fluctuation is already less strong in production scenario 1, the effect of decreasing the seasonal fluctuation in production scenario 2 is less visible.

For the gas based scenario, the required storage capacity decreases from 23.4 TWh to 18.0 TWh. For the combined scenario, the required storage capacity decreases from 24.0 to 17.7 TWh. This is a decrease of 26.6% for the gas based scenario, and 23.1% for the combined scenario. The difference between the change in these two system scenarios is due to the change in the electricity generation pattern. Because in the combined scenario, part of the electricity demand is directly fulfilled without conversion to hydrogen, the system becomes more efficient when the electricity demand and supply pattern are better matched. This reduces the required storage capacity even more.

When comparing the three system scenarios for production scenario 2, still the electricity based scenario requires least storage capacity. Also, the required storage capacity for the gas based scenario is still approximately equal to that of the combined scenario.

6.2.3 CCGT capacity

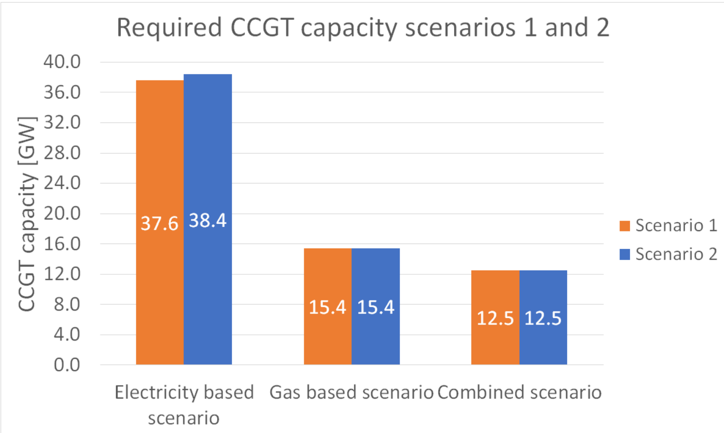


Figure 6.9: Required CCGT capacity for the first and second production scenarios in the electricity based scenario, gas based scenario and combined scenario.

For the CCGT capacity, not a lot changes when production scenario 2 is compared to production scenario 1. The required capacity is determined by the peak in electricity demand that needs to be fulfilled by the CCGT. In the electricity based scenario, the increase in required capacity is due to an incidental mismatch in energy supply and demand. A few hours of low energy production coincide with high energy demand. In the gas based scenario, the CCGT electricity production is not related to the electricity production pattern. Since all energy is first converted into hydrogen, all electricity demand needs to be fulfilled by the CCGT production. The CCGT capacity is then only determined by the peak electricity demand, and is not changed by the change in production pattern. In the combined scenario, part of the electricity demand is already delivered form solar PV or wind production. In this case, the peak CCGT production is caused by an hour with no electricity production. Changing the installed capacities, as is done in scenario 2 compared to scenario 1, does not increase the electricity production if there is no sun and no wind. Because of this, the required CCGT capacity does not change here.

6.2.4 Electrolyzer capacity

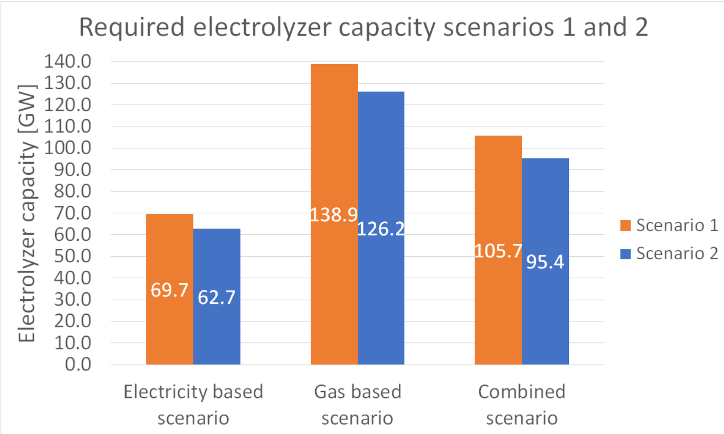


Figure 6.10: Required electrolyzer capacity for the first and second production scenarios in the electricity based scenario, gas based scenario and combined scenario.

For all three system scenarios, the required electrolyzer capacity decreases a bit. The decreased mismatch between energy supply and demand causes a decrease in the production of hydrogen surpluses. More electricity is produced during hours of high demand, and less electricity is produced during hours of low demand. Additionally, because lower production capacities are needed to supply all required energy, the peaks in electricity production are less high. The observed effect is similar for all the system scenarios.

6.3 Scenario 3

In scenario 3, offshore wind, onshore wind, and solar PV are installed as 55%, 10% and 35% of the total production capacity respectively. Installed capacities are equal to scenario 2. Wind speed patterns of 2015 are used.

Since the installed capacities for offshore wind, onshore wind and solar PV are left unchanged compared to scenario 2 (fig. 6.6), these are not shown again. However, required storage capacity, electrolyzer capacity and CCGT capacity do change due to the changed wind pattern in scenario 3. Figures 6.11 to 6.14 compare the required capacities for scenarios 2 and 3.

6.3.1 Hydrogen storage

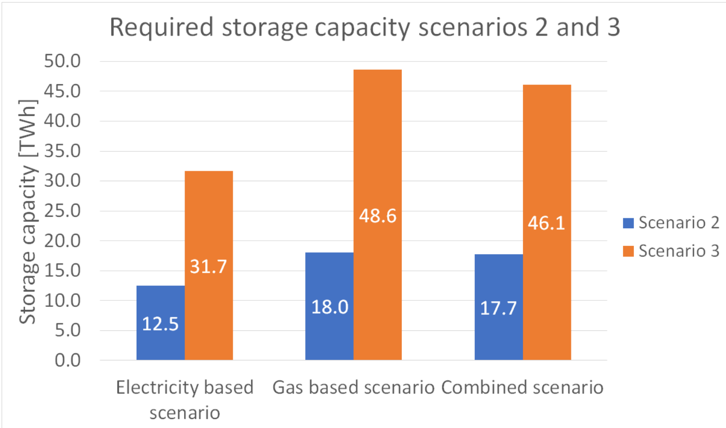


Figure 6.11: Required storage capacity for the second and third production scenarios in the electricity based scenario, gas based scenario and combined scenario.

With the change in wind pattern, the required hydrogen storage capacity increases significantly. For the electricity based scenario, the required storage capacity increases by 154%. For the gas based scenario, the required storage capacity increases by 170%. The required storage capacity of the combined scenario increases by 160%. The change is the largest for the gas based scenario, because in this system all generated electricity is converted into hydrogen and send to the storage. In the electricity based scenario and the combined scenario, part of the additional electricity that is generated can be directly used to fulfil the electricity demand. In the electricity based system, the electricity demand is higher because it includes the electricity demand from heat pumps as well. Because of this, a larger part of the extra produced electricity can be directly used. This explains the difference in increased required storage capacity for the system scenarios.

The increase in required storage capacity can be illustrated by looking at the amount of hydrogen saved in the storage throughout the year. As an example, the behavior of the hydrogen storage for the gas based scenario is shown in figure 6.12. The graphs for the electricity based scenario and the combined scenario can be found in appendix E. From figure 6.12 one can see that with the installed capacity and the new wind pattern, more hydrogen is produced than consumed. By the end of the year, the storage contains much more hydrogen than at the start of the year. The production capacities were fine tuned to match the wind pattern of 2014. Figure 6.12 shows that during a year with higher average wind speeds, this would lead to large hydrogen surpluses. From this figure one can also see that the hydrogen production in scenario 3 is lower during the first 2800 hours of the year. The amount of hydrogen stored decreases faster in scenario 3 compared to scenario 2. This is important to note, because it indicates that the differences in yearly production patterns can be large. When designing a reliable energy system, this must be taken into account. To ensure a reliable energy system, enough hydrogen must be available during all times.

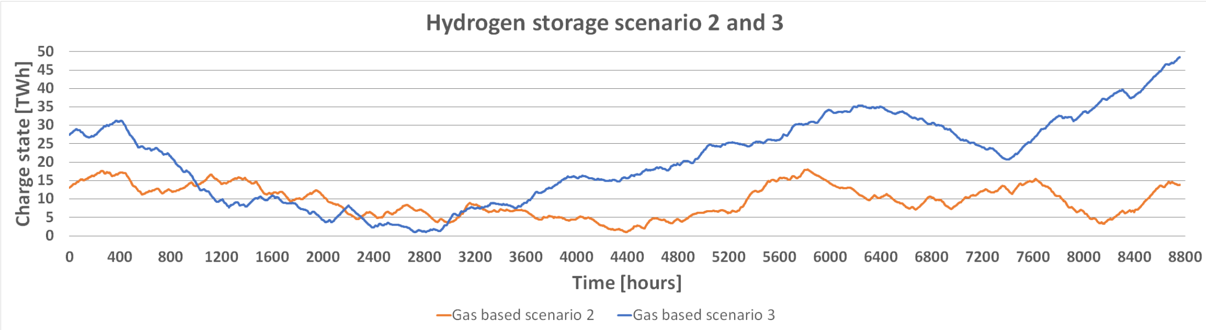


Figure 6.12: The charge state for the gas based scenario with the second and third production scenario, indicating the amount of hydrogen that is stored in the storage during every hour of the year.

6.3.2 CCGT capacity

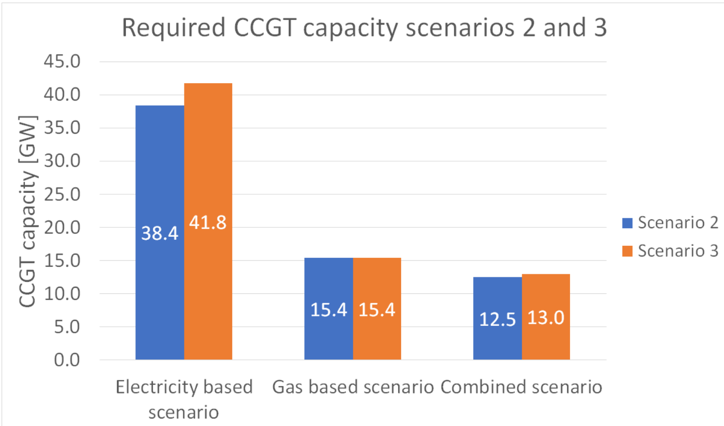


Figure 6.13: Required CCGT capacity for the second and third production scenarios in the electricity based scenario, gas based scenario and combined scenario.

The CCGT capacity for the three system scenarios does not change a lot for scenario 3, compared to scenario 2. In the electricity based and the combined scenarios, the required capacities increase a little bit. Compared to scenario 2, the energy production in scenario 3 is a less good match to the energy demand. During some hours with high demand, less electricity is generated. This causes a higher required CCGT capacity. In the gas based scenario the CCGT capacity remains the same, because it does not depend on the production pattern, as explained in the previous section.

6.3.3 Electrolyzer capacity

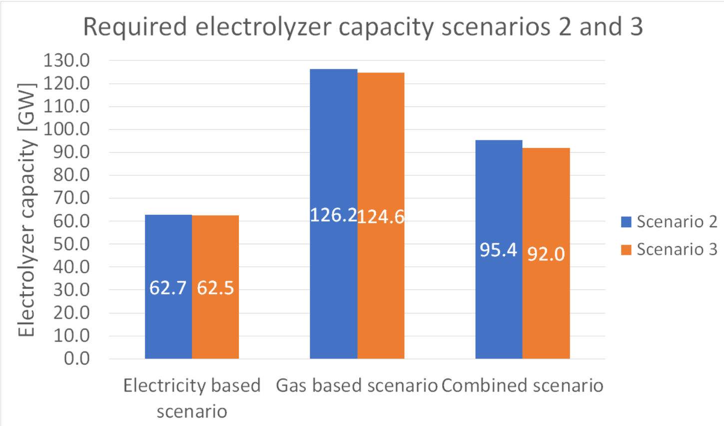


Figure 6.14: Required electrolyzer capacity for the second and third production scenarios in the electricity based scenario, gas based scenario and combined scenario.

In scenario 3, the electricity production peaks are a bit reduced compared to scenario 2. This leads to a slight reduce in the required electrolyzer capacity. This is caused by incidental differences in fluctuations rather than fundamental differences in the scenarios. In the wind pattern that is used in scenario 3, fewer outliers with high wind speeds appear.

6.4 Qualitative comparison

To create an overview of the requirements for the different system scenarios, a qualitative comparison is done. For this comparison, offshore wind, onshore wind and solar PV capacity are included as one category, called electricity generation. Next to required electricity generation, also required hydrogen storage capacity, CCGT capacity, electrolyzer capacity and required electricity grid extension are compared. For each technology, the electricity based scenario, gas based scenario and combined scenario are compared. The scenario that requires least capacity is labeled green, the scenario that requires most capacity is labeled red, and in between, a scale is defined as explained in section 2.2 of chapter 2. If the required capacities for two scenarios are close to each other, as indicated by the defined scale, they are given the same label. The given labels did not change for the different production scenarios that were analyzed. Figure 6.15 shows the overview that is created. For grid extension, no quantitative values were analysed. Based on reasoning it is only determined which of the systems requires most, least and intermediate extension of the grid.

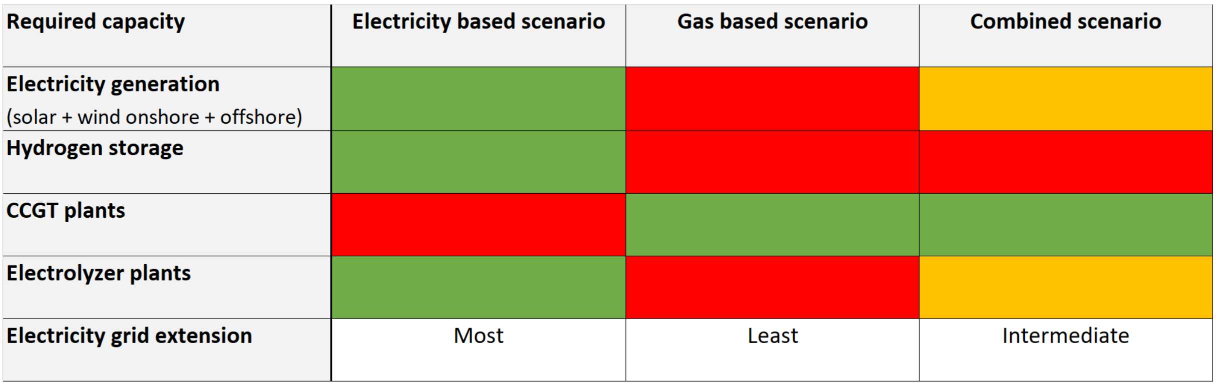


Figure 6.15: Qualitative comparison of the required capacities for electricity production, hydrogen storage, CCGT plant capacity, electrolyzer plant capacity and required grid extension.

When looking at the qualitative comparison, it stands out that the electricity based scenario has the most green labels, and the gas based system has the most red labels. This reflects the overall efficiency of the scenarios. However, the impact of each of the labels is not known. Also, the requirements for grid extension are not quantified, and only based on reasoning. For each of the labels, the financial and environmental impact must be understood as well, before a final conclusion can be drawn on which scenario is most favorable.

6.5 Spatial requirements

In the sections above, the necessary capacities of technologies for the different system scenarios using different production scenarios are compared. Based on these required capacities, the spatial requirements can be estimated as well. In the before mentioned research executed by CE Delft [14], estimates were done for spatial requirements of offshore wind, onshore wind, solar PV and electrolysis plants. The results of this research are used to calculate what the spatial requirements would be for the electricity based scenario, gas based scenario and combined scenario, using production scenario 2. Table 6.1 presents an overview of the results of this analsyis. The spatial requirements for CCGT plants and storage are not included in the tables, since no estimates of spatial requirements for these technologies could be found.

Table 6.1: An overview of the installed capacities and the associated land area that is required for this, based on the results of production scenario 2.

	Electricity based		Gas based		Combination	
	Capacity [GW]	Area [km^2]	Capacity [GW]	Area [km^2]	Capacity [GW]	Area [km^2]
Wind offshore	60.0	8,762	106.2	15,514	84.7	12,379
Wind onshore	10.9	1,635	19.3	2,895	15.4	2,310
Solar PV	38.2	409	76.6	724	53.9	578
Electrolysis	62.7	50	126.2	101	95.4	76
Total area		10,856		19,234		15,343

When comparing the three systems in this way, one can see that the spatial requirements are lowest for the electricity based system, highest for the gas based system, and in between for the combination system. To give some more context to the spatial requirements, the numbers are divided by the available surface area of the Netherlands. The total land area of the Netherlands covers 33,690 km^2 [58], and the total North Sea area of the Netherlands covers 59,000 km^2 [57].

Table 6.2: Percentage of the North Sea area of the Netherlands covered by offshore wind turbines and the percentage of the land are of the Netherlands covered by onshore wind turbines, solar PV and electrolyzer plants for the different system scenarios, assuming production scenario 2.

	Electricity based Area covered [%]	Gas based Area covered [%]	Combination Area covered [%]
North Sea area Netherlands	14	26	21
Land area Netherlands	6	11	9

Chapter 7

DISCUSSION AND CONCLUSION

This section will start out with a further discussion of some of the results that were found in the last chapter. Additionally, a critical look will be taken at this research itself. Assumptions that were made that may have significantly affected the results are discussed. This also leads to some suggestions for further research, that would lead to a more complete understanding of the system. The chapter ends with a summary of the final conclusions.

7.1 Interpretation of the results

7.1.1 CCGT capacity combined scenario

For each of the production scenarios, the required CCGT capacity is shown in the results. According to these results, the combined scenario requires less CCGT capacity than the gas based scenario. However, to make the energy system more reliable, also in the combined scenario the CCGT capacity should be able to fulfil all electricity demand during peak load hours. It could happen that during hours of peak electricity demand, wind turbines and solar panels cannot produce electricity, due to unfavorable weather patterns. In this situation, the energy system must still be able to fulfil all electricity demand. Because of this, the combined scenario would require a CCGT capacity similar to that of the gas based scenario.

7.1.2 Impact weather patterns

Scenario 3 analyzed the impact of changing the weather pattern on the system. It is found that a weather pattern from a different year can lead to different requirements for the energy system. An energy system that is designed to function under average weather conditions does not guarantee a balanced energy system under different weather conditions. This is mostly visible in storage capacity requirements. There is no big change in the requirements for CCGT and electrolyzer capacity. These results emphasize the fact that sufficient storage capacity is very important for the system to function also under exceptional circumstances. This increases the difficulty to realize such a system. Also, it increases the cost, because the high storage capacity will only be used incidentally. In some cases, import or export of electricity or hydrogen might be a solution. This is outside the scope of this research, but could be interesting for future research.

7.1.3 Production capacities

As explained in section 5.2.1 in chapter 5, the initial ratios that were determined for the renewable production capacities, were based on existing scenario studies. When looking at the required production capacities that are found in this research, and comparing these to the scenarios by CE Delft [14], the required renewable production capacities in this research are much higher. In the CE Delft scenarios, the required capacity varies from 28 GW to 126 GW. The scenarios by CE Delft however, include some aspects that were left outside the scope of this research. For example, battery storage is included, increasing system efficiency, and reducing required renewable production capacities. Also, the transport sector is included in the CE Delft research. This adds an energy demand sector, but also offers possibilities for energy storage. However, next the the renewable production capacities, also green gas and biogas are used as energy sources, and the use of fossil fuels is not completely excluded. In some of the CE Delft scenarios, CCS is included. These different aspects can contribute to understanding the difference in required generation capacities.

7.1.4 Qualitative comparison

Figure 6.15 shows the labels that were assigned to each system scenario for the different technology capacities. This overview shows the differences between the system scenarios based on capacity requirements. However, for a more fair comparison between the different technologies, the different technologies could be assigned a weight to measure their impact with respect to the complete system. When realizing an energy system, aspects like technology cost, environmental impact or spatial requirements also need to be included. If all these aspects are included, a more fair comparison can be done.

7.1.5 Spatial requirements

The spatial requirements as presented in table 6.1 show what percentage of the surface area of the Netherlands would be taken up by energy related technologies in the system scenarios. The social acceptance of the scenarios is expected to be related to the land area that will be taken up by these technologies. If more land area is covered, social acceptance will decrease. Based on this, for the gas based scenario, most social resistance can be expected. The electricity based scenario is expected to be most easily accepted.

7.2 System boundaries

7.2.1 Transport sector

For this research it was chosen to focus on using hydrogen to replace the current functions of natural gas. In choosing these system boundaries, some aspects fell outside the scope, that would actually be interesting to include to get a more complete overview of the energy sector. Expanding the system boundaries may lead to new insights and conclusions. For example developments in passenger and goods transport technologies lead to increased electricity and hydrogen demand. Electricity driven cars have been on the market for many years, and different projects are experimenting with buses fuelled by hydrogen [59]. Including these energy demand patterns in the system boundaries may lead to different energy system requirements.

7.2.2 Biofuels

It was chosen for this research to not include the use of biofuels. Biofuels are fuels that are produced from biomass, which can be any type of plant or animal material. Because use of biomass requires a lot of land area and may compete with food production, this is not always considered a sustainable solution. Also, because biofuels can be produced from a wide variety of materials, like waste, it involves more complexity to the system. Because of this, it was decided to leave the use of biofuels outside the system boundaries.

7.2.3 Import and export

In this research the focus was on finding alternatives for natural gas in the Netherlands based on domestic, renewable energy production. Therefore, export and import of electricity or hydrogen were not included in the research. However, if in the future the use of hydrogen as an energy carrier would increase in the Netherlands as well as in surrounding countries, trading hydrogen could be a potential way to get rid of hydrogen surpluses or solve hydrogen shortages. Even trade on a global scale could offer opportunities [60]. Trading on a global scale could also help overcome seasonal fluctuations in supply, due to global differences in climate and seasons.

7.2.4 Grid capacity

To transport electricity or hydrogen from one point to another, an electricity grid or a gas grid is required, that can carry a certain amount of energy per time unit. This grid capacity was assumed to be infinite for this research, so that any amount of energy could be transported instantly and in unlimited amounts from one technology to the next. When an energy system is to be actually realized, grid capacities do need to be taken into account. Based on this, gas pipelines need to be adapted to allow for carrying hydrogen, and electricity grid capacities may need extension.

7.2.5 Time range

Balancing an energy system on an hourly basis does not automatically mean that it will also function properly on a minute or second basis. The impact of activities that require a lot of energy in a very short time, say a couple of minutes, will be attenuated because the energy demand is averaged over the hour. Because of this, an hourly analysis may give a distorted result. Doing a minute or second based analysis however, requires demand patterns and weather patterns for this time scale as well as strong modelling programs that are capable of dealing with an increased amount of data points. For this research, these were not available.

7.3 Technologies

7.3.1 Hydrogen storage capacity

As explained in chapter 3, the estimated potential hydrogen storage capacity in salt caverns in the Netherlands is 34.6 TWh. In the analysis of the different scenarios, the maximum storage capacity was set to a higher number. This was done to be able to find out what the required storage capacity would be if the potential was unlimited, for a more complete understanding of the system dynamics. For most of the scenarios, the required storage capacity is well below 34.6 TWh. Only in scenario 3, with higher average wind speeds resulting in overproduction of hydrogen, more storage capacity is required. In such a situation, export might offer a solution. Also, other storage techniques might be used to add to the available storage capacity.

7.3.2 Solar panel tilt

To optimize the electricity output, solar panels are usually installed with a certain tilt. Sun rays reach the surface of the Netherlands under a certain angle. If solar panels are tilted so that the sun rays come in at an angle closer to 90°, the electricity yield increases. This was not included in the model for this research. By neglecting this aspect, the production of solar panels in the model is expected to give a lower output than if the tilt would have been optimized.

7.3.3 Use of constants

When the model was built, assumptions had to be made to allow for easy use and transparent modelling. Some examples of assumptions that were made are a constant inverter efficiency of solar panels, a constant production efficiency for electrolyzer plants, and ignoring the start-up and shut-down time of the electrolyzer. For the purpose of this research, it was not deemed necessary to make more accurate calculations, since this would require a disproportional investment of additional time.

7.3.4 Heat pump correction factor

For the heat pump, as explained in chapter 3, a correction factor of 0.2 was chosen, to compensate for lost efficiency in buildings that are not suitable for heating by heat pumps. This number was chosen as an educated guess. Although this approach corrects for the efficiency loss, the changes in electricity and hydrogen demand are not accounted for. For a more accurate analysis of the heat demand pattern, a combination of heat pumps and boilers should be included in the model. This would give a better representation of reality.

7.3.5 Battery storage

An alternative method to store electricity is battery storage. Batteries have a higher round trip efficiency than hydrogen storage. Depending on the type of battery, efficiencies can go up to 90% [61]. Compared to hydrogen, batteries have a high self-discharge rate, meaning that the longer energy is stored in the battery, the lower the final energy output will be. This makes batteries less suitable for long-term energy storage. For day-night storage however, batteries could be a suitable solution. To increase the overall system efficiency, hydrogen storage for seasonal fluctuations could be combined with battery storage for day-night fluctuations. This would also create more storage capacity and reduce the required electrolyzer capacity.

7.3.6 Future efficiency improvement

The scenarios that are used in this research are for hypothetical situations that may lie far ahead in the future. Because of this, it is difficult to foresee how technologies will have developed by that time. Technology efficiencies may have risen significantly, but to what extent this will actually happen is uncertain. Also, new technologies may come into play. In the research, the used technologies are either already used in practice, or seem promising in their development.

7.3.7 Fuel cells

Instead of using a CCGT and boiler running on hydrogen, it is also possible to use fuel cell technologies. Fuel cells can convert hydrogen to electricity in a more direct way. By using two electrodes and an electrolyte, the chemical energy can be harvested from the hydrogen and directly converted into electricity, producing water as only reaction product [62]. In theory this conversion is more efficient than CCGT conversion, since the conversion steps to heat and mechanical energy are skipped. However, currently fuel cells efficiencies do not exceed efficiencies of CCGT plants [63]. Since currently existing CCGT power plants can be transformed into plants running on hydrogen [43], it was decided to stick with using CCGT in this research.

For residential heating, fuel cells can be used in combined heat and power (CHP) technology. The fuel cell generates electricity with the recovery and use of the by-product heat. Although the overall efficiency of such a system can reach to 80%, the thermal efficiency is generally no more than 55% [63]. Also to keep the complexity of the model low by separating heat and electricity production, it was decided to not include fuel cell CHP production.

7.4 Other assumptions

From the sensitivity analysis it was found that the impact of some of the model variables are relatively high. Because a high percentage of electricity generation is coming from offshore wind turbines, changing the weather pattern has a large impact on the model outputs. This impact is also increased by the fact that only two different weather patterns are used. In practice every location experiences different wind speeds, leading to different generation patterns. This simplification might lead to unrealistic results. The same holds for the weather patterns for onshore wind and solar PV. The overall impact of these technologies is lower since the capacities are lower, but including more weather patterns for different locations would give a more representative output.

Also the electrolyzer and storage efficiency for the gas based scenario have a relatively large impact on the model outputs. More precise data on electrolyzer and storage efficiency are not yet available, but the large impact of these technologies must be kept in mind when looking at the results.

The demand patterns in this research were based on energy demand patterns in 2015. Possible energy savings were included in the scenarios, but the fluctuating pattern was kept constant. Since 2015, use of electric vehicles and heat pumps has already increased. This affects the demand patterns. Also in the future, these fluctuations are expected to change, due to changes in used technologies. For example, efficiencies of household appliances change, new appliances will be used, other appliances may not be used anymore, and insulation of houses may decrease heat demand patterns. Also, smart demand systems could manage energy demand so that it better matches the energy supply. For example, dishwashers or washing machines would switch on during the day when solar irradiance peaks. This could lead to a change in energy demand patterns that was not included in this research.

The weather patterns that are used are not all coming from the same year. For wind speed, in production scenarios 1 and 2, weather patterns from 2014 are used. The patterns for energy demand, solar irradiance and temperature are based on 2015. It was assumed that the wind pattern was not related to the solar irradiance and temperature patterns. However, in reality the solar irradiance and wind speed could be related.

For the gas demand from industry it was assumed that the demand for natural gas could be directly substituted by a demand for hydrogen. This is a very rough assumption, because natural gas is used for different purposes and hydrogen cannot always be used as a direct replacement. In industry, part of the natural gas that is consumed nowadays, is used for production of hydrogen. If hydrogen is delivered to industry instead of natural gas, within the industry sector, this conversion step from natural gas to hydrogen is no longer necessary. However for other industrial processes, natural gas may be needed. If hydrogen is delivered to industry, methanation of hydrogen would be required, introducing additional conversion steps. Also, the demand pattern for gas from industry that was used includes gas consumption of power plants. In the model, all electricity demand was already fulfilled by the production of renewables and the CCGT production. This leads to an overlap in electricity production, both by the CCGT and in industry. This means that in the modeled scenarios, the gas consumption from industry is higher than it would be in real life.

7.5 Conclusion

Despite the set of critical remarks, this research gives an insight in the differences between three system scenarios for the Netherlands. In most of the compared aspects, the differences are very obvious and can be understood by further looking into the system dynamics. For the scenarios that are analyzed in this research it is shown that technically it is possible to generate enough renewable electricity to fulfil all energy demand in the Netherlands, by making use of hydrogen for energy storage. The three system scenarios were compared to each other based on required installed capacity of renewables, storage capacity, CCGT capacity and electrolyzer capacity.

It is found that the electricity based scenario is most efficient based on required capacity of renewable energy sources, storage capacity and electrolyzer capacity. In this system, heat pumps are used for domestic heating, and only electricity surpluses are converted to hydrogen for storage. This leads to lower space requirements and lower costs for realizing the required capacities. However, such a scenario would also require extension of the electricity grid, which is expensive to realize. Also for this scenario the highest amount of CCGT capacity is necessary, to fulfil heat and electricity demand during cold days with low electricity generation.

The gas based scenario is least efficient when looking at required capacity of renewable energy sources, storage capacity and electrolyzer capacity. All generated electricity is converted into hydrogen, which is associated with high conversion losses. Also a lot of space is required for installing high capacities of offshore- and onshore wind parks and solar PV fields. Since all generated electricity is converted into hydrogen, the highest electrolyzer capacity and hydrogen storage capacity are needed. In this scenario, domestic heating will happen using boilers running on hydrogen. This allows for hydrogen transport through gas pipelines and avoids the need for electricity grid extension. The needed CCGT capacity is lower than for the electricity based scenario.

The required capacity of renewable energy sources for the combined scenario is higher than for the electricity based scenario, but lower than for the gas based scenario. To connect all generated electricity to the electricity grid, extension of the grid is necessary. However, domestic heating happens using hydrogen boilers, so transporting the energy for heating to buildings can happen via the gas grid. This reduces the total required grid extension. Also the needed electrolyzer capacity is in between the other two systems. Not all electricity needs to be converted into hydrogen, as for the gas based scenario. Still more hydrogen needs to be produced compared to the electricity based scenario, because of the hydrogen demand for heating. To be able to fulfil all heat demand during cold winter days, the needed hydrogen storage capacity is just as high as for the gas based scenario. To ensure a reliable electricity supply, the same CCGT capacity is required as for the gas based scenario.

In all systems, to fulfil all energy demand, large investments in renewables are needed. Also a good balance between installed wind- and solar PV capacities is necessary. Solar PV electricity generation shows a strong seasonal fluctuation, that leads to the need for more hydrogen storage. Since the available storage capacity in the Netherlands is limited, this must be taken into account.

When looking at the results of this research together with developments that are already happening, a system where all electricity is converted into hydrogen seems very unlikely. First of all, the low efficiency of the gas based scenario leads to high costs for renewable energy generation capacities. Also, the high required generation capacities lead to a large coverage of the surface area in the Netherlands. This makes this scenario less likely to be socially accepted. Furthermore, electrification is already happening in different sectors, like domestic heating and transport. Because renewable energy sources often produce electricity, electrification of the energy system seems to be a logical step. Additionally, the high efficiency of electric heat pumps are a big advantage that should not be neglected. The energy system to aim for should probably be a compromise between the electricity based scenario and the combined scenario. With the ongoing electrification, extension of the electricity grid is already a likely requirement to support a future energy system. Given the high efficiency advantages, this seems like a reasonable investment. Hydrogen could be used for storage, for industrial purposes and for heating buildings that are not suitable for heat pump heating. This would reduce the pressure on the electricity grid and allow for low-emission gas use in sectors that are not suitable for electrification. However, to be able to decide what system would be best to realize, additional financial, environmental and social analyses are necessary. These analyses could tell us more about the cost of the different systems, the environmental impact of the required installed capacities of different technologies and grids, and the perspective of people towards the technologies and change of land use.

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APPENDIX A: Wind turbine power curves

Two different turbine types were included in the model, namely one onshore wind turbine, and one offshore wind turbine. For construction of these two sub modules, information was gathered about currently existing types of wind turbines. Wind-turbine-models.com published a database containing technical information about many different types of wind turbines from different manufacturers [24]. It was chosen to use 5 MW wind turbines for onshore wind parks, and 10 MW wind turbines for off-shore wind parks. For the 5 MW onshore wind turbine, an example power curve could be found for the Multibrid M5000 turbine (fig 7.1a). The following power curve was used in the model:

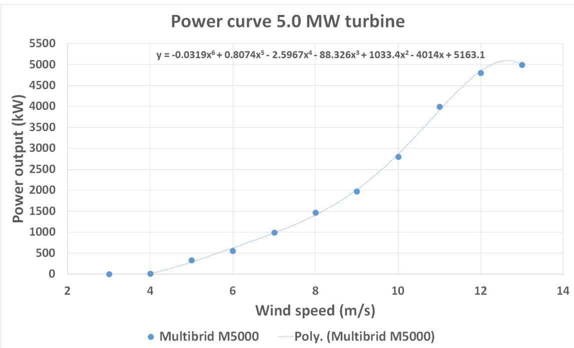
$$y = -0.0319x^6 + 0.8074x^5 - 2.5967x^4 - 88.326x^3 + 1033.4x^2 - 4014x + 5163.1 \quad (7.1)$$

The start speed for this power curve is 4 m/s, the rated speed 12 m/s, and the cut-off speed 25 m/s. The hub height was assumed to be 110 m.

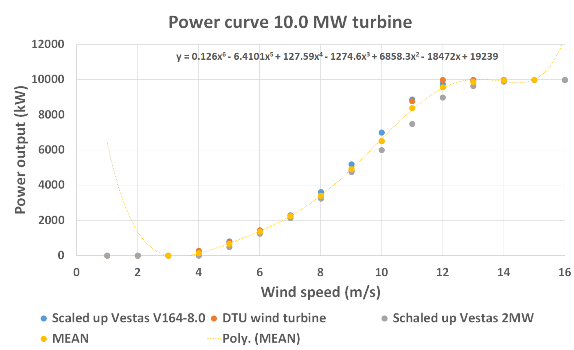
For the 10 MW offshore wind turbine, not one example power curve was found from the same reference. Instead, power curves of a 2 MW and an 8 MW turbine were scaled up, and a 10 MW power curve from a different reference was used. The average power curve resulting from these three curves was used for the 10 MW turbine (fig 7.1b).

$$y = 0.126x^6 - 6.4101x^5 + 127.59x^4 - 1274.6x^3 + 6858.3x^2 - 18472x + 19239 \quad (7.2)$$

The start speed for this power curve is 4 m/s, the rated speed 13 m/s, and the cut-off speed 25 m/s. The hub height was varied in the different scenarios, between 130 and 150 m. For both the offshore and onshore wind sub modules, the measurement location height and the roughness length have to be determined per measurement location.



(a) 5 MW power curve



(b) 10 MW power curve

Figure 7.1: Figures show the trends fitted to power curve data points for a 5 MW and a 10 MW wind turbine.

APPENDIX B: Verification and validation details

Extreme condition test

When the total heat and electricity demand are set to zero, the output NLS's reflect only the effects of generating electricity, electrolysis and hydrogen storage. This results in NLS's of zero for the first part of the year, and in a surplus of hydrogen after the hydrogen storage has been filled till its maximum capacity.

For the heat pump, if the Carnot efficiency is set to zero, the electricity consumption is zero while the model does provide the demanded heat to the system. This is not a correct representation of reality. In reality a Carnot efficiency of zero would result in an infinitely high electricity demand, and a "DIV/0" error in Excel. However, this was not included in the model in that way, to prevent the following situation. In case the outside temperature is warmer than the inside temperature, the calculated COP would be negative and the heat pump would function as a refrigerator. This is not how a heat pump will function in reality. To prevent the model from making this calculation, the COP is set to zero in case the outside temperature is warmer than the inside temperature. To prevent the electricity consumption from giving a "DIV/0" error in case of a zero COP, it was modeled so that the electricity consumption is equal to zero in case of a zero COP. The person using the model should be aware of this, to prevent misinterpretation of a Carnot factor of zero.

For the On- and offshore wind sheets, the amount of installed turbines and the turbine capacity were set to zero in turn. In all cases this resulted in a zero output of wind energy production.

For Solar PV, when the number of installed solar fields and the number of panels were set to zero in turn, the output also became zero. When the watt-peak power per panel was set to zero however, the output didn't become zero. This needed to be corrected in the model formulas. Before, the watt-peak power per solar panel was not included in the solar panel production formula. This was corrected, so that now if the watt-peak power is set to zero the total production results in zero. All the other variables are correctly linked in the sub model.

For the electrolyzer plants, if the amount of plants is set to zero, the output becomes either zero or a "DIV/0" error. When setting the plant capacity to zero, the output shows only zeros. When setting the electrolyzer efficiency to zero, the electricity NLS shows only "DIV/0" errors.

For the hydrogen storage, if the storage capacity is set to zero, the storage doesn't do anything and all output NLS's are equal to their input NLS. If the max. charge power is set to zero, the storage cannot recharge. It will be emptied as soon as the electricity demand adds up to more than the start state of the storage, and stay empty from that moment onward. The same happens when the charge efficiency is set to 0%. If the maximum discharge power is set to zero, the storage unit does not empty and hydrogen will be added until the storage is full. If the discharge efficiency is set to 0, a "DIV/0" error appears for the discharge loss. From here the error will appear in all following calculations and in the output NLS. In case the depth of discharge is set to zero, meaning that the storage will not discharge at all, the storage will also store hydrogen until it is completely filled up. Self-discharge is already set at 0. If it is changed to for example 1%, it is visible that the amount of energy stored goes down a bit, because part of the stored energy is lost due to leaks.

If the amount of gas turbines in the hydrogen CCGT sheet is set to zero, a "DIV/0" error appears in all columns of the model sheet. If the turbine capacity is set to zero, the CCGT production gets to zero and output NLSs are equal to input NLSs. Setting the turbine efficiency to zero results in a "DIV/0" error. This cell is also used in the storage sheet, to determine the amount of hydrogen that has to be taken out of the storage to provide the energy for the CCGT.

For the gas based model, the hydrogen boiler sheet was added and needs to be checked. A "DIV/0" error appears since the storage sheet is using the boiler efficiency to determine how much hydrogen must be discharged from the storage to be able to deliver the demanded amount of energy.

Data relationship correctness

ELECTRIC HEAT PUMP: In the electric heat pump sheet, the Carnot factor can be changed. This is now 0.2. If the value would be put to 0 there should appear a div/0 error.
If the value would be put to >0, «1, the electricity demand for heating will become really large.
If the value would be put to »1, the heat pump electricity demand will approach zero.
Electricity demand, split up in the grid demand and the electricity for heating demand, are plotted. Changes the Carnot factor should appear in these plots. All the above mentioned hypotheses about the effect of changing the Carnot factor on the electricity demand are confirmed by trying it out in the model.

OFF- AND ONSHORE WIND: The produced electricity should be linearly dependent on the amount of wind turbines installed. This number is now 6000 for 10 MW offshore wind turbines (-> 60 GW of offshore wind installed). This linear relationship was confirmed by trying out multiple numbers of installed turbines.
The power output of one turbine should show a linear relationship with the total production. Some changes were made to assure that this was the case. With these changes the power output of the turbine-total production relationship is again tested. A linear relationship is confirmed.
Also the turbine efficiency and efficiency of reformers should show a linear relation with the production. It was found that the turbine and reformer efficiency are not included in the function. The reformer efficiency was deleted from the technical inputs. The turbine efficiency is included in the wind production formula. The turbine efficiency is changed from 100% to various lower values to check for a linear relation. This linear relation is confirmed.
The start speed of the turbine and the cut off speed are changed to see the effect. The start speed cannot be set below 4. If this is done, the formula calculates higher production for wind speeds below 4, which is not correct. This number should not be a changeable variable in the model. Changing the cut off speed barely gives any change in the power output. The calculations were checked to see what the effect of the cut off speed should be. The Cut off speed always has to be higher than the Rated speed, which again always has to be higher than the Start speed, because in that order, the values are included in the formula. This makes sense since in reality this should also be the case. There is barely any change noticeable because the wind speeds are generally lower than the Cut off speed, and even lower than the rated speed.
A higher turbine height should result in a higher corrected wind speed with some logarithmic relation. The original height was 15 m.

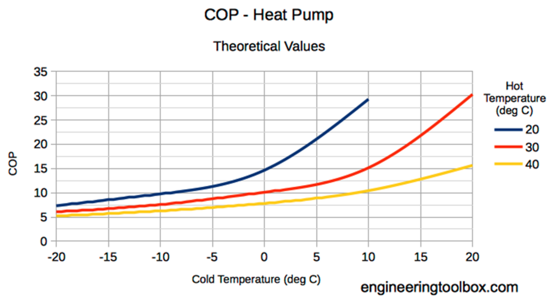
SOLAR PV: Linear relation expected between production and amount of solar fields. This relation is confirmed by trying different values in the model.
Amount of solar panels per field should also be linearly related to production. This relation is confirmed by trying different values in the model.
Relation to solar panel efficiency should be linear. Is confirmed.
Relation to inverter efficiency should be linear. Is confirmed.
Linear relation expected between production and surface area per panel. This relation is confirmed by trying different values in the model.

ELECTROLYSER SHEETS: Linear relation expected between production and amount of electrolysis plants, up until the point where the input electricity is less than the maximum plant capacity. This relation is confirmed by trying different values in the model.
Electricity consumption single unit is determined by hydrogen production single unit and efficiency. Hydrogen production single unit determined by input electricity NLS, number of plants, electrolyzer efficiency and maximum capacity.
Electricity consumption and hydrogen production total is determined by consumption/production single

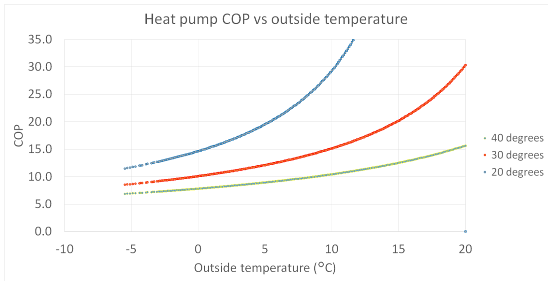
unit times number of units.

Event validity analysis heat pump

To compare the functioning of the heat pump node to a real life situation, two aspects were compared. First, the relation between the COP and the difference between the outside temperature and the hot water temperature was plotted for the model results. This plot was compared to a reference plot. The plots are shown in figure 7.2a. From the plots it can be seen that the calculations made by the model show the same relations as the reference system. From this it can be confirmed that the calculations are correctly implemented in the model.



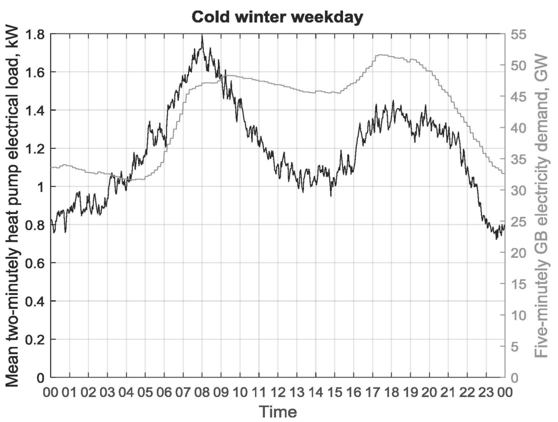
(a) Reference plot



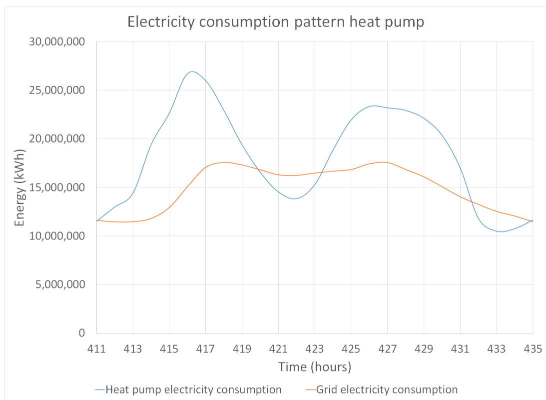
(b) Model plot

Figure 7.2: The relation between the theoretical COP and the outside temperature for different heating temperatures. The figures show the relation found from the modeled heat pump and a reference plot [64].

Next to the comparison of this COP-temperature relation, also the daily pattern of energy consumption of a heat pump on a cold winter day was compared with literature. Figure 7.3 shows this comparison. The plots show two lines, one representing the demand from the national electricity grid, and one presenting the electricity demand of heat pumps. In the reference plot [65], the electricity consumption of one single heat pump is plotted. In the model plot, the electricity consumption of all heat pumps in the Netherlands was added up. However, the two figures show a similar pattern in shape. This confirms that the heat pump module has an energy consumption that can be related to a real life situation. Also the shape of the electricity consumption looks similar. However, this is not relevant for the heat pump module.



(a) Reference plot



(b) Model plot

Figure 7.3: These plots show the electricity demand of a heat pump during a cold winter day, and the grid electricity demand of the United Kingdom. The reference plot was published by Love et al. [65]. The model plot is based on data from a random cold winter day. [64].

Event validity analysis wind turbines and solar PV

For the Wind turbine sheets, data were looked up of Dutch energy production by wind turbines. On the website "https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70960ned/table?fromstatweb" and "https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610NED/table?ts=1582731738506", data are published showing how much wind capacity was installed and how much energy was generated by this in total throughout the year. In 2018, at the end of the year 3436 MWe onshore wind capacity was installed. In this year, the normalized production of wind energy was 6578 mln kWh = 6578 GWh. To check the model, the same amount of installed capacity was given as model input, and the output was compared with the published production. If 3450 MW of wind capacity is given as input in the model, with the used wind pattern, 3033 GWh of wind energy was produced. This is about half of the measured production from statline. Can further look into where this difference is coming from. It could be the turbine height, or the location of the installed wind parks. In reality, the turbines are more spread and respond to a different wind pattern while in the model all installed turbines respond to the same wind pattern. When the turbine height is adjusted in the model to 120 m, the output generated electricity over a year is 6556 GWh. This is much closer to the real data. A wind turbine of around that height is also more realistic.

The same approach as used for the Wind turbine sheet can also be used for Solar PV production. From "https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610NED/table?ts=1582731738506" also data about solar PV production can be found. In 2018, 4522 MWe solar PV capacity was installed, and 3693 GWh electricity was generated. When 4488 MWe installed capacity / 44 solar fields is given as input in the model, the solar electricity production for the whole year is 4066 GWh. This is a bit higher than the number found from the data. The efficiencies can be adapted to correct for this. For example with a solar panel efficiency of 16.5 and an inverter efficiency of 92, the yearly production becomes 3674 GWh.

APPENDIX C: Input scenario data

Electricity demand	Demand pattern	01012015-01012016 hourly demand ** 0.8*	https://transparency.entsoe.eu/ Savings estimate based on Infrastructure Outlook Tennet Gasunie “25% base-load savings through more efficient appliances”
Heat demand	Demand pattern	01012015-01012016 hourly demand ** 0.8*	https://www.gasunietransportservices.nl/downloads-en-formulieren : column distribution Estimate based on Infrastructure Outlook Tennet Gasunie “23% low-temperature heat savings”
	Gas to heat efficiency	87.91%	Autoriteit Consument en Markt - Besluit Maximumprijs Warmte 2019
Gas demand industry	Demand pattern	01012015-01012016 hourly demand ** 0.5*	https://www.gasunietransportservices.nl/downloads-en-formulieren : column industry Infrastructure Outlook Tennet Gasunie: 60% savings due to circular industry and ambitious process innovation
Electric heat pump	Carnot factor	0.2	(2012) Zottl, Nordman, Miara - Benchmarking method of seasonal performance (heat pump systems)
	Temperature space heating water	40 °C	(2012) Staffell, Brett, Brandon, Hawkes - A review of domestic heat pumps, page 9302
Offshore wind K13	Offshore capacity	…	
	Wind pattern	K13 2014	
	Power output one turbine	10 MW	Based on existing offshore wind turbines (for example at https://en.wind-turbine-models.com/)
	Turbine efficiency	100%	Assumed that efficiency is already in power curve
	Start speed	4 m/s	From power curve
	Cut off speed	25 m/s	Desmond, Murhpy, Blonk, Haans (2016). Description of an 8 MW Reference Wind Turbine., Vestas V164-8.0 turbine from https://en.wind-turbine-models.com/powercurves
	Rated speed	13 m/s	from power curve
	Power curve	0.126*v^6 - 6.4101*v^5 + 127.59*v^4 - 1274.6*v^3 + 6858.3*v^2 - 18472*v + 19239	Desmond, Murhpy, Blonk, Haans (2016). Description of an 8 MW Reference Wind Turbine., Vestas V164-8.0 turbine from https://en.wind-turbine-models.com/powercurves
	Hub height turbine	130 m	https://en.wind-turbine-models.com/ https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine
	Measurement location height	75 m	At K13 platform See De Haij (2009)
	Roughness location	0.0002	(1983) Wieringa, Rijksoort - Windklimaat van Nederland page 157, location roughness appendix
Offshore wind Europlatform	Measurement location height	29 m	At Europlatform See De Haij (2009)
	Wind pattern	Europlatform 2014	

Onshore wind Maastricht	Onshore capacity	…	
	Wind pattern	Maastricht 2014	
	Power output turbine	5 MW	Based on existing offshore wind turbines (for example at https://en.wind-turbine-models.com/)
	Turbine efficiency	100 %	Assumed that efficiency is already in power curve
	Start speed	4 m/s	
	Cut off speed	25 m/s	
	Rated speed	12 m/s	
	Power curve	-0.0319*v^6 + 0.8074*v^5 - 2.5967*v^4 - 88.326*v^3 + 1033.4*v^2 - 4014*v + 5163.1	
	Hub height	110 m	https://en.wind-turbine-models.com/
	Height measurement location	10 m	KNMI_20200318_hourly_Maastricht2015
	Roughness location	0.05 m	(1983) Wieringa, Rijksoort - Windklimaat van Nederland page 157 location roughness appendix
Onshore wind De Bilt	Height measurement location	10 m	C:\Users\annei\Google Drive\Anne\Study\Energy and Environmental Sciences\Master Thesis\Data\KNMI_20200318_hourly (17)_Hoogeveen2015
	Wind pattern	De Bilt 2014	
Solar PV De Bilt and Maastricht	Total solar capacity	…	
	Solar pattern	De Bilt 2015	
	Solar pattern	Maastricht 2015	
	Max. output one solar field	100 MWp	https://www.powerfield.nl/ projecten/
	Max. power output of one panel	375 Wp	https://www.lg.com/us/business/solar-panels/lg-lg375a1c-v5, https://www.zonnefabriek.nl/assets/uploads/-datasheets/zonnepanelen/SunPower/SPWR-MAX3-375-BLK%20datasheet.pdf
	Solar panel efficiency	21%	https://www.lg.com/us/business/solar-panels/lg-lg375a1c-v5, https://www.zonnefabriek.nl/assets/uploads/-datasheets/zonnepanelen/SunPower/SPWR-MAX3-375-BLK%20datasheet.pdf https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/
	Efficiency of inverters	90%	Vignola, Mavromatakis, Krumsick (2007)
	Surface area per panel	1.75 m2	https://www.lg.com/us/business/solar-panels/lg-lg375a1c-v5, https://www.zonnefabriek.nl/en/our-products/sunpower-solar-panels/ 1690 x 1046: 1.77 m2
	Solar irradiation patterns:		KNMI_20200318_hourly_DeBilt2015 KNMI_20200318_hourly_Maastricht2015
Electrolyser	Amount of electrolysis plants	“unlimited”	Let this not be a limiting factor in the reference analysis

	Plant maximum capacity	20 MW	https://mcphy.com/en/our-products-and-solutions/electrolyzers/, https://www.fch.europa.eu/news/launch-refhyne-worlds-largest-electrolysis-plant-rhineland-refinery, https://constructionreviewonline.com/2019/07/uk-to-build-worlds-largest-hydrogen-electrolysis-plant-in-germany/
	Electrolyser efficiency	75%	http://www.h2data.de/, Götz, Lefebvre, Mörs et al. (2016). Renewable Power-to-Gas, A technological and economic review, Smolinka, Ojong, Garche (2015) - Hydrogen Production from Renewable Energies Electrolyzer Technologies (book chapter 8), https://mcphy.com/en/our-products-and-solutions/electrolyzers/, Blanco, Faaij(2018) - A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage Schmidt, Gambhir, Staffell, Hawkes, Nelson, Few - Future cost and performance of water electrolysis: An expert elicitation study (Appendix E)
Storage	Storage capacity	34,600 GWh	Michael Susan (2019) - Exploring the Energy Storage Capacity of Salt Caverns in the Netherlands
	Max. charge power	0.004166 * storage capacity	Crotogino et al. (2010). Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies
	Charge efficiency	90%	Makridis (2016) - Hydrogen Storage and Compression fig. 1.3, IEA (2005) - Prospects for Hydrogen and Fuel Cells, Pellow, Emmott, Barnhart, Benson (2015) - Hydrogen or batteries for grid storage A net energy analysis
	Max. discharge power	0.004166 * storage capacity	Crotogino et al. (2010). Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies
	Discharge efficiency	100%	Articles/papers don't mention a discharge efficiency, just a "storage efficiency" or a compression efficiency. Assumed decompression doesn't cost additional energy.
	Depth of Discharge	100%	Assumed that the storage capacity already takes this into account.
	Self-discharge	0	If no leaks, no self-discharge. Storage is supposed to be leak free
	Storage threshold	0	-
	Start state	…	-
H2 CCGT	Amount of gas turbines	"unlimited"	Let this not be a limiting factor in the reference analysis
	Turbine capacity	500 MW	https://www.powermag.com/ mhps-will-convert-dutch-ccgt-to-run-on-hydrogen/, Element Energy (2019) - Hy-Impact Series Study 3 - Hydrogen for Power Generation - Opportunities for Hydrogen and CCS in the UK Power Mix
	Turbine efficiency	60%	https://powerplants.vattenfall.com/ magnum, http://www.ipieca.org/resources/energy-efficiency-solutions/power-and-heat-generation/combined-cycle-gas-turbines/

			Ibrahim, Rahman, Abdalla (2011) - Optimum Gas Turbine Configuration for Improving the Performance of Combined Cycle Power Plant
H2 boiler	Efficiency	90%	https://www.energy.gov.au/sites/default/files/hvac-factsheet-boiler-efficiency.pdf, HydroGEM (2018) - Hydrogen-Powered Catalytic Boiler CCF01-2018 https://www.homeheatingguide.co.uk/efficiency-tables, https://www.accuservheating.com/blog/conventional-vs-condensing-boilers/, https://www.energy.gov.au/sites/default/files/hvac-factsheet-boiler-efficiency.pdf

APPENDIX D: Sensitivity analysis

Electricity based system

SHEET	Thing	Number	Electricity not delivered			Hours no electricity delivered	
			Normal value	-24,482	GWh	Normal value	2286 h
			Change in output for change in value			Change in output for change in value	
			+10%	-10%		+10%	-10%
Electricity demand	Electricity demand pattern		12.7	-12.2		8.3	-8.8
Heat demand	Heat demand pattern		8.6	-8.2		4.2	-4.2
Gas demand industry	Gas demand pattern		3.2	-5.7		4.7	-6.5
Electric heat pump	Carnot factor	0.3	-7.5	9.5		-3.8	4.5
	Outside temperature column		-1.5	1.5		-1.5	1.2
	Temperature space heating water	40 °C	9.0	-8.8		4.9	-4.8
Offshore wind	Installed capacity	60,000 MW	-12.9	12.1		-14.8	14.0
	Power output turbine	10 MW	0.0	0.0		0.0	0.0
	Turbine efficiency	100%	-12.9	12.1		-14.8	14.0
	Hub height turbine	130 m	-1.9	2.2		-2.0	2.3
	Height measurement location	75 m	2.0	-2.2		2.3	-2.4
	Roughness location	0.0002 m	-0.08	0.08		-0.1	0.1
	Wind pattern per hour		-23.5	30.3		-27.6	32.0
Onshore wind	Installed capacity	4000 MW	-0.1	0.1		-0.2	0.1
	Wind pattern per hour		-0.6	0.3		-0.6	0.5
	Power output turbine	5 MW	0.0	0.0		0.0	0.0
	Turbine efficiency	100%	-0.1	0.1		-0.2	0.1
	Hub height turbine	110 m	-0.08	0.05		-0.09	0.04
	Height measurement location	114.3 m	0.04	-0.09		0.04	-0.09
	Roughness location	0.05 m	0.0002	-0.0002		0.0	0.0
Solar PV De Bilt	Installed capacity	17.5 GWp	-1.2	1.3		-1.7	1.6
	Solar irradiance pattern per hour		-1.2	1.3		-1.7	1.6
	Max. power output one panel	375 Wp	1.2	-1.3		1.5	-1.7
	Solar panel efficiency	21%	-1.2	1.3		-1.7	1.6
	Inverter efficiency	90%	-1.2	1.3		-1.7	1.6
	Surface area per panel	1.75 m2	-1.2	1.3		-1.7	1.6
Electrolyser	Max. plant capacity	20 MW	0.0	0.0		0.0	0.0
	Electrolyser efficiency	70%	-5.8	4.0		-6.8	5.6
Storage	Storage capacity	34,6000 GWh	0.0	0.0		0.0	0.0
	Max. charge power	10% of storage	0.0	0.0		0.0	0.0
	Charge efficiency	90%	-5.8	4.0		-6.8	5.6
	Max. discharge power	10% of storage	0.0	0.0		0.0	0.0
	Discharge efficiency	100%??	-5.8	4.0		-6.8	5.6
	Depth of discharge	99.99%???	0.0	0.0		0.0	0.0
	Storage threshold	0					
	Start stage	0.01					
H2 CCGT	Turbine capacity	500 MW					
	Turbine efficiency	50%	-0.3	0.5		-0.5	0.6

Electricity based system

SHEET	Thing	Number	Hydrogen for industry not delivered		Hours no hydrogen delivered	
			Normal value	-70,383 GWh	Normal value	4443 h
			Change in output for change in value		Change in output for change in value	
			+10%	-10%	+10%	-10%
Electricity demand	Electricity demand pattern		5.5	-5.6	5.3	-5.1
Heat demand	Heat demand pattern		2.7	-2.8	1.9	-2.6
Gas demand industry	Gas demand pattern		20.3	-18.6	11.3	-11.2
Electric heat pump	Carnot factor	0.3	-2.6	3.0	-2.3	2.2
	Outside temperature column		-0.9	0.8	-1.0	0.6
	Temperature space heating water	40 °C	3.1	-3.3	2.5	-3.2
Offshore wind	Installed capacity	60,000 MW	-14.3	15.4	-15.2	17.3
	Power output turbine	10 MW	0.0	0.0	0.0	0.0
	Turbine efficiency	100%	-14.3	15.4	-15.2	17.3
	Hub height turbine	130 m	-1.8	2.0	-2.0	1.8
	Height measurement location	75 m	1.9	-2.1	1.7	-2.4
	Roughness location	0.0002 m	-0.08	0.09	-0.07	0.05
	Wind pattern per hour		-24.8	26.6	-25.4	24.9
Onshore wind	Installed capacity	4000 MW	-0.1	0.1	-0.1	0.1
	Wind pattern per hour		-0.5	0.4	-0.6	0.2
	Power output turbine	5 MW	0.0	0.0	0.0	0.0
	Turbine efficiency	100%	-0.1	0.1	-0.1	0.07
	Hub height turbine	110 m	-0.07	0.06	-0.1	0.05
	Height measurement location	114.3 m	0.05	-0.08	0.05	-0.07
	Roughness location	0.05 m	0.0003	-0.0003	0.0	0.0
Solar PV De Bilt	Installed capacity	17.5 GWp	-1.2	1.1	-1.3	0.9
	Solar irradiance pattern per hour		-1.2	1.1	-1.3	0.9
	Max. power output one panel	375 Wp	1.0	-1.3	0.7	-1.4
	Solar panel efficiency	21%	-1.2	1.1	-1.3	0.9
	Inverter efficiency	90%	-1.2	1.1	-1.3	0.9
	Surface area per panel	1.75 m2	-1.2	1.1	-1.3	0.9
Electrolyser	Max. plant capacity	20 MW	0.0	0.0	0.0	0.0
	Electrolyser efficiency	70%	-9.4	10.6	-10.9	13.1
Storage	Storage capacity	34,6000 GWh	0.0	0.0	0.0	0.0
	Max. charge power	10% of storage	0.0	0.0	0.0	0.0
	Charge efficiency	90%	-9.4	10.6	-10.9	13.1
	Max. discharge power	10% of storage	0.0	0.0	0.0	0.0
	Discharge efficiency	100%??	-9.4	10.6	-10.9	13.1
	Depth of discharge	99.99%???	0.0	0.0	0.0	0.0
	Storage threshold	0				
	Start stage	0.01				
H2 CCGT	Turbine capacity	500 MW				
	Turbine efficiency	50%	-0.6	0.6	-0.8	0.5

Gas based system

SHEET	Thing	Number	Electricity not delivered			Hours electricity not delivered		
			Normal value	-26,865	GWh	Normal value	4225	h
			Change in output for change in value			Change in output for change in value		
			+10%	-10%		+10%	-10%	
Electricity demand	Electricity demand pattern		20.0	-18.6		6.7	-7.9	
Heat demand	Heat demand pattern		0.0	-0.02		0.0	-0.02	
Gas demand industry	Gas demand pattern		0.0	-0.03		0.0	-0.04	
Offshore wind	Installed capacity	60,000 MW	-11.2	12.1		-12.9	12.5	
	Power output turbine	10 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-11.2	12.1		-12.9	12.5	
	Hub height turbine	130 m	-2.0	2.2		-1.9	2.2	
	Height measurement location	75 m	2.1	-2.3		2.1	-2.3	
	Roughness location	0.0002 m	-0.09	0.09		-0.09	0.2	
	Wind pattern per hour		-25.6	30.0		-27.4	27.0	
Onshore wind Hoogeveen	Installed capacity	4000 MW	-0.2	0.2		-0.2	0.2	
	Wind pattern per hour		-0.8	0.7		-0.7	0.8	
	Power output turbine	5 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-0.2	0.2		-0.2	0.2	
	Hub height turbine	110 m	-0.1	0.1		-0.1	0.1	
	Height measurement location	15.8 m	0.1	-0.1		0.2	-0.2	
	Roughness location	0.05 m	-0.03	0.06		-0.05	0.07	
Onshore wind Maastricht	Installed capacity	4000 MW	-0.08	0.08		-0.09	0.1	
	Wind pattern per hour		-0.4	0.3		-0.4	0.2	
	Power output turbine	5 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-0.08	0.08		-0.09	0.1	
	Hub height turbine	110 m	-0.06	0.04		-0.09	0.09	
	Height measurement location	114.3 m	0.04	-0.07		0.09	-0.09	
	Roughness location	0.05 m	0.0002	-0.0002		0.0	0.0	
Solar PV De Bilt	Installed capacity	17.5 GWp	-1.4	1.4		-1.1	1.3	
	Solar irradiance pattern per hour		-1.4	1.4		-1.1	1.3	
	Max. power output one panel	375 Wp	1.3	-1.5		1.1	-1.1	
	Solar panel efficiency	21%	-1.4	1.4		-1.1	1.3	
	Inverter efficiency	90%	-1.4	1.4		-1.1	1.3	
	Surface area per panel	1.75 m2	-1.4	1.4		-1.1	1.3	
Solar PV Maastricht	Installed capacity	17.5 GWp	-1.4	1.4		-1.1	1.4	
	Solar irradiance pattern per hour		-1.4	1.4		-1.1	1.4	
	Max. power output one panel	375 Wp	1.3	-1.6		1.2	-1.2	
	Solar panel efficiency	21%	-1.4	1.4		-1.1	1.4	
	Inverter efficiency	90%	-1.4	1.4		-1.1	1.4	
	Surface area per panel	1.75 m2	-1.4	1.4		-1.1	1.4	
Electrolyser	Max. plant capacity	20 MW	0.0	0.0		0.0	0.0	
	Electrolyser efficiency	70%	-14.2	15.5		-15.8	14.4	
Storage	Storage capacity	34,6000 GWh	0.0	0.0		0.0	0.0	
	Max. charge power	10% of storage	0.0	0.0		0.0	0.0	
	Charge efficiency	90%	-14.2	15.5		-15.8	14.4	
	Max. discharge power	10% of storage	0.0	0.0		0.0	0.0	
	Discharge efficiency	100%??	-14.2	15.5		-15.8	14.4	
	Depth of discharge	99.99%???	-100.0	0.0		-100.0	0.0	
H2 CCGT	Turbine capacity	500 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	50%	-12.7	14.4		-13.3	13.1	
H2 boiler	Boiler efficiency	85%	-1.4	1.4		-1.9	2.2	

Gas based system

SHEET	Thing	Number	Heat not delivered			Hours heat not delivered		
			Normal value	-73,970	GWh	Normal value	5,594	h
			Change in output for change in value			Change in output for change in value		
			+10%	-10%		+10%	-10%	
Electricity demand	Electricity demand pattern		3.8	-4.1		2.2	-2.6	
Heat demand	Heat demand pattern		11.7	-11.6		1.3	-1.8	
Gas demand industry	Gas demand pattern		0.009	-0.01		0.03	-0.04	
Offshore wind	Installed capacity	60,000 MW	-11.0	10.4		-14.4	12.2	
	Power output turbine	10 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-11.0	10.4		-14.4	12.2	
	Hub height turbine	130 m	-0.8	0.8		-1.5	1.6	
	Height measurement location	75 m	0.8	-0.9		1.5	-1.8	
	Roughness location	0.0002 m	-0.03	0.03		-0.1	0.02	
	Wind pattern per hour		-10.2	10.3		-18.4	17.5	
Onshore wind Hoogeveen	Installed capacity	4000 MW	-0.3	0.3		-0.3	0.3	
	Wind pattern per hour		-0.6	0.7		-0.9	0.7	
	Power output turbine	5 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-0.3	0.3		-0.4	0.3	
	Hub height turbine	110 m	-0.07	0.1		-0.1	0.1	
	Height measurement location	15.8 m	0.1	-0.1		0.1	-0.1	
	Roughness location	0.05 m	-0.02	0.03		-0.02	0.0	
Onshore wind Maastricht	Installed capacity	4000 MW	-0.1	0.1		-0.2	0.07	
	Wind pattern per hour		-0.4	0.3		-0.6	0.4	
	Power output turbine	5 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	100%	-0.1	0.1		-0.2	0.07	
	Hub height turbine	110 m	-0.05	0.04		-0.02	0.04	
	Height measurement location	114.3 m	0.04	-0.05		0.02	-0.04	
	Roughness location	0.05 m	0.0002	-0.0002		0.0	0.0	
Solar PV De Bilt	Installed capacity	17.5 GWp	-0.3	0.3		-0.8	0.8	
	Solar irradiance pattern per hour		-0.3	0.3		-0.8	0.8	
	Max. power output one panel	375 Wp	0.3	-0.4		0.7	-1.0	
	Solar panel efficiency	21%	-0.3	0.3		-0.8	0.8	
	Inverter efficiency	90%	-0.3	0.3		-0.8	0.8	
	Surface area per panel	1.75 m2	-0.3	0.3		-0.8	0.8	
Solar PV Maastricht	Installed capacity	17.5 GWp	-0.4	0.4		-0.9	0.8	
	Solar irradiance pattern per hour		-0.4	0.4		-0.9	0.8	
	Max. power output one panel	375 Wp	0.3	-0.4		0.7	-1.1	
	Solar panel efficiency	21%	-0.4	0.4		-0.9	0.8	
	Inverter efficiency	90%	-0.4	0.4		-0.9	0.8	
	Surface area per panel	1.75 m2	-0.4	0.4		-0.9	0.8	
Electrolyser	Max. plant capacity	20 MW	0.0	0.0		0.0	0.0	
	Electrolyser efficiency	70%	-12.1	11.4		-16.6	13.9	
Storage	Storage capacity	34,6000 GWh	0.0	0.0		0.0	0.0	
	Max. charge power	10% of storage	0.0	0.0		0.0	0.0	
	Charge efficiency	90%	-12.1	11.4		-16.6	13.9	
	Max. discharge power	10% of storage	0.0	0.0		0.0	0.0	
	Discharge efficiency	100%??	-12.1	11.4		-16.6	13.9	
	Depth of discharge	99.99%???	-100.0	0.0		-100.0	0.0	
H2 CCGT	Turbine capacity	500 MW	0.0	0.0		0.0	0.0	
	Turbine efficiency	50%	-7.7	8.2		-11.4	10.7	
H2 boiler	Boiler efficiency	85%	-3.7	3.9		-4.6	4.3	

Gas based system

SHEET	Thing	Number	Hydrogen for industry not delivered			Hours no hydrogen delivered		
			Normal value	-159,225	GWh	Normal value	8672	h
			Change in output for change in value			Change in output for change in value		
			+10%	-10%		+10%	-10%	
Electricity demand	Electricity demand pattern		1.0	-1.2		0.5	-0.7	
Heat demand	Heat demand pattern		0.6	-0.7		0.2	-0.3	
Gas demand industry	Gas demand pattern		10.4	-10.4		0.4	-0.6	

APPENDIX E: Additional results and graphs

Hydrogen storage fluctuations

Figure 6.2 shows that the required storage capacity for the combined scenario is a bit higher than the required storage capacity for the gas based scenario. Since in the gas based scenario the hydrogen demand is higher to fulfill all electricity demand, one might expect that more hydrogen storage would be required. However, during moments of high energy surpluses, the amount of hydrogen in the storage increases faster in the combined scenario. This can be seen in figure 7.4 between hours 4000 and 6000. In the gas based scenario, more energy is lost due to conversion losses, and the hydrogen in the storage increases slower. This leads to a higher peak amount of hydrogen that needs to be stored in the combined system.

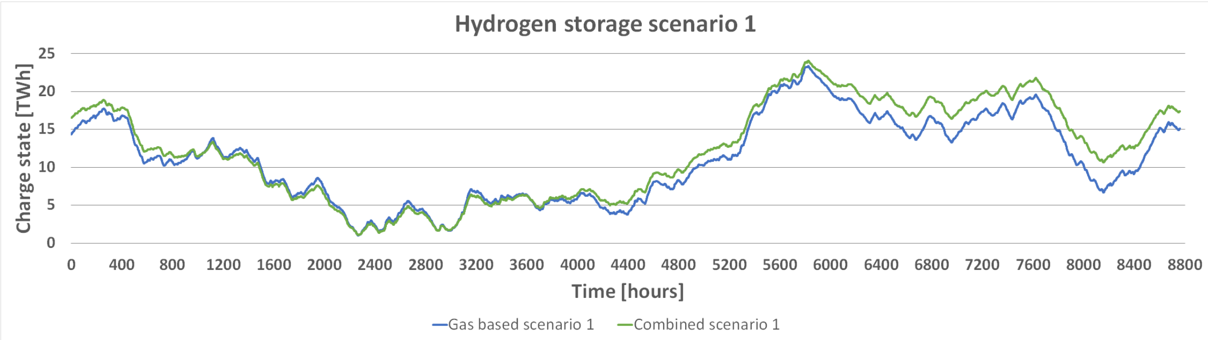


Figure 7.4: The behavior of the hydrogen storage for the gas based and combined system scenarios for production scenario 1.

Figure 7.5 and 7.6 show the comparison of fluctuations in the hydrogen storage for production scenarios 1 and 2 for the electricity based and combined scenario.

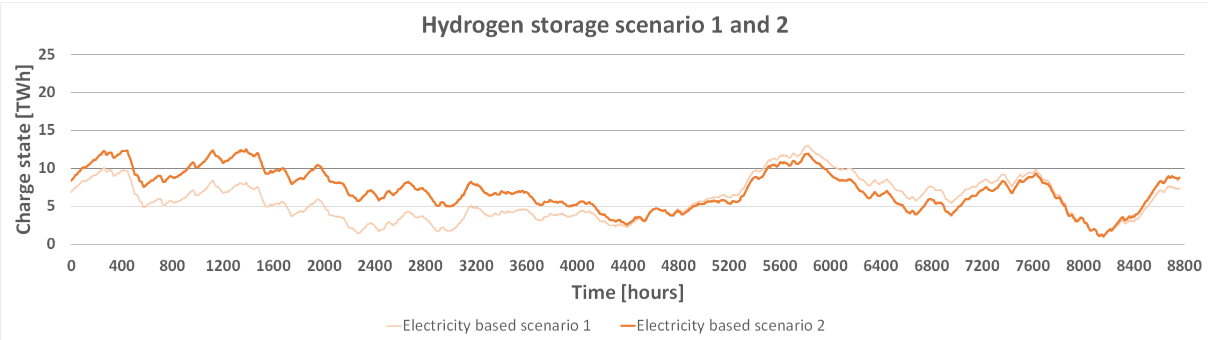


Figure 7.5: The behavior of the hydrogen storage for the electricity based system scenario for production scenario 1 and 2.

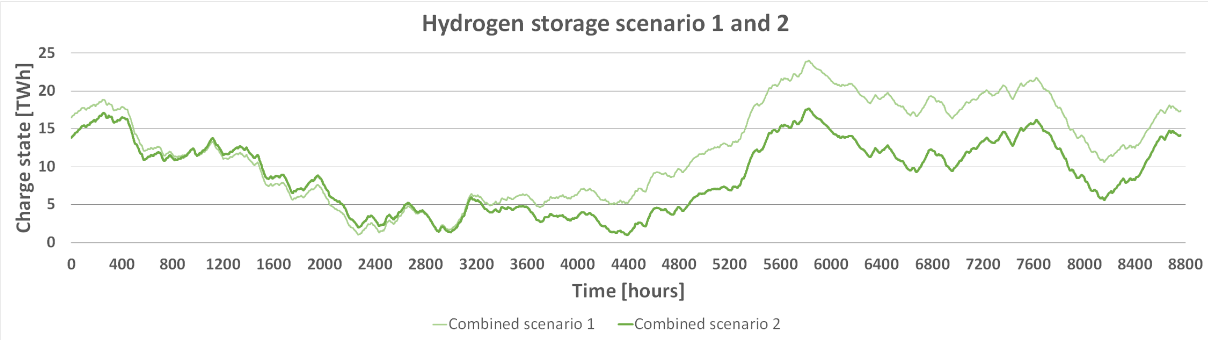


Figure 7.6: The behavior of the hydrogen storage for the combined system scenario for production scenario 1 and 2.

Figure 7.7 and 7.8 show the comparison of fluctuations in the hydrogen storage for production scenarios 2 and 3 for the electricity based and combined scenario.

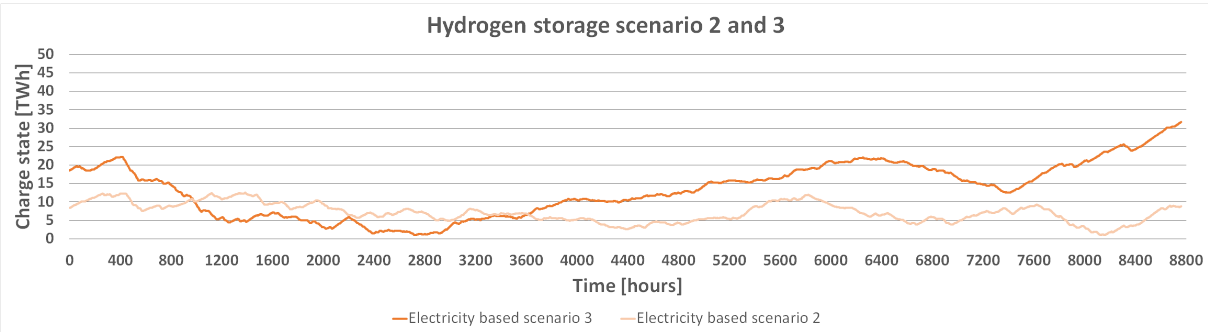


Figure 7.7: The behavior of the hydrogen storage for the electricity based system scenario for production scenario 2 and 3.

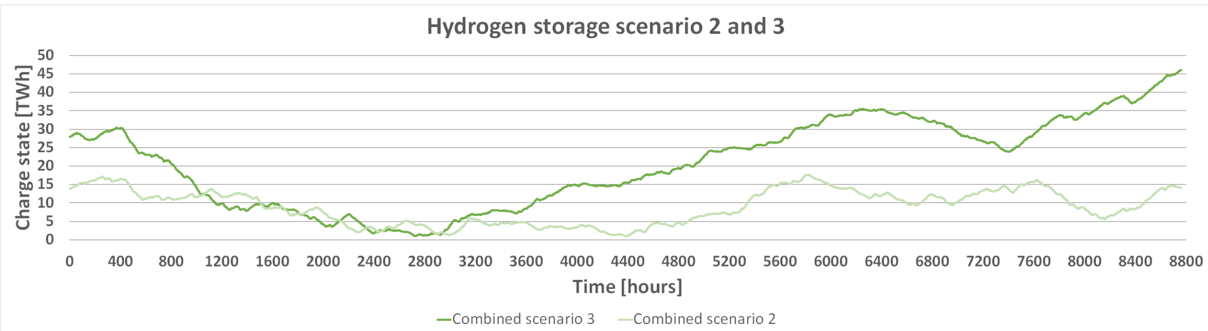


Figure 7.8: The behavior of the hydrogen storage for the combined system scenario for production scenario 2 and 3.