A Balanced, Fully Renewable National Energy Scenario with Electricity Based Production in the Netherlands Given its Land Use

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Abstract

The Netherlands must reach its goal of decreasing greenhouse gas emissions by 95% compared with 1990 levels by 2050 [1]. In order to achieve this, the current energy system needs to be completely transitioned to a renewable energy system (RES). However, to achieve a balanced system, conversion and storage methods must be used. This paper will aim to produce a balanced, self-sufficient national energy system with electricity based production using the Power Nodes method. In addition, a spatial plan is produced along with a sensitivity analysis of every input variable in the model. Domestic heating, industrial heating, and electricity was included in the energy demand which was supplied with geothermal heating, hydrogen gas, solar PV, off- and onshore wind energy. To balance the system, hydrogen gas was stored in salt caverns which was then converted using PEM electrolysers and hydrogen combined-cycle gas turbines (CCGT). It was concluded that for a balanced, self-sufficient national energy system a minimum of 14,648 km^2 total area was required where most of the land use (75%) would be for offshore wind in the North Sea. A focus on the constant conversion of energy rather than the storage would largely impact the seasonal fluctuations and keeping a balanced system. The largest gap in knowledge was found to be the lack of transparency in research when building scenarios for such energy systems. There was insufficient data in previous research for an accurate comparison of results. Furthermore, the spatial requirement of each technology had to be estimated given the values found. For a complete spatial plan, more information on the spatial requirements for the different systems is necessary.

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1 Introduction

It is becoming more apparent how climate change is affecting everyone everyday with new temperature and precipitation records being broken in the past decade. Global warming has become the predominant driving force towards sustainability. Global warming is a result of the Greenhouse Gas (GHG) emissions produced from multiple sources of energy, specifically the use of fossil fuels. In 2015, the Paris Agreement was signed by 195 parties vowing to keep the rise in mean global temperature to 2 °C above pre-industrial levels and reaching net-zero emissions by 2050 [2]. In 2018, 90% of the Netherlands' energy came from fossil fuels and had only succeeded in reducing their emissions by 15% compared with 1990 levels [1].

With the increasing urgency of moving to a carbon neutral country, the Netherlands must turn to alternative energy sources. To achieve a decentralised sustainable system, renewable energy (RE) production is required [3]. However, due to seasonal patterns that affect RE production, conversion and storage capacities are necessary for a balance between demand and supply in the energy systems [4].

Furthermore, industry and heat demand heavily depend on natural gas which can be replaced by hydrogen gas as another energy carrier which can be converted from electricity generation [5, 6]. Converting electricity into hydrogen allows for energy storage, transport through gas pipelines, and use for industrial purposes [7]. Despite the limitations, such as low efficiency rates causing large energy loss, this was concluded to be the best gas energy carrier [7, 8]. Overall, for a decentralised balanced system RE production, conversion technologies between electricity and gas, and storage facilities must be increased.

On the other hand, the Netherlands is one of the most populous countries by density in the world [9]. With a land area of about 42,000 km^2, 54% of it is used for agriculture and farming purposes while only 34% is made up of nature and open water [10]. For a realistic renewable energy system (RES), the free land must be carefully planned to spatially allow for a balanced system.

There has been research done covering different scenarios where several things were considered. For example, a regional, national, European and international plan were compared where RE production, conversion, and storage capacities were considered [11]. In another study, the spatial requirement for the RES was calculated but the conversion and storage systems were excluded from the spatial planning [7]. Furthermore, previous research did not explain how the spatial values were obtained. To the author's knowledge, a complete illustration that includes the balance and spatial planning of a 100% RE based production is lacking [7, 11, 12, 13].

1.1 Research aim & questions

Given the collection of previous research on RES in the Netherlands, it was concluded that the most reasonable energy sources given the Dutch infrastructure is on-shore wind, off-shore wind, and PV solar cells. In addition, conversion technologies include Combined Cycle Gas Turbine (CCGT) and electrolysers while hydrogen storage is done in salt caverns.

The main goal of this research is to find the spatial impacts of a national RES for local regions. Taking into account the spatial planning of the Netherlands, this paper will strive to achieve a balanced, fully renewable energy system based on electrification of production. This is important because we can not rely solely on one energy source in the case of weather changes or power outages. It is critical to look into all energy sources as well as storage and conversion for electrification.

This brings us to the main research question of the report:

"How can the Netherlands achieve a balanced, fully renewable energy system given its land use?"

This question will be answered through finding the answer to the following sub-questions:

- Will it be possible to have a self sufficient energy supply on a national level?
- What is the production of renewable technologies that is needed for a balanced scenario?
- What capacity of storage technologies needed for a balanced scenario?
- How sensitive is each energy source and how does that affect the spatial planning?

The focus of this paper will be on building a national balanced energy scenario considering the spatial planning and available technologies. Through the comparison of existing literature with a scenario built through modeling, this paper will dive into the possibilities of having a 100% sustainable energy system. Within this article, first, the scenario is built with the energy demand patterns and RE production in the Netherlands. Second, the balancing system is optimised to use the least space. Third, a sensitivity analysis is done to investigate the effect of each input variable on the output per technology. Finally, the outputs are assessed and discussed based on a balanced case.

2 Methodology

For a cohesive structure in the research done, a proper roadwork needs to be constructed. There are countless factors that can be incorporated in the national energy plan; hence, first system boundaries must be laid out. Then, the methods used will be explained as this case study has a skeleton which it was built on.

2.1 System boundaries

To narrow down the focus of this research, boundaries were set for the system's inputs. These boundaries indicate which elements of the Dutch energy system are included in the research, and which elements are excluded. The system boundaries presented in this research are summarised in figure 2.1

The main element that was excluded from this research is the transportation sector. The complexities that come with including this sector are beyond the scope of the time provided for this research.

As the goal of this research is to build a completely sustainable energy plan, the renewable energy sources that were taken into account include PV solar cells, on-shore wind, and off-shore wind. These technologies are quite well-established in the Netherlands and there are several plans in place for the rapid growth in the conversion to these energy sources [14, 15].

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 regards to gas, only hydrogen gas was considered as an alternative to natural gas with geothermal heating for industrial heating. Biogas was excluded as it has a more complicated production process which could alter the model structure used and has been concluded to not be as efficient.

As for heating, geothermal systems were included in addition to heat pumps. The electric heat pump was used for domestic heating (up to 50°C) while hydrogen gas was used for industrial heating at high temperatures.

The technical feasibility and sensitivity is studied in depth while the spatial planning is briefed at the end. Hence, the environmental impact is briefly discussed while the financial feasibility and social acceptance are overlooked in this research.

All of the technologies and reasoning behind the elements used in this research will be further explained in section 4.1 and their values are given in table 11.

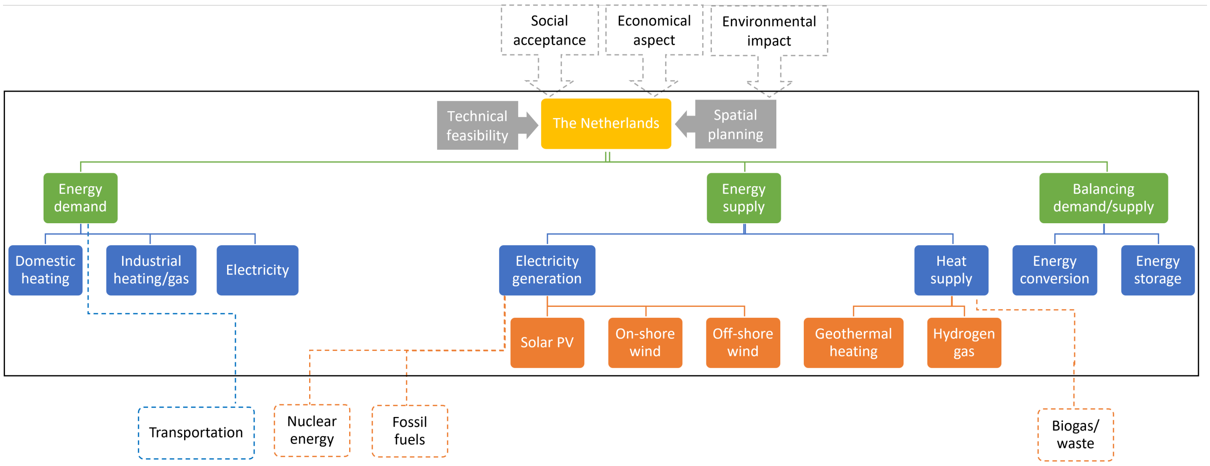


Figure 2.1: Schematic of the system boundaries. The elements in the dashed boxes were excluded from this research. Everything within the black box was within the system boundary and was investigated.

2.2 Literature review

Many separate studies have been done in the elements that make this research possible. This was especially the case for the technological aspects, spatial requirements and availability, weather patterns, and energy demand patterns. Furthermore, there are databases available on the production of wind, solar and geothermal energy which was used as a reference to the amount needed in the scenarios.

2.3 Scenario study

To answer the research questions, scenarios were compared depicting different Dutch energy systems. These scenarios were built using the Power Nodes method for a more efficient study [16]. Power Nodes is based on hourly data which generates a Net Load Signal (NLS) that represents energy shortages and surpluses per hour to indicate the balance on the energy grid. Electricity, gas and heat demand and weather patterns to generate renewable electricity is used as input data on an hourly basis. While as output, the model gives a net load signal to indicate the national grid balance.

The biggest advantage to this was that there was an existing model that had been developed in Microsoft Excel. This was modified to fit this research by understanding what was happening inside the model. Additionally, it is possible to add environmental and economic data to the model which is useful for the extension of this research in the future.

2.4 Expression of Results

For evaluating, comparing and analysing all the results provided by literature and the scenario study, the following main indicators were used in this report [17]:

1. Production mix: The share of renewable energy within the Netherlands on an annual basis was indicated as percentages of the total electricity demand of the country. The self-consumption and

overproduction was also noted.

2. Balance indicator: The indicator for (im)balance is based on the Load Duration Curve, which indicates the amplitude of the demand (in kW) per hour ranging from the highest amplitude to the lowest as a function of time, distributed over a year [5, 6]. To indicate both demand and overproduction, the Load Duration Curve is adapted. By subtracting local demand (P_D) from RE production (P_{I-RE}) per hour, a load is calculated, which indicates either over or under production, the NLS, as shown in equation 1 [6]. When the NLS is positive, there is overproduction; when negative, there is demand, and when zero, local production is equal to demand. Plotting the NLS in a selection from high to low will result in the Net Load Duration Curve (NLDC) as seen in figure 2.2.

$$NLS = P_{I-RE} - P_D[kW] \tag{1}$$

3. Space indicator: The share of space used per technology was indicated with a percentage of the total land available. Furthermore, the land usage of below the ground, on the ground, and above the ground was tabulated to distinguish between the different land uses.

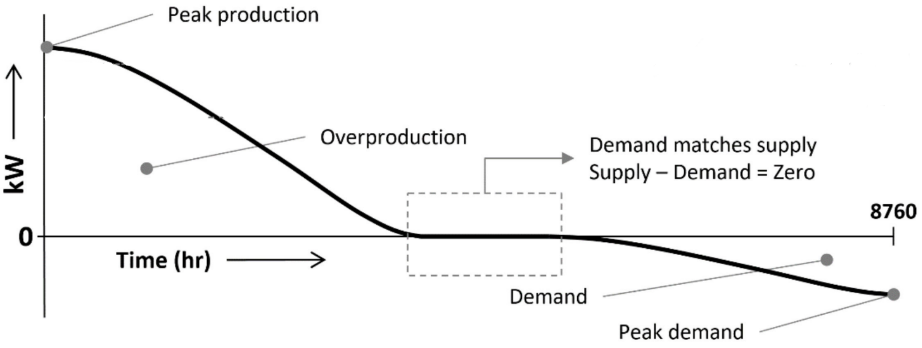


Figure 2.2: Example of NLDC [17].

2.4.1 Verification and validation

A model can only be credible after going through verification and validation processes. As Sargent defines it: Model verification is often defined as “ensuring that the computer program of the computerized model and its implementation are correct”. Model validation is usually defined to mean “substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model” [18]. Different validation and verification techniques are used, based on methods described by Sargent [18] and Pierie et al. [19].

Verification is achieved through the following questions [19]:

1. Does the model add to scientific understanding or societal benefit?
2. Does the model provide clear answers?
3. Has the model been reviewed (e.g. literature review etc.) and verified by experts in the field (e.g. professors, researchers)?

Model verification is achieved through a number of processes [19]. The ones notable for this model were comparison to other models, data relationship correctness, event validity, extreme condition test, and face validity. Moreover, the model was explained to other experts in the field and traced to determine the logical path in which the energy flowed.

2.4.2 Sensitivity analysis

One of the sub-questions of this research is *"How sensitive is each energy source?"* A sensitivity analysis measures the impact of single input variables on the model outputs. Through this analysis, the importance of each component in the energy sources, conversion methods, and storage units were measured. Thereafter, the impact of each technology was studied. This analysis also adds to the verification of the model.

2.5 Power Nodes model

As described in section 2.3, the Power Nodes method, developed by Pierie et al. [16], was used to build the model in Microsoft Excel for this research. This was done for the scenario to be comparable to other literature studies found. Furthermore, the input variables are transparent and easily adjusted to be up-to-date with the current technological trends.

A schematic of the model used for this research is shown in figure 4.1, where every horizontal bar depicts an energy flow and the colored circles depict the nodes. In Excel, every node was built in a separate sheet where the technology characteristics were specified. Based on these characteristics and node-inputs, hourly data was generated for one year. The model is further explained in section 6.1.

3 Literature review

There have been many literature studies delving into different scenarios that the Netherlands must undergo through to achieve their target of being CO_2 neutral by 2050. To conduct this research, the studies are compared and the gap is bridged. Furthermore, a lot of the data provided in the below reviews were included as inputs for the model used in this paper as will be further explained in section 4.1. A summary of the literature used in this research is given in table 9.

3.1 The role of large-scale energy storage in the energy system

In 2020, TNO conducted a study project to take a deep dive into *'Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields'* [13]. The reference scenarios used were based on the Climate Agreement of June 2019 for 2030 (CA2030) and the National Management scenario for 2050 (NM2050). The background for CA2030 is the reference scenario of the national *'Climate and Energy Outlook 2019'* [20]. This report was updated with better calculations in 2020 which was used in this research to compare with the results produced using the PowerNodes method [21]. NM2050 is derived from one of the four scenarios presented in *'Climate neutral energy scenarios 2050'* [12]. It is the most electrified scenario described in the study and closely related to this paper.

Two optimisation models, which use hourly inputs, were utilised to analyse the scenarios: a European electricity market model (COMPETES) and a national integrated energy system model of the Netherlands (OPERA). The results included the hydrogen demand for mobility and for heating in the built environment. It is important to note that the networks used in both models have their advantages and disadvantages in measuring the capacities. COMPETES includes a detailed modeling of the power system in the Netherlands and Europe; however, the incorporation of the hydrogen system still needs to be developed. Conversely, OPERA encompasses all energy demand and supply sectors in the Netherlands, including hydrogen; yet, the power system is less detailed than that of COMPETES. Overall, COMPETES is more suitable to calculate the storage needed while OPERA can be used to optimise the integrated energy system in the Netherlands.

For both models, an additional electrolysis capacity of 2 GW was assumed. Although transportation and batteries were also considered in the TNO study project, they are not noted here. A summary of the results relevant to this paper are given in tables 1, 2, and 3.

Table 1: Summary of the hydrogen storage capacities needed using two models: OPERA and COMPETES.

	Size	Volume	FCE [#]	Charge power	Discharge power
OPERA (CA2030)	10.2 GWh	21 GWh	2	10 MW	1300 MW
COMPETES (CA2030)	66 GWh	900 GWh	14	156 MW	765 MW
OPERA (NM2050)	2893 GWh	17126 GWh	6	13200 MW	21200 MW
COMPETES (NM2050)	1536 GWh	21697 GWh	14	4505 MW	8631 MW

Table 2: Summary of the installed capacities of power generation technologies and the power demand and supply for COMPETES.

COMPETES	Unit	CA2030	NM2050	Unit	CA2030	NM2050
Wind offshore	GW	13.4	51.5	TWh	59.6	205.9
Wind onshore	GW	6	20	TWh	18	76.7
Solar PV	GW	25.1	106	TWh	22.8	98.1
Other RES	GW	1.6	0.4	TWh	7.5	0.1
Power-to-Heat (household heat pumps)	GW	0.205	9.47	TWh		
Power-to-Hydrogen (electrolysis)	GW	1.38	19.3	TWh	6.7	76

Table 3: Summary of the installed capacities of power generation technologies and the power demand and supply for OPERA. Note that the value given for Solar PV is only including large scale facilities such as solar farms. Electrolysis is given a negative number as it requires power. CCGT only includes the use of hydrogen gas.

OPERA	Unit	CA2030	NM2050	Unit	CA2030	NM2050
Wind offshore	GW	13.5	57.8	TWh	60	302.5
Wind onshore	GW	6.1	20	TWh	19.7	76.4
Solar PV	GW	8.9	24.8	TWh	26	50
Power-to-Hydrogen (electrolysis)	GW	-2	-31.5	TWh	0.2	134.3
CCGT	GW	0	9.1	TWh	0	0.8

3.2 Climate and Energy Outlook 2020 - PBL

In 2019, the first *'Climate and Energy Outlook'* was written by PBL where the GHG emissions and Dutch energy system were analysed and a prediction was made based on the current trajectory. The previous study's inputs for one of its models (COMPETES) were based on the *'Climate and Energy Outlook 2019' (KEV 2019)*. Since then, the report has been updated with more accurate measurements and incorporates policy changes made within that year [21]. In comparison to *KEV 2019*, the emissions projected for 2030 are higher due to uncertainties in the costs.

Six general observations were made:

1. The pace of emissions reduction must double to achieve the 2030 reduction target.
2. Achievement of the Urgenda target is uncertain, even with a large, second coronavirus wave.
3. Largest emission reductions in the power sector, fewer reductions among the end-use sectors.
4. Renewable heating and fuels lag behind and the energy savings rate decreases.
5. The Netherlands is increasingly dependent on imported natural gas.

6. The Netherlands' GHG footprint is larger than its national GHG emissions.

Overall, this means that the Netherlands must make a radical shift in their energy transition plans and accelerate their pace to achieve the reduction target set for 2030. The electricity consumption and energy supply has been summarised in table 4.

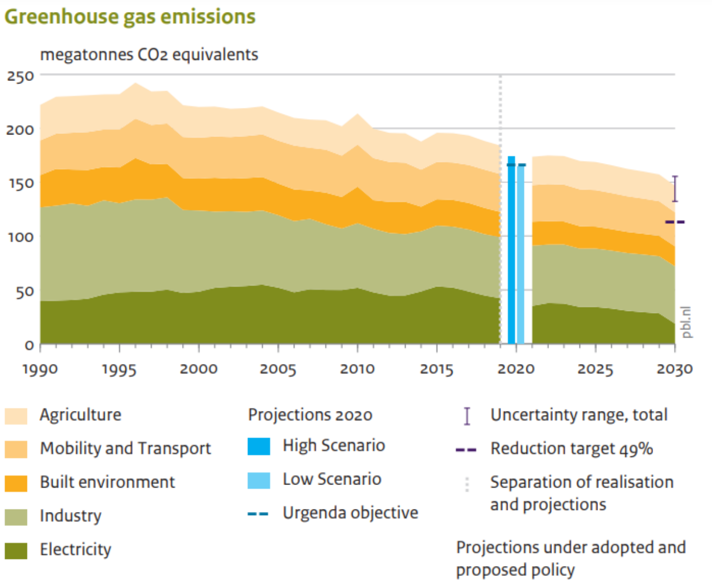


Figure 3.1: KEV 2020 GHG emissions projections [21]. The sector with the largest GHG emissions is the industry followed by electricity.

Table 4: Results produced by KEV 2020 [21].

In 2030	Supply (electricity)	Consumption (energy)
Wind	65.3 TWh	65 TWh
- Offshore		48.3 TWh
- Onshore		16.8 TWh
Solar PV	23.6 TWh	23.6 TWh
Other RES	2.8 TWh	36.3 TWh
Geothermal heat		4.9 TWh
Ground energy and outdoor air heat		8.1 TWh

3.3 Grid for the Future - CE Delft

In a paper published in 2017 by CE Delft [22], four scenarios for a climate neutral society in 2050 were produced: a national scenario, a regional scenario, an international scenario, and a generic scenario. As this research focuses on a self-sufficient and balanced national energy plan, the regional scenario was looked into where there is no import of energy and people are pro-active in making the transitions necessary. The importance of new technologies is highlighted, namely electricity-to-hydrogen conversion and hydrogen-based storage. The CE Delft study included transport in their scenario studies while the following research will not. Energy saving measures are given as 25%, 23% and 60% for electricity, heat and gas, respectively. Heat grids were to be all-electric and the industry to be circular.

The energy infrastructure under the regional scenario development would undergo a drastic change where the required capacity of electrical grids needs to be increased by a factor of 5 for some elements. As a consequence, the landscapes will be massively affected. Although the gas grids will be sufficient in capacity, the infrastructure will need to be adapted for hydrogen. In any case, electricity will become far more important as an energy carrier as the renewable sources such as solar and wind are more attainable.

Geothermal systems, electric heat pumps, and hybrid heat pumps are required to provide heating to homes and buildings.

The installed capacities and spatial requirements are summarised in table 5. The visible space requirement of the large amounts of solar meadows and wind farms is greater, because the table includes the amount of ground surface of the wind farms, but the impact on the landscape is greater.

The conclusion of this study was that the gravity of the tasks at hand are too substantial to be achieved by the citizens, companies and governments proactively to be self-sufficient in 30 years. This is especially true with the societal resistance on the change in the landscape in the Netherlands. Therefore, imports or other trade-offs might be necessary.

Table 5: A summary of the installed capacities and spatial requirements as described in [22]. Solar energy is installed on all available house rooftops as well in addition to solar farms in plains and water.

	Installed capacities	Spatial requirements
Wind offshore	26 GW	3,800 km^2
Wind onshore	16 GW	2,400 km^2
Solar PV	84 GW	900 km^2
Total	126 GW	7,100 km^2
Electrolysers	75 GW	60 km^2
Hydrogen storage	100 TWh	
Battery storage	60 GW	

3.4 Infrastructure Outlook 2050 - Gasunie and TenneT

Following CE Delft's study *'Grid for the Future'*, Gasunie and TenneT conducted a study to give insights on infrastructure implications given the different scenarios [23]. As this paper will focus on the national energy scenario (as described in the previous section), that is what will be considered from the *'Infrastructure Outlook 2050'*.

The conclusion was that coupling electricity and gas will give the energy system the flexibility it needs. The existing gas transmission grid has enough capacity to fulfill its fundamentally changed role in the future energy system, although some technical adaptations are needed due to the different characteristics of hydrogen. Most of the investment needs to be made into Power-to-Gas (P2G) infrastructures such as electrolysers. Location, capacity and operation of required P2G systems are decisive factors and must be aligned with the rest of the grid. As technology progresses rapidly, so will the costs of the developments needed to reach the goals set by the government by 2030.

3.5 Integral Infrastructure Exploration 2030-2050

In 2020, the project *Integral Infrastructure Exploration 2030-2050 (II3050)* was launched along with multiple partners [11]. This project was completed in three phases:

- Phase I - The scenarios.
  Four sustainable energy systems were made based on four scenarios: regional, national, European and international. This is further explained in section 3.5.
- Phase II - The infrastructure.
  Supply, demand and balancing resources were distributed geographically across the Netherlands

to determine the infrastructure needed to facilitate the transportation of electricity, methane, hydrogen, heat and CO_2. This is further explained in section 3.5.

- Phase III - The consequences.
  Shows the consequences of each scenario in cost, space and feasibility after each crucial decision moment in the development path. This is further explain in section 3.5.

Upon the completion of the last phase, *'The Energy System of the Future 2030-2050'* was published as the final report. The intention behind it is to update the report continuously as new insights and more specific data is collected.

Climate neutral energy scenarios 2050

A scenario study was conducted for phase I of II3050 in 2020 [12]. This is the same study used for the reference scenario NM2050 described in section 3.1. Following *'Grid for the Future'* and the *'Infrastructure Outlook 2050'*, adjustments were made for more accurate results. The goals set in the Climate Agreement for 2030 are used as the reference point, hence the results for 2050 scenarios can be larger than that of *'Grid for the Future'*. Furthermore, international shipping and aviation were included in this study giving the bigger picture. However, this is irrelevant to this paper and will not be discussed here.

The Energy Transition Model was used for most calculations [24]. The installed capacities for the national scenario in 2050 is summarised in table 6. Overall, the study concluded that the energy supply and demand in all sectors will undergo significant changes that are possible with existing technology.

Table 6: The installed capacities for the national scenario.

Solar PV	106.4	GW
Offshore wind	72	GW
Onshore wind	20	GW
Geothermal	0.98	GW
Hydrogen (CCGT)	45	GW
Electrolysis	45	GW
Power-to-heat (heat pumps)	17	GW
Hydrogen storage	16	TWh

The Energy System of the Future 2030-2050

Following the previous two studies, *'The Energy System of the Future'* [11] was written in 2021 and concludes II3050 by providing phase II and III of the study. Similarly to the previous studies, the main conclusions were that more speed is necessary, location is a decisive factor, large-scale flexibility is needed, and the infrastructure for electricity must be greatly expanded.

Table 7: National scenario capacities taking 1987 weather patterns as it is the year with the worst weather patterns for renewables.

	Installed capacities	Spatial requirement
Offshore wind	192.3 TWh	
Onshore wind	45.4 TWh	2300 km^2
Solar PV	89.2 TWh	570 km^2
Hydrogen storage	37 TWh	
Geothermal	13.4 TWh	
Heat storage	3.4 TWh	
Electrolysers		9 km^2

3.6 Green hydrogen gas in the Netherlands

The model and groundwork for this research paper was made in 2020 by Anne in 't Veld titled *'Green Hydrogen gas in the Netherlands'* [7]. Hence, the focus was on the role of hydrogen in an electricity-based system and a gas-based system along with RES and conversion technologies. As in 't Veld's research had already completed a qualitative analysis of the different scenarios, only the best scenario was taken for this research. Namely, the electricity-based system scenario with a dependence on wind energy.

However, many inputs had to be modified to best resemble the future of these technologies in the fast pacing field of RES. Furthermore, geothermal systems were added as a source of domestic heating.

Table 8: Electricity based system scenario 2 [7]. Note the difference in units with table 7.

	Installed capacities		Spatial requirement	
Offshore wind	60	GW	8762	km^2
Onshore wind	10.9	GW	1635	km^2
Solar PV	38.2	GW	409	km^2
Hydrogen storage	12.5	GW		
Hydrogen CCGT	38.4	GW		
Electrolysers	62.7	GW	50	km^2

Summary of literature used

A summary of all the gathered literature with their gaps are illustrated in table 9. This paper will focus more on the spatial capacities for the scenario built as a continuation to all of the above literature and studies. It is important to note that the input variables for the different technologies used in all the above studies, except for in 't Veld's, were not found in the literature. Therefore, it was difficult to compare with the results found in this research. Furthermore, as previously noted, all of the above studies, with the exception of in 't Veld's, included transportation in their scenario. It was concluded the ones indicated in bold would be best aligned with the scenario made in this research for a comparative study. This paper will further emphasis the importance of transparency within the models as the results are shown in section 6.

Table 9: Summary of all available technologies from the above literature reviews. In this research all five will be given: RES capacities, geothermal heat, electrolysers, CCGT, and hydrogen storage. In comparison, II3050 is the only study that includes all five components. However, it does not provide the technological aspect details for a complete comparison.

Literature	RES capacities	Geothermal heat	Electrolysers	CCGT	Hydrogen storage
Role of large-scale energy storage in the energy system [13]	✓	✗	✓	✓	✓
Climate and energy outlook [21]	✓	✓	✗	✗	✗
CE Delft [22]	✓	✗	✓	✗	✓
Infrastructure Outlook [23]	✓	✗	✓	✗	✓
II3050 [11]	✓	✓	✓	✓	✓
in 't Veld [7]	✓	✗	✓	✓	✓

Table 10: Further research and limitations of each literature review is summarised below. Many studies include the spatial requirements of some of their technological capacities. Once again, II3050 provides the best comparison to the research in this paper.

Literature	Further research	Limitations
Role of large-scale energy storage in the energy system [13]	Other RES, household heat pumps, complete specifications of hydrogen storage	Spatial requirements
Climate and energy outlook [21]	Other RES and heat consumption	Conversion and storage
CE Delft [22]	Battery storage and spatial requirements	CCGT and geothermal heating
Infrastructure Outlook	Economical insight and grid network	CCGT and geothermal heating
II3050 [11]	Spatial requirements for CCGT and storage	
in 't Veld [7]		Spatial requirements for conversion and storage

4 Model

Below, the inputs required for the nodes are described and explained. A summary of all the inputs and their references are given in table 11. Then the sub models as given in the nodes are explained as a basis for the scenario study. A diagram of the model including all the nodes and their flow is shown in figure 4.1.

The nodes were connected in a merit order from left-to-right which determines in what order the energy flows from one node to the other. Demand nodes represent the demand for one type of energy, such as electricity (white), gas (orange), or heat (red). Production nodes (green) represent technologies that are used to generate electricity, such as solar PV, on-shore wind, off-shore wind, or geothermal. Conversion nodes (purple) represent the conversion of one type of energy into another; for example, an electrolyser converts incoming electricity into hydrogen, an electric heat pump converts incoming heat into electricity, and CCGT converts hydrogen into electricity. Storage nodes (black) represent a storage unit for energy; at moments of overproduction, the energy was moved to the storage unit. At moments of energy shortages, the storage unit provided additional energy. The grid nodes (yellow) represent the electricity, hydrogen and gas grids that would connect the described system to any larger energy system. However, for this research the goal was to create a system that can be balanced by itself, hence the grid nodes were not considered.

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. The solid lines between the nodes represent the NLS's while the dashed lines represent information flows included in the calculations inside the nodes.

All the node inputs, calculations, and outputs can be found in detail in 't Veld's research paper where this model was based on [7]. The only NLS that was added is the geothermal heating which is explained in section 11 along with brief explanations on any differences in the inputs.

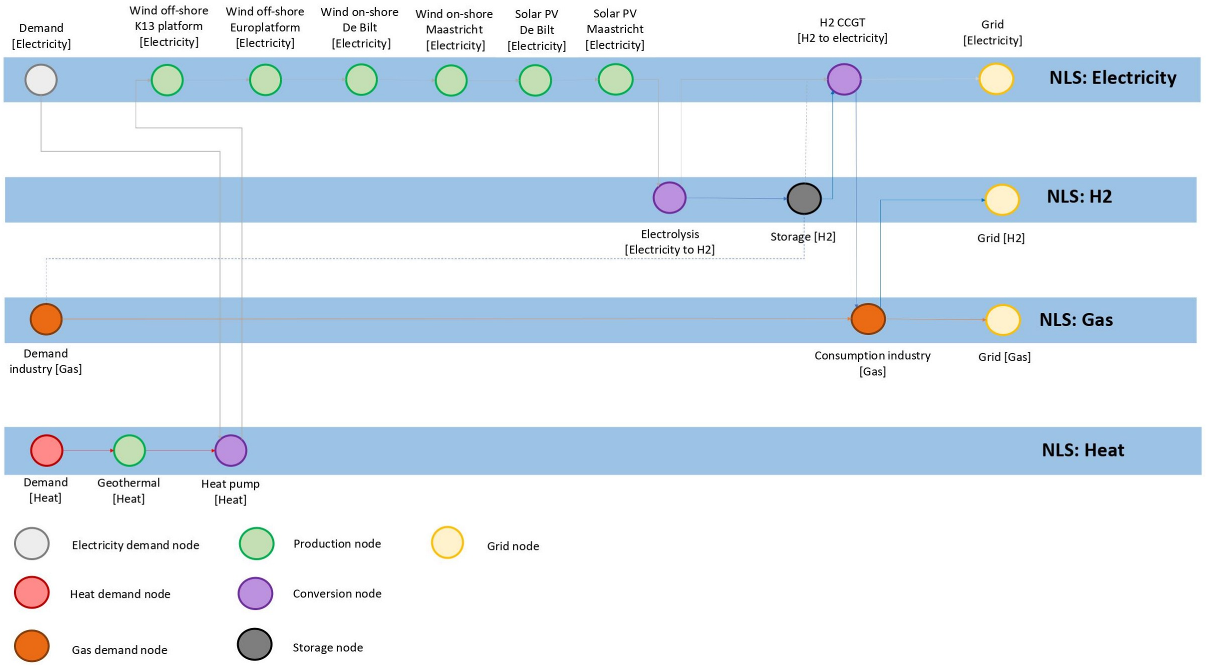


Figure 4.1: Model of the electricity scenario using the Power Nodes method.

4.1 Technical inputs

The most efficient technologies at the time of writing this paper were integrated in the input calculations at the nodes to the best of the writer's ability. In all cases but the RES, the technologies are planned to be commercially available within the next year or two [25, 26, 27]. There were also cases where this was not accurately possible, such as that for offshore and onshore wind. The power curve formula could not be found for the more efficient cases.

The values that are different from that of in 't Veld's paper are indicated in bold. The demand savings were adjusted to represent the reference used. All the demands were taken from the year 2015 to reflect the average weather patterns. However, the supply technologies were based on the most recent available specifications.

4.1.1 Geothermal production node

Geothermal heating was an entirely new node in this model. As explained earlier, there have been new plans to expand the use of geothermal heating in the coming few years [28, 29]. In total, the master plan predicts that the subsurface of the Netherlands can realise over 1000 PJ (278 TWh) of geothermal energy output annually [28].

The geothermal production node supplies energy to the domestic heat demand.

Node input

A geothermal production node receives one single input NLS. These are negative values since it is preceded by a demand node.

Node calculations

In this model, it was assumed that there is a constant production rate in the geothermal well.The thermal power of the well was calculated using equation 2.

$$P_{well} = q \cdot \Delta T \cdot C_{brine}, \tag{2}$$

where P_{well} is thermal power well [W], q is the flow rate [m^3/s], ΔT is the temperature difference between the producer and the injector [°C], and C_{brine} is the volumetric heat capacity of the brine [J/m^3K] [30]. To calculate the thermal power of the system, the components' efficiencies must also be considered using equation 3.

$$P_{system} = P_{well}(\nu_{facility} \cdot \nu_{trans}), \tag{3}$$

where P_{system} is the thermal power capacity system [W], P_{well} is the thermal power capacity well [W], $\nu_{facility}$ is the efficiency surface facilities [%], and ν_{trans} is the efficiency heat network [%]. Finally, this was multiplied by the number of doublets in the model.

Node output

The geothermal node is connected to the heat pump for the remaining heat demand to be supplied using an electric heat pump. If there is excess geothermal energy, the node output is zero and the surplus energy is disregarded.

4.1.2 Other nodes

As for the electric heat pump, the Carnot factor, which is set to be the maximum Coefficient of Production (COP) in the model, was increased from 0.2. In the previous paper, this was based on an educated guess and concluded that a boiler should be combined with the heat pump for a more accurate depiction of the energy system for the heating of larger temperature gradients. A boiler was not added in this scenario due to a lack of time. The Carnot factor was increased to 0.3 in this research as many papers indicate a higher COP trend in the coming years [31].

The hub height for the offshore wind turbine was increased to 140 m to match the reference used. The same follows for the height measurement locations for onshore wind.

Within the last two years, a larger solar field has started to be operational in the Netherlands; therefore, the value was increased to 110 MWp to reflect that. In regards to the solar PV panel and inverter, the most efficient model commercially sold was described. Consequently, the surface area per panel was increased.

The electrolyser's efficiency was taken to resonate with the plans provided by RWE who is also involved in the largest electrolyser systems [32]. It must be noted that the efficiency is non linear and decreases faster with time [33].

More references were found for hydrogen storage wells which aided in finding the values for the charge/discharge efficiency. This was 90% in the previous paper which represents the energy loss due to compression. It has been increased to 99% for the charge efficiency to align with the only literature found for this [34].

The most impressive technological advancement made within the past year is the hydrogen Combined Cycle Gas Turbine (CCGT). The capacity has increased from 500 MW with an efficiency of 64% to 800 MW with an efficiency of 64%. Currently, the model the values are based on can only make production with 50% hydrogen fuel in 2021; however, there is a pathway to 100% hydrogen [35].

Table 11: Specifications of the input variables and values for all the nodes. The values in bold are the changes made compared to in 't Veld's inputs [7].

Node	Name	Direct coefficient	Unit	Source
Demand [Electricity]				
	Electricity demand data points	. . .	kW	[36]
	Electricity demand after savings	**75**	**%**	[22]
Demand industry [Gas]				
	Gas demand data points	. . .	kW	[37]
	Industry demand after savings	**40**	**%**	[22]
Demand [Heat]				
	Natural gas demand data points	. . .	kW	[37]
	Gas to heat efficiency	87.91	%	[38]
	Heat demand after savings	**77**	**%**	[22]
Geothermal heating	**Technical inputs**			
	Vertical depth	2,539	m	[39]
	Spacing	2.1	km	[39]
	Area	8.8	km^2	[39]
	Production rate	360	m^3/h	[39]
	Production temperature	95	°C	[39]
	Capacity	21	MW	[39]
	Pumps efficiency	70	%	[30]
	Facilities efficiency	98	%	[30]
	Specific heat capacity of brine	3.92	MJ/m^{3}K	[30]
	Injected temperature	35	°C	[30]
Electric heat pump	**Outside temperature column**			
	Temperature datapoints	. . .	°C	[40]
	Technical inputs			
	Carnot factor	**0.3**		[31]
	Temperature space heating water	40	°C	[41]
Offshore wind	**Technical inputs**			
	Total installed capacity	. . .	MW	Dependent on the scenario
	Power output turbine	10	MW	[42], [43]
	Turbine efficiency	100	%	Considered in power curve
	Start speed	4	m/s	[42], [43]
	Cut off speed	25	m/s	[42], [43]
	Rated speed	13	m/s	[42], [43]
	Hub height turbine	**140**	**m**	[42], [43]
	Swept area	21,124	m^2	[44]
	Height measurement at K13	75	m	[44]
	Height measurement at Europlatform	29	m	[44]
	Technical lifetime	20	year	[45]
	Roughness location	0.0002	m	[46]
	Wind data column			
	Wind pattern	. . .	m/s	[47]
	Turbine production			
	Power curve formula	$y = 0.126v^6 - 6.4101v^5 + 127.59v^4 - 1274.6v^3$ $+6858.3v^2 - 18472v + 19239$	kW	[42]
Onshore wind	**Technical inputs**			
	Total installed capacity	. . .	MW	Dependent on the scenario
	Power output turbine	5	MW	[42]
	Turbine efficiency	100	%	Considered in power curve
	Start speed	4	m/s	[42]
	Cut off speed	25	m/s	[42]
	Rated speed	12	m/s	[42]
	Hub height turbine	110	m	[42]
	Swept area	10,568	m^2	[42]
	Height measurement De Bilt	**1.9**	**m**	[44]
	Height measurement Maastricht	**114.3**	**m**	[44]
	Technical lifetime	20	year	[45]
	Roughness location	0.03	m	[46]
	Wind data column			
	Wind pattern	. . .	m/s	[40]
	Turbine production			
	Power curve formula	$y = -0.0319v^6 + 0.8074v^5 - 2.5967v^4 - 88.326v^3$ $+1033.4v^2 - 4014v + 5163.1$	kW	[42]
Solar PV	**Technical inputs**			
	Total installed capacity	. . .	MWp	Dependent on the scenario
	Max power output one solar field	**110**	**MWp**	[48]
	Max power output one panel	**420**	**Wp**	[49], [50]
	Solar panel efficiency	**22**	**%**	[49], [50]
	Inverter efficiency	**96**	**%**	[51]
	Surface area per panel	**1.88**	**m^2**	[49], [50]
	Lifetime	25	year	[49], [50]
	Solar irradiation			
	Solar irradiation pattern Maastricht	. . .	Wh/m^2/h	[40]
	Solar irradiation pattern De Bilt	. . .	Wh/m^2/h	[40]
Electrolysis	**Technical inputs**			
	Total installed capacity	10,000	units	"unlimited"
	Max plant capacity	20	MW	[52], [53], [25]
	Electrolyser efficiency	**86**	**%**	[33], [32]
	Area	**500**	**m^2**	[54]
H2 storage	**Technical inputs column**			
	Storage capacity per cavern	34,600	GWh	[8]
	Max charge/discharge power per day	10% of storage	kWh	[55]
	Charge/discharge efficiency	**99**	**%**	[34]
	Depth of discharge	100	%	[56]
	Self discharge	0		[55]
	Storage threshold	0%	kW	[57]
H2 CCGT	**Technical inputs column**			
	Total installed capacity	10,000		"unlimited"
	Turbine capacity	**800**	**MW**	[35]
	Turbine efficiency	**64**	**%**	[35]

4.2 Validation and verification

As outlined in section 2.4.1, several steps needed to be taken to trust the outputs given by a model. These will be confirmed below.

Model validation

To ensure the model was valid for the intended research, three questions must be answered [19].

1. Does the model add to scientific understanding or societal benefit?
   The model is a simplified flow chart of the energy system in the Netherlands on a national level, excluding imports, imports and transportation. The interaction between the different sub systems in heat, electricity, gas and storage were generated on an hourly basis to display energy shortages or surpluses at each node. This was then implemented into a sheet for spatial planning across the Netherlands. Optionally, environmental, societal and economic aspects can be included in the model for future research. Therefore, the model does allow for additional scientific understand and societal benefits.

2. Does the model provide clear answers?
   A description was given on every sheet to explain the displayed hourly data points in each column. At each node, a graph was presented to summarise the production or storage of energy. Thereafter, a results sheet would compile the different production, conversion and storage technologies in a table.

3. Has the model been reviewed and verified by experts in the field?
   The basic model had been previously reviewed [16]. Any additions were verified once again during a walk-through session where the model was presented and traced with another researcher.

Based on the above steps, the model validation was confirmed and viewed suitable as a method for investigating the intended research.

Model verification

There are many techniques for verifying a model. The ones listed by Pierie et al. were taken for this research [19].

Comparison to other models

Several values for the energy capacities needed were found from literature review as shown in section 3. Most of the models used there were based on the Energy Transition Model [24].

Data relationship correctness

To confirm data relationship correctness, the input data must be compared to the output data produced to prove a logical relationship between the two. This was done by changing the values of different inputs to see the effect it has on the output. For example, the produced heat by geothermal wells should be linearly dependent on the number of doublets and capacity of each well. The data relationship correctness for this model was confirmed in previous research for the electric heat pump, off- and onshore wind, solar PV, and electrolyser [7]. The analysis of the remaining sub-systems (geothermal heating, hydrogen storage, and hydrogen CCGT), expressed in the model as Excel sheets, are found in appendix A.

Event validity

Event validity implies that the model is applicable to real events by comparing the two. This cannot be done for the complete system; however, it can be implemented for several sub-systems. The event validity of the heat pump, wind turbines, and solar PV were done in previous research [7]. However, these were once again validated given the new efficiencies in appendix A.

Extreme condition test

An extreme condition test determines whether the model outputs under extreme and unlikely scenarios is plausible. Individual inputs and individual sub modules were set to zero to compare the effect this has on the model outputs. In this way, any possible mistakes can be detected and corrected by fixing the links between the data. This has already been done by a previous paper for this model [7]. Only geothermal heating was added in this model; therefore, the process is detailed in appendix A.

Face validity test

In the case of face validity, individuals who are familiar with the system are asked whether the model and its behavior seem reasonable. This was already done in previous research for most of the model [7]. Whenever something was changed in the model, the previous expert on the Power Nodes method was consulted and a walk-through was done to ensure the validity of the model.

4.3 Sensitivity analysis

As part of the validation process, a sensitivity analysis must be carried out to see the impact of every single variable on the model outputs. This was done by varying the model variables by 10% one-by-one. 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. These values were presented in tables in appendix E.

The capacity sensitivity was done in an unbalanced scenario to see the effects on the shortages while the space sensitivity was done in a balanced scenario (as shown in the results in section 6) to see the requirements in conversion and storage to balance the scenario. The results arrived at from this were further discussed in section 6.4 as it was conducted after the foundation of a balanced scenario.

5 Case Netherlands

A scenario was made for this research that was expanded on previous research to be compared with the scenarios taken from literature as shown in section 3. The scenarios taken for comparison are that of CE Delft, II3050, and in 't Veld's [22, 11, 7]. A summary of the different scenarios with their published dates are shown in table 12. The model consists of one sheet per node in Excel that run calculations based on the inputs and flow of the schematic presented in figure 4.1. The ratio of the RES were based on the last results found in the II3050 report and then adjusted to result in a balanced system with the least spatial requirements. In regards to the scenario made, most things were kept the same as in the previous model with the addition of geothermal heating [7].

All the values inputted were found from the most recent commercially available technologies or technologies that were soon to be put in the market. As systems are becoming becoming more efficient at an accelerating rate, these values give a realistic prediction on what can be used on a wide scale in the near future. Compared to research conducted only two years ago[7], it is already evident that many technical inputs have improved. The input variables of the different technologies is shown in table 11.

Table 12: Summary of the scenarios used in this case study. In this research all five will be given: RES capacities, geothermal heat, electrolysers, CCGT, and hydrogen storage. In comparison, II3050 is the only study that includes all five components. However, it does not provide the technical inputs for a complete comparison.

Literature	RES capacities	Geothermal heat	Electrolysers	CCGT	Hydrogen storage	Month/Year
CE Delft [22]	✓	✗	✓	✗	✓	11/2017
II3050 [11]	✓	✓	✓	✓	✓	04/2021
in 't Veld [7]	✓	✗	✓	✓	✓	04/2020
Current scenario	✓	✓	✓	✓	✓	08/2021

5.1 Weather patterns

Before the scenario studies could be conducted, the wind pattern and temperature. The demand patterns were based on weather patterns. Below the reasoning behind the patterns used was summarised. More explanation on the conclusions arrived at for the weather patterns can be found in in 't Veld's paper [7].

To measure the output of electricity from the wind turbine nodes, the wind speed per hour needs to be known. There are different stations around the country that record the weather patterns and are then published by the Dutch weather institute, KNMI. This is similar to the case of electricity from the solar PV node where it is dependent on the solar irradiation. Furthermore, the temperature data points are needed as input for the electric heat pump node output.

As a continuation to in 't Veld's research, the same locations were used for the onshore wind, offshore wind, and solar PV calculations: K13 platform, Europlatform, De Kooy, De Bilt and Maastricht [40, 47]. This gives rise to an uncertainty but also a range in the electricity generation as it is not dependent on one single weather pattern.

The year average for solar irradiance and temperature was 2015, while the year average for the wind pattern was 2014 [7].

It is important to note that the literature used for the comparative study uses the 1987 weather patterns as it is a less optimistic scenario [11].

5.2 Spatial plan

In the spatial plan, there were many variables estimated or proportionally calculated. The spatial specifications were based on data presented in table 13.

To provide a spatial plan, an estimate of the space required per technology was needed. For geothermal wells, the number of doublets were taken as projected in the master plan proposed by for the Netherlands [28]. Then, the average area of influence was found given the current wells in the Netherlands [39]. However, this area is underground which will be further discussed in section 6.3.

For the RES, the largest park built in the Netherlands was used to calculate the land use per turbine in the case of wind energy and per field in the case of solar cells.

As for the electrolysers, the value given is based on a 1 GW PEM plant with 100 modules of 10 MW. The minimum area with a compact design of the land use to give 8 ha. This includes the electrolyser building, electrical equipment, hydrogen processing section and offices [54]. In the model, each plant has a maximum capacity of 20 MW which was taken account for by assuming 50 modules of 20 MW in a 1 GW PEM plant.

Note that for salt caverns, it was assumed that electrolysis efficiency is 70% and CCGT efficiency is 60% [8]. This is lower than the efficiencies used in the scenario study. The area and power provided per salt cavern was taken from literature [8].

The area needed for a CCGT station was the most difficult to estimate. To the author's knowledge, there is only one place to find the area needed and that was in the database for all stations in the Netherlands. One most comparable to the one used for this scenario was taken and used to estimate the area needed. This was the Eems CCGT power plant [58].

Table 13: The space required per production, conversion or storage system.

Geothermal	Amount of doublets	175		[28]
	Area of influence	8.8	km^2	[39]
Offshore wind	Area per turbine	2.75	km^2	[59]
Onshore wind	Area per turbine	0.995	km^2	[60]
Solar PV	Area per field	0.973	km^2	[61]
Electrolyser	Area per station	0.08	km^2	[62]
	Amount of modules per station	50		[62]
Salt cavern	Area per salt cavern	13	km^2	[8]
Hydrogen CCGT	Area per station	0.43	km^2	[58]

6 Results

Below the scenario outputs are explained including the production, hydrogen storage, CCGT, and electrolyser capacities. First, the production mix in regards to each technology is shown in a balanced scenario and compared to the scenarios found in literature as summarised in table 9. To highlight the balance, NLDC graphs are shown in the balanced scenario and compared to the NLDC without hydrogen storage as an indicator. NLDC graphs without the conversion technologies and geothermal heating are also presented and explained in appendix C. Then, the spatial planning of the balanced scenario is compared to that of the scenarios found in literature. They are also presented as a percentage of the total land available in the Netherlands for each spatial requirement. This is followed by a sensitivity analysis in relation to the space used. Only one scenario was analysed: a fully electricity based system scenario with a production based on table 6 from the literature described in [11]. The number of systems required per technology is given in table 17 in appendix D

6.1 Production mix

The production mix, as our energy indicator, is expressed below for each RES, storage and conversion.

6.1.1 Production capacity

For the supply of heat, geothermal heating was constantly produced to give a total of 3.5 GW. Additionally, there was a surplus during some hours in the summer totalling to 70 GWh. This is shown in figure B.1 in appendix B.

To obtain a balanced scenario, the capacities had to be adjusted and deviate from the percentages aligned with the reference scenario. This is due to an overproduction of energy during some times of the year. Hence, the capacities were reduced. As there is more support for solar energy and the area required is less, the wind energy was almost halved and solar energy nearly doubled. Moreover, onshore wind is unfavorable as it requires more space on mainland Netherlands. The resulting capacities are shown in table 14.

Additionally, to avoid any seasonal fluctuations, the offshore wind energy capacity and solar PV capacity was equalised. In general, there is more solar energy and less wind energy in the summer; and vice versa in the winter. Therefore, to maintain a balanced production throughout the year, setting both capacities equal seemed like the best solution.

The scenario result is shown in comparison to CE Delft's study [22], the II3050 paper [11], and in 't Veld's results [7] in figure 6.1. What's most noticeable is that in the balanced scenario conducted for this research is that far less RES supply is required. This aligns with the lowered demand as transportation is not included in this research.

Table 14: The ratios based on table 6. The values in italics are the reference values which also correspond to the unbalanced scenario.

	unbalanced [GW]	balanced [GW]
Offshore wind	*58.85 (36%)*	40 (44.4%)
Onshore wind	*40.5 (10%)*	10 (11.2%)
Solar PV	*12.5 (54%)*	40 (44.4%)

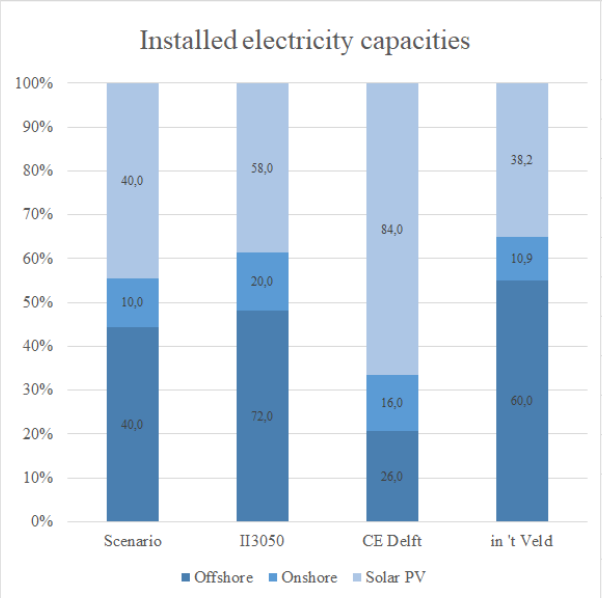
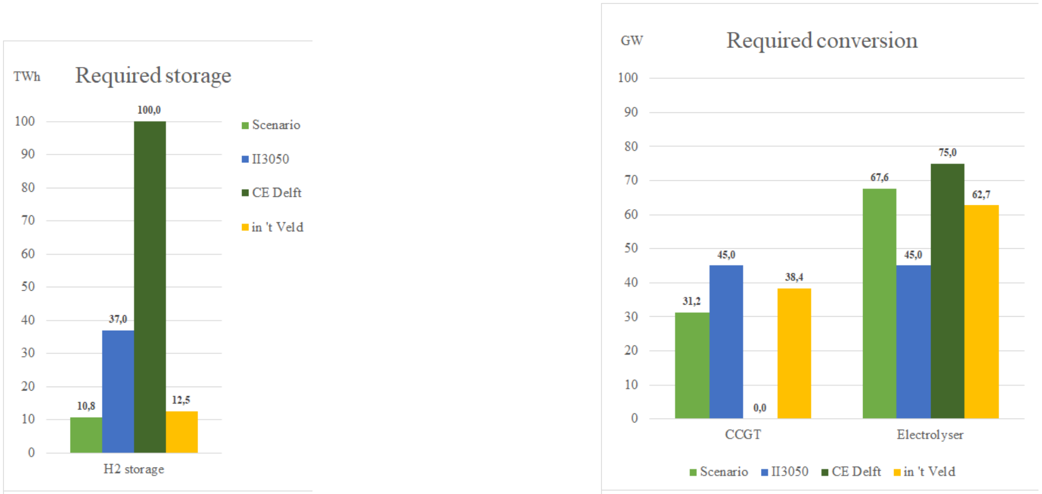


Figure 6.1: Different models with their installed capacities of RES within the bars along with their percentage. The ratio of onshore wind electricity production is comparable in all scenarios at around 10-15%. The main differences lie in the ratio of solar to offshore wind electricity production.

6.1.2 Conversion & storage capacities

All the resulted capacities needed for hydrogen storage, CCGT for the conversion of hydrogen into electricity and electrolysers for the conversion of electricity into hydrogen is summarised in figure 6.2. As previously mentioned, the least amount of land usage is preferable in this research. Therefore, there is a greater focus on using conversion and storage methods than the production from RES to compensate for seasonal changes.

In order to use the least amount of hydrogen and maintain a stable supply throughout the year with all its seasonal changes, only 10 TWh of hydrogen is required in the balanced scenario as there is a lower production from RES. As an effect, more electrolysers are needed.



(a) A diagram showing the required amount of storage for each scenario.

(b) A diagram showing the required capacities for conversion for each scenario.

Figure 6.2: In this paper's model, the dependence on storage is far less as an effect of the use of geothermal heating and less heat pumps. Furthermore, the equal dependence on solar and offshore wind energy compensates for the seasonal changes. Note that CCGTs were not included in the CE Delft study.

6.2 Load demand curves

The balance indicator is shown as NLDC graphs similar to figure 2.2. The final scenario is a balanced one, hence it is constantly at 0; however, the same scenario was simulated without geothermal heating, without hydrogen storage, without electrolysers, and without CCGT. In this way, the importance of using all resources is highlighted. Hydrogen storage is key for maintaining the balance of this scenario which is shown below. The NLDC graphs of the other simulations is presented in appendix C.

You would expect an overproduction at some points; however, in this scenario it was important that a balance was always maintained while keeping the spatial use at a minimum. Hence, any excess electricity production was converted into hydrogen which was then used as gas in the industry or converted into electricity when there was a deficit in RES production. This results in a constant NLDC of 0 as shown in figure 6.3.

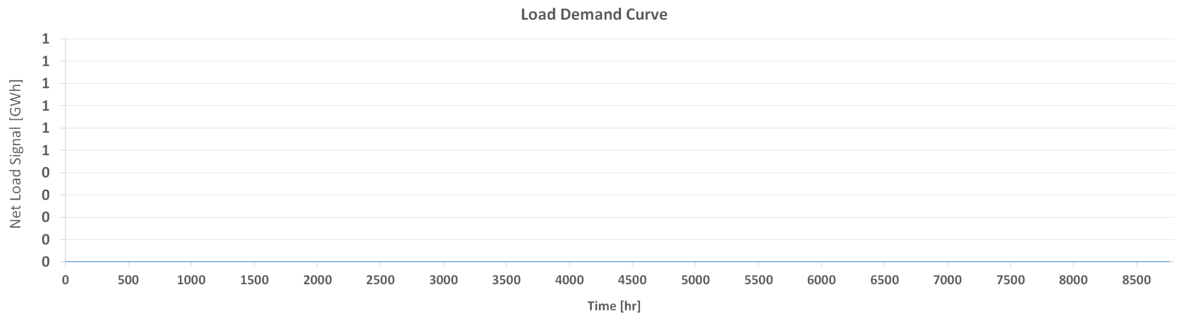


Figure 6.3: Graph of the NLDC in the balanced scenario. The same graph is presented for the demand of electricity and hydrogen gas as they are balanced.

All the overproduced electricity is converted into hydrogen and placed in storage as shown in figure 6.4. When there is more need for electricity at certain points, it is converted back into electricity through CCGT and put into the grid. To keep the storage at a minimum, the electricity was produced in such a way that it does not fluctuate heavily. This is also to combat any seasonal related production as explained in section 6.1. The difference between the end state and start state was also minimised to indicate a realistic flow into the following year.

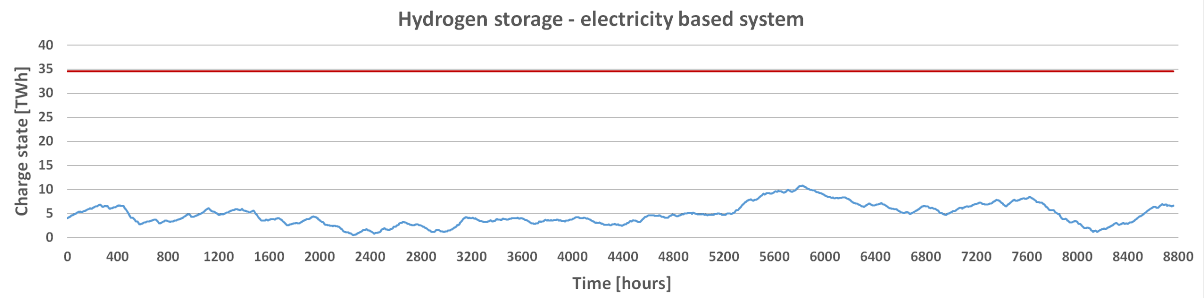
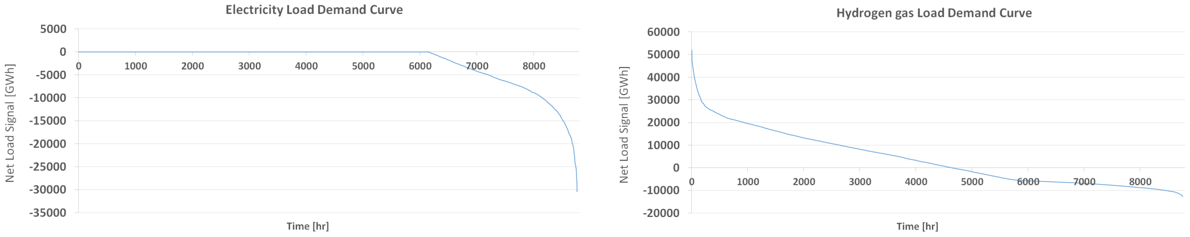


Figure 6.4: Graph of the NLS of hydrogen storage in the salt caverns. The red line indicates the maximum storage capacity available in the Netherlands which was set to 34.6 TWh as specified in table 11. The difference between the end state and start state was 2.6 TWh. The minimum required start state for a balanced scenario is 60% of the end state.

In contrast, when we remove hydrogen storage from the scenario and plot the NLDC with all the other inputs kept constant, a clear overproduction and demand is shown as in figure 6.5.



(a) The electricity NLDC when there is no hydrogen storage.

(b) The hydrogen gas NLDC when there is no hydrogen storage.

Figure 6.5: The two graphs show that electricity is in demand while there is an overproduction of hydrogen as electrolysers continue to convert the hourly excess electricity into hydrogen. Without storage, the opportunity for the CCGT to work is limited as the nodes calculate at an hourly rate.

6.3 Spatial planning

It was difficult to estimate the spatial requirements given the dimensions as illustrated in table 13 since not all areas are at the same level and some technologies can vary depending on the size and location of the field. This is especially true for wind energy [63]. However, based on the numbers presented in section 5.2, the total areas were found as shown in figure 6.6. The land use of water, land and underground salt caverns was calculated and compared to the other scenarios.

Due to a lack of information and transparency, areas for specific technologies and scenarios had to be calculated using the same values as this research. This provides several assumptions. There is a wide error as comparing the values given in the reports compared to the calculated values presented double the area used. It is unclear where this error comes from. This needs to be researched by asking the authors of the previous scenario studies and comparing the inputs.

The percentages shown in table 15 clearly indicate what is feasible and what is not given the current status of the Netherlands' spatial capacity. The land total area includes agricultural, forest and open nature land. However, most of the agricultural land is currently used and cannot be utilised for RES. It is not entirely clear what portion of the Netherlands can be used for RES.

As the salt caverns were calculated using the same inputs, the land usage is directly proportional to amount of hydrogen storage needed in the different scenarios. Hence, CE Delft requires almost ten times the amount of land for salt caverns as in the scenario in this study.

Not all technologies require land area. For example, offshore wind is in the sea and geothermal energy is in the ground. Table 16 shows the division of space. A further discussion is presented in section 7.3.

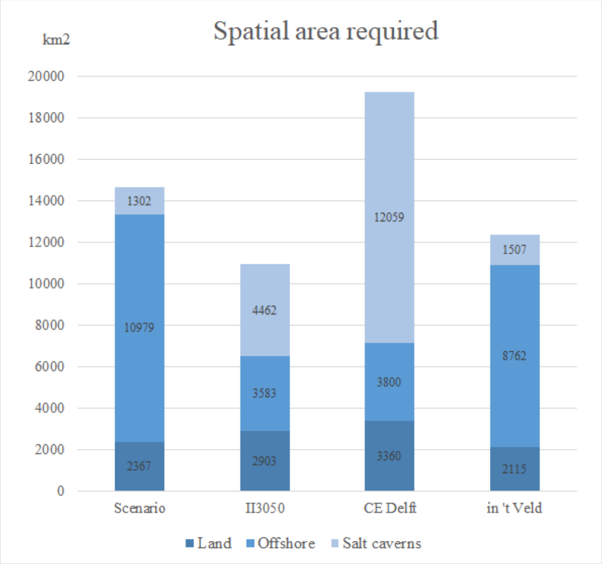


Figure 6.6: The spatial area required on land includes onshore wind turbines, solar PV, CCGT, and electrolysers. The land usage for hydrogen storage and energy conversion was not given in any of the scenarios found in literature. Furthermore, the land use of offshore wind was missing in II3050. These blanks were filled using the values in table 13.

Table 15: Percent of land usage calculated based on the numbers given by CBS [10]. The value of the area taken for land includes agricultural, forest and open nature land. The land usage includes onshore wind, solar fields, CCGT, and electrolysers. This does not include geothermal wells.

	Available	Scenario	II3050	CE Delft	in 't Veld
Land	27353 km^2 [10]	9%	11%	12%	8%
Offshore	4153 km^2 [10]	264%	86%	92%	211%
Salt caverns	4173 km^2 [8]	31%	107%	289%	36%

Table 16: The spatial division below the surface, on the ground, and in the air. Note that both geothermal wells and hydrogen storage likely also have an area covered on the ground that are not noted in this table.

Area below the surface:			
Hydrogen storage	1302.2	km^2	
Geothermal well	1540.0	km^2	
Area on the ground:			
Offshore wind	10979.3	km^2	
Onshore wind	1990.7	km^2	
Solar PV	353.7	km^2	
CCGT	16.8	km^2	
Electrolyser	5.4	km^2	
Area in the air:	Swept area [km^2]	Height [m]	Rotor diameter [m]
Offshore wind	21.1	140.0	164
Onshore wind	10.6	102.0	116

6.3.1 Water bodies area requirement

The most land area needed is in water for offshore wind energy. However, the percentage is relative to the open water area that is within the Dutch territory. The distribution of water area that belongs to the Netherlands is depicted in figure 6.7. It is also possible to include more area from the North Sea. Officially, that is 59,000 km^2 [14], compared to 4,153 km^2 of total open water given by CBS, which means that only 19% is required to provide 40 GW.

According to future scenarios published by governmental organisations, all offshore wind turbines will be built in the North Sea [14]. The plan is shown in figure 6.8. Hence, the area required for the scenario in this paper (10,979 km^2) is more realistic as it covers 19% of the available Dutch area.

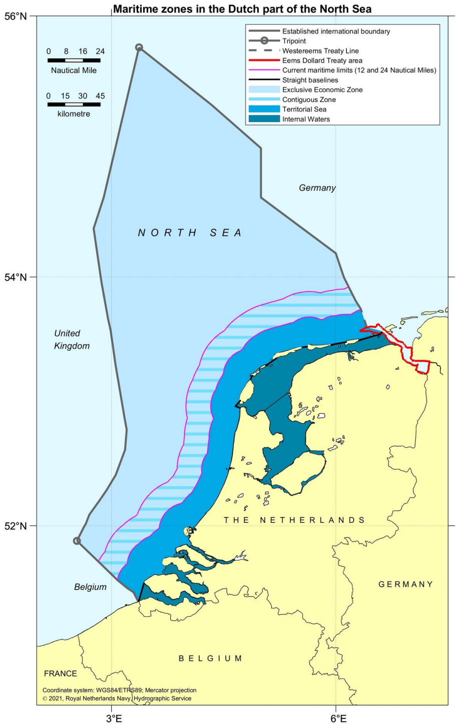
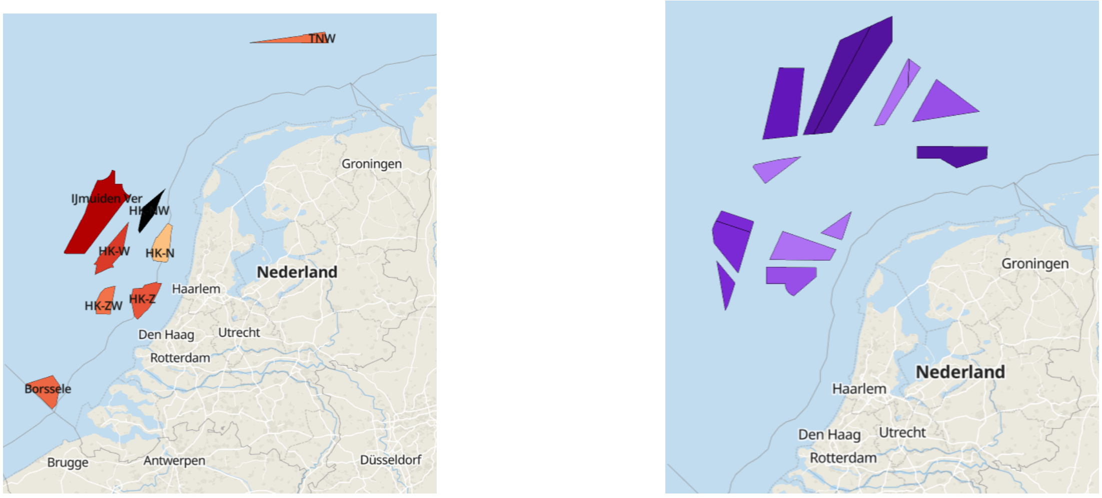


Figure 6.7: A map of the North Sea territorial division in the Netherlands [64]. Only the territorial sea is included in the value given by CBS for the open land water. However, the water area belonging to the Netherlands extends all the way to the grey boundary.



(a) Plan for the North Sea in 2030 [65]. (b) Plan for the North Sea in 2050 [65].

Figure 6.8: All offshore wind turbines are placed in the North Sea. When compared to figure 6.7, it is evident that none of this is in the territorial sea. Hence, the percentage given in table 15 is incorrect.

6.4 Sensitivity analysis

Essentially, not all input variables affect the outputs significantly. When looking at the sheets presented in appendix E, the most significant outcome of the sensitivity analysis was that a 10% increase in the reference value of an input does not necessarily result in the exact opposite effect when a 10% decrease is implemented. Hence, it is important to investigate which variables affect the outputs the most.

The power output per piece was the most effective way to increase electricity production. Interestingly, an increase or decrease in the wind pattern resulted in a larger change in the electricity consumed than the electricity produced. This resulted in a shortage or surplus in hydrogen twice the reference amount or more. The other variable with the largest sensitivity was the temperature outside for the heat pump. This would result in a similar outcome as the wind pattern in the sense that it would greatly affect the hydrogen shortage or surplus. The change in demand savings would not have a proportionate affect to the consumption likely as a result of the demand in other forms of energy remaining the same.

As for the spatial sensitivity analysis, similar results were derived. The largest influence to save space, was the power output per wind turbine followed by the turbine efficiency of CCGT. The largest increase in space use was a result of the solar panel efficiency. Interestingly, increasing the solar panel efficiency did not results in saving the total space required. This was the case for more variables: demand savings, weather patterns, electrolyser efficiency, and charge/discharge efficiency of hydrogen storage. As it may save space on the specific technology, it might cost more space in conversion or storage. Consequently, the total space required for that particular change in scenario increases.

7 Discussion

7.1 Limitations

Making an energy system is quite complex which is why it is sometimes more beneficial to condense the boundaries. As a result, there are limitations to every model. May that be in the inputs, outputs or links in between.

Transportation & aviation

Transportation was not included in this model. One of the largest uses of gas is transportation. This can be electrified. However, research must be done as to how this is approached and whether hydrogen fuel has a future in the Netherlands. 18% of the energy consumption is within the transportation sector [10]. This is a large addition to the energy demand which should be accounted for in future scenarios. In addition to land transportation, there is transportation at sea and in the air which must be accounted for carefully.

Battery storage becomes more important in this case. Therefore, when including transportation in the demands, battery storage should also be considered to balance it with the energy supply.

Weather patterns

The average weather pattern is taken and the demand of that year is reflected on it. Although the wind average was in 2014, 2015 was taken for a common year amongst all patterns. There was less wind than average that year. Weather conditions are constantly changing; therefore, it is best to seriously consider hydrogen storage and expand on that. The cycles are long and the capacity in the Netherlands is large [8]. In this scenario, only a third of the full salt cavern capacities were required.

Grid network

The grid was not considered in this research. The costs and societal effects the construction of the grid can have is vast. Previous research has calculated how much is needed [11]. Dutch regions must consider the fact that they must work together to achieve the goals with the optimal spatial planning. Not all regions have geothermal resources or hydrogen storage space. The north should be predominantly used for hydrogen storage while the center geothermal. A balanced national energy scenario would mean cooperation between all the parts of the country to do their part.

Literature

Every scenario found in literature that was used in this research to compare the results lacked in a certain topic as outlined in table 9. The largest setback was the missing information about the technologies used. It was difficult to estimate the spatial impact each scenario had. As a result, the comparative analysis made is inaccurate. It is crucial for future research to carefully document all their inputs as well as their outputs for proper continuation of their study.

7.2 Technological aspects

Heat supply

Geothermal energy was included in this model. However, there is limited information on how to include large geothermal doublets in a model for domestic heating. This is especially true in regards to deep geothermal wells of 60-90 °C. For simplicity, the hourly supply of geothermal heat was kept constant which is not accurate when compared to reality. Furthermore, a geothermal system should include an aquifier and heat pump. This would use more electricity similarly to the heat pump and, in turn, increase the electricity demand. A more complex but realistic approach to how much energy is used in the production of geothermal heating should be used in this model. TNO has developed a great tool for geotechnology related calculations [66]. This can also be used to map out the optimal locations and develop a more concrete spatial plan.

In previous research, it was concluded that a boiler should be added for high temperature heating over 40 °C for the electric heat pump. Including a hybrid heat pump could be investigated as they are also commercially available. Furthermore, the Carnot factor was increased to 0.3 to align with the current trend in the increased efficiency of heat pumps. However, with a more intricate model where a boiler is also added and there is a switch between using hydrogen gas or electricity, this can make an even more efficient system.

Off- & onshore wind energy and solar PV

The capacity densities of both wind energy technologies heavily depends on the location [67]. This can be included in a future model where the spatial impact is further analysed and incorporated into the scenario.

After the making of this model, an even larger wind turbine with a power output of 15 MW was announced to be released in 2022 (V236-15.0 MW) [27]. In that case, the model should be updated and a new power curve made. With this in mind, and the assumption that "for a 900 MW wind farm, the model boosts production by five percent with 34 fewer turbines," a larger dependence on offshore wind energy is possible in the near future. Similarly, it was recently announced that larger onshore wind turbines were being produced. The Haliade 150-6MW has a power capacity of 6 MW [68]. This would also decrease the spatial requirements.

The societal impact that onshore wind energy has is greater than both offshore wind energy and solar PV [69]. Research on public acceptance of offshore wind energy has proven that it is far more favorable over onshore wind energy as it does not affect the landscape. Therefore, there is a lesser dependence on it in this scenario.

As for solar PV, the spatial requirements are small in comparison. However, the large seasonal dependence and lack of solar energy in the Netherlands makes it an inefficient production technology for the national energy system. In the CE Delft study, the solar energy includes the production from house rooftops [22]. Integrating solar panels into buildings and windows could also be a possibility to save space.

Hydrogen storage and conversion

The efficiencies in the study that found the salt cavern capacities in the Netherlands were far lower than the electrolysis and CCGT efficiencies used in the model [8]. This could be a source of error in relation to the spatial use for hydrogen storage. When the conversion efficiencies are higher, the charge and discharge rate are affected and could result in faster cycles for storage in salt caverns. However, in this paper's scenario, the required storage was less than a third of the resources calculated to be available in the Netherlands. Therefore, it is already feasible.

The PEM electrolyser used for this model was far more efficient with RES than alkaline electrolysers used in the previous model [7]. It was assumed that each station's capacity was 1 GW [62]. Furthermore, PEM electrolysers are quite costly due to its compact and intricate design when compared to alkaline electrolysers. As they still have not been commercially used in large-scale plans, the reliability and lifetime characteristics still have to be validated [70]. However, this is the case with most new technology included in this research and will likely be solved within the coming year or two given the plans. Anion Exchange Membranes (AEM) are the latest technology in the electrolysis business with only a few companies putting it in the market. There is quite some potential with this new electrode as it combines the best characteristics of the alkine electrolysers with the simplicity and efficiency of a PEM electrolyser [70].

The hydrogen CCGT technology used in this research requires large amounts of water and electrolysis which was not considered in the model [35].

7.3 Spatial planning

Conducting an accurate study on the spatial requirements and comparing them to the land available in the Netherlands proved to be difficult. Data was lacking in many aspects to determine the actual land needed for technologies such as geothermal wells, electrolysers, and CCGT systems.

Geothermal wells do not only require land below the surface, but depending on the type of well, this does not necessarily mean that anything can be built above it. There are several different types of geothermal systems that extract the energy in the form of heat. Often, many pumps are required for the extraction and transmission of heat through the building. This uses electricity which was not included in this model. In addition, geothermal wells tend to be localised and more efficient when used in the surrounding area. This makes it difficult to connect to the grid. Further research must be done to continue that of van Dogen [30] and be incorporated into this model more realistically.

Electrolysers and CCGT are usually a part of a larger system with hydrogen in the grid. This makes it hard to guess how much space is required per unit. In the future, it might be more beneficial to equate the use of hydrogen and its spatial requirement as a system rather than individual technologies. Afterall, they are directly linked.

According to figure 6.6, it seems as though it is feasible to acquire this model given the current land use in the Netherlands. However, to the best of the author's knowledge, there was no value for the amount of *unused* land. It was assumed that agricultural, forest and open nature land can be used for RES. It was evident that offshore wind energy requires the largest area. Knowing that 59,000 km^2 of the North Sea can be used by the Netherlands, 10,979 km^2 is only 19% of the total sea area. Yet, the trade and maritime use of the North Sea must be considered. Through a collaboration with the countries surround the North Sea, it could be possible to facilitate this. There already are plans in place up to 2050 [14]; nonetheless, these could be expanded further.

Therefore, it might be more accurate to investigate the number of systems used as shown in table 17 in appendix D.

7.4 Other technologies

There were many other energy sources that could be included such as biomass, hydro, and nuclear energy. Many research has been done on biomass to the point that there has been a final report given to the government to advise them against the use of biomass on a national level in the future sustainable plan [71]. As for hydroenergy, there is a lot of water flow in the Netherlands but little topological variation making it unrealistic to rely on a large-scale level. However, it could be incorporated locally with the old windmill installation in Limburg and Twente [72]. Nuclear energy is quite reliable and has a long lifetime. Yet, there is a reluctance as it has always been a controversial topic with its environmental impacts and safety precautions. At the moment, there are very little serious discussions around the topic of nuclear energy in the future of the energy transition plan [73]. On the other hand, it has no dependence on the weather so it is much more reliable for constant energy production. It would be beneficial to compare the current scenario with another that includes one nuclear power plant to explore the spatial outcome.

As previously mentioned, water boilers and hybrid heat pumps would considerably affect the heat supply and make the model more realistic. Therefore, they should be added to the model in future research.

7.5 Future research

As previously mentioned, for a nationally balanced energy scenario that is renewable, Dutch municipalities must work together. This must be further investigated through effective policies. Previous studies have looked into this in addition to the economical feasibility for geothermal energy [30]. Policies must be implemented to accelerate the pace at which a plan turns into construction and is connected to the grid.

Moreover, the environmental impacts of such a scenario must be examined. For example, geothermal doublets can have quite an impact on the earth as proven by previous research [74, 75]. The effects of storing hydrogen in salt caverns has also previously been researched [76]. Yet, a complete environmental analysis covering the entire scope of this model has not been done.

8 Conclusion

There is an infinite amount of ways to achieve a balanced energy scenario using the model. However, given the boundary conditions and the spatial capacity of the Netherlands, there are more factors to be considered that are not necessarily in the model. For example, the transportation sector would contribute nearly 20% to the energy demand. The most important thing to note about the different scenarios is that the technological aspects were not found in the literature. Transparency and consistency is key in building and comparing scenarios made by other authors and organisations.

Furthermore, the efficiencies of the technologies included in this research are constantly increasing. Simply by comparing it to the research done using the same modeling method, it is clear that the efficiencies have significantly improved [7]. The fast paced direction that the world is moving in will make it all the more economically feasible which in turn will make it possible in every aspect. Additionally, the aforementioned technologies in section 7.4 such as hybrid heat pumps and nuclear energy, could potentially solve any problems presented in this scenario and make it comparable to the real world.

Weather patterns hold the greatest uncertainty in models as it is constantly changing. Considering the worst year in the past and modeling that in combination with future energy demands would greatly improve the results found. The country would be better prepared for a crisis or energy shortage in that sense. Therefore, including a reliable energy source like nuclear power plants could be a potential solution to combat the unpredictable weather changes.

Overall, this research answered the questions asked. There is a wide variety of RES, storage and conversion technologies that are improving at an accelerating speed. The scenario was balanced and reachable given the current Dutch spatial capacity. In addition, the power output of each technology was the most sensitive component of the systems meaning that generally the larger the technology, the higher the efficiency. In conclusion, it is possible to have a self sufficient energy supply on a national level. It is up to policy makers to make the change and accelerate the process towards a more sustainable future.

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References

[1] IEA, “The netherlands 2020,” 2020, energy Policy Review by the IEA. [Online]. Available: https://www.iea.org/reports/the-netherlands-2020

[2] UNFCC, “Paris agreement,” Paris, France, November 2018.

[3] R. Viral and D. Khatod, “Optimal planning of distributed generation systems in distribution system: A review,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, pp. 5146–5165, 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032112003498

[4] S. Impram, S. Varbak Nese, and B. Oral, “Challenges of renewable energy penetration on power system flexibility: A survey,” *Energy Strategy Reviews*, vol. 31, p. 100539, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211467X20300924

[5] B. Tarroja, F. Mueller, J. D. Eichman, and S. Samuelsen, “Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing,” *Energy*, vol. 42, no. 1, pp. 546–562, 2012, 8th World Energy System Conference, WESC 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544212001351

[6] F. Ueckerdt, R. Brecha, G. Luderer, P. Sullivan, E. Schmid, and N. B. et al., “Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves,” *Energy*, vol. 90, pp. 1799–1814, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544215008993

[7] A. in ‘t Veld, “Green hydrogen gas in the netherlands: A system comparison between an electricity based and a gas-based energy system,” Master’s thesis, University of Groningen, 2020.

[8] M. Susan, “Exploring the energy storage capacity of salt caverns in the netherlands,” Master’s thesis, University of Groningen, 2019.

[9] H. Ritchie, “Which countries are most densely populated?” [Online]. Available: https://ourworldindata.org/most-densely-populated-countries

[10] CBS, “CBS open data statline,” 2021.

[11] “Het energiesysteem van de toekomst,” Netbeheer Nederland, Tech. Rep., April 2021.

[12] B. den Ouden, J. Kerkhoven, J. Warnaars, R. Terwel, M. Coenen, and T. V. et al., “Toekomstscenario’s II3050,” Berenschot and Kalavasta, Tech. Rep. 61689, March 2020.

[13] J. Sijm, G. Janssen, G. Morales-Espana, J. van Stralen, R. Hernandez-Serna, and K. Smekens, “The role of large-scale energy storage in the energy system of the netherlands, 2030-2050,” TNO, Tech. Rep. 060.36821, August 2020.

[14] J. Matthijsen, E. Dammers, and H. Elzenga, “The future of the north sea,” PBL, Tech. Rep. 2728, 2018.

[15] M. Werther, W. van Hooff, K. Colijn, and R. Blokdijk, “Next generation solar power,” Dutch Enterprise Agency (RVO), Tech. Rep., 2020.

[16] F. Pierie, “Perspective on the development of the we-energy tool,” 2018.

[17] F. Pierie, C. E. van Someren, S. N. Kruse, G. A. Laugs, R. M. Benders, and H. C. Moll, “Local balancing of the electricity grid in a renewable municipality; analyzing the effectiveness and cost of

decentralized load balancing looking at multiple combinations of technologies," *Energies*, vol. 14, no. 16, p. 4926, 2021.

[18] R. G. Sargent, "Verification and validation of simulation models," in *Proceedings of the 2010 winter simulation conference.* IEEE, 2010, pp. 166–183.

[19] F. Pierie, C. van Someren, W. Liu, J. Bekkering, E. J. Hengeveld, and J. e. a. Holstein, "An integrated approach for the validation of energy and environmental system analysis models: Used in the validation of the flexigas excel biogas model," 2016.

[20] PBL, "Netherlands climate and energy outlook 2019," Nov 2019. [Online]. Available: https://www.pbl.nl/publicaties/klimaat-en-energieverkenning-2019

[21] ——, "Netherlands climate and energy outlook 2020," Oct 2020. [Online]. Available: https://www.pbl.nl/publicaties/klimaat-en-energieverkenning-2020

[22] M. Afman and F. Rooijers, "Net voor de toekomst," *CE Delft*, November 2017.

[23] Gasunie and TenneT, "Infrastructure outlook 2050." [Online]. Available: https://www.tennet.eu/company/publications/infrastructure-outlook-2050/

[24] Quintel, "Energy transition model." [Online]. Available: https://pro.energytransitionmodel.com/

[25] T. njoroge, "Uk to build world's largest hydrogen electrolysis plant in germany," Jul 2019. [Online]. Available: https://constructionreviewonline.com/news/uk-to-build-worlds-largest-hydrogen-electrolysis-plant-in-germany/

[26] *HA technology now available at industry-first 64 percent efficiency*, Dec 2017. [Online]. Available: https://www.ge.com/news/press-releases/ha-technology-now-available-industry-first-64-percent-efficiency

[27] A. Durakovic, "Vestas launches 15 mw offshore wind turbine," News article, February 2021.

[28] Stichting Platform Geothermie, Dutch Association of Geothermal Operators, Stichting Warmtenetwerk, and Energie Beheer Nederland, "Masterplan geothermal energy in the netherlands," 2018.

[29] EBN, "Ebn annual report 2020," 2021.

[30] B. van Dongen, "The economic potential of deep, direct use geothermal systems in the netherlands," 2019.

[31] R. Nordman, A. Zottl, and M. Miara, "Benchmarking method of seasonal performance under consideration of boundary conditions," 2012.

[32] J. Bernholz, "Rwe‘s former, current and possible future energy storage applications," RWE Technology International GmbH, Tech. Rep., September 2018.

[33] R. Markillie, "Energy storage: Significant system efficiency of 86% for rwe power-to gas plant," 2015. [Online]. Available: https://www.linkedin.com/pulse/energy-storage-significant-system-efficiency-86-rwe-gas-markillie

[34] A. Prasanna and V. Dorer, "Feasibility of renewable hydrogen based energy supply for a district," *Energy Procedia*, vol. 122, pp. 373–378, Sep. 2017. [Online]. Available: https://doi.org/10.1016/j.egypro.2017.07.420

[35] GE, *9HA.02*, 2020.

[36] "Total load - day ahead." [Online]. Available: https://transparency.entsoe.eu/

[37] G. transport services, "Gas balance 2015," Tech. Rep., May 2016. [Online]. Available: https://www.gasunietransportservices.nl/en/downloads-en-forms

[38] J. Dielesen, "Heat tariffs to increase in 2019 because of taxes and link with gas price." [Online]. Available: https://www.acm.nl/en/publications/heat-tariffs-increase-2019-because-taxes-and-link-gas-price

[39] C. Willems and H. M. Nick, "Towards optimisation of geothermal heat recovery: An example from the west netherlands basin," *Applied Energy*, vol. 247, pp. 582–593, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261919307469

[40] "Uurgegevens van het weer in nederland (hourly data for the weather in the netherlands)," 2021. [Online]. Available: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens

[41] I. Staffell, D. Brett, N. Brandon, and A. Hawkes, "A review of domestic heat pumps," *Energy & Environmental Science*, vol. 5, no. 11, pp. 9291–9306, 2012.

[42] L. Bauer and S. Matysik, "Welcome to wind-turbine-models.com." [Online]. Available: https://en.wind-turbine-models.com/

[43] C. Desmond, J. Murphy, L. Blonk, and W. Haans, "Description of an 8 mw reference wind turbine," in *Journal of Physics: Conference Series*, vol. 753, no. 9. IOP Publishing, 2016, p. 092013.

[44] M. de Haij, "Automatische validatie van druk- en windwaarnemingen op het knmi - een verkenning," 2009.

[45] C. Bouty, S. Schafhirt, L. Ziegler, and M. Muskulus, "Lifetime extension for large offshore wind farms: Is it enough to reassess fatigue for selected design positions?" *Energy Procedia*, vol. 137, pp. 523–530, 2017.

[46] J. Wieringa and P. J. Rijkoort, "Windklimaat van nederland," *ISBN 9012044669*, 1983.

[47] "Uurgegevens van noordzee stations (hourly data from the north sea stations)." [Online]. Available: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens_Noordzee

[48] Powerfield, "Ontwikkeling & realisatie van zonneparken en zonnedakprojecten." [Online]. Available: https://www.powerfield.nl/projecten/

[49] Zonnefabriek, *SunPower Maxeon 3 solar panel*, June 2020.

[50] L. USA, *LG440QAC-A6: 440W*, 2021.

[51] Zonnefabriek, *SUNNY BOY 1.5 / 2.0 / 2.5 with SMA SMART CONNECTED*, 2020.

[52] Jul 2021. [Online]. Available: https://refhyne.eu/

[53] "Electrolyzers: the production of industrial hydrogen on-site, on demand, according to your specifications," 2019. [Online]. Available: https://mcphy.com/en/equipment-services/electrolyzers/

[54] "Integration of hydrohub gw electrolysis facilities in five industrial clusters in the netherlands," Institute for Sustainable Process Technology, Tech. Rep., June 2020.

[55] F. Crotogino, S. Donadei, U. Bünger, and H. Landinger, “Large-scale hydrogen underground storage for securing future energy supplies,” in *18th World hydrogen energy conference*, vol. 78, 2010, pp. 37–45.

[56] M. A. Pellow, C. J. M. Emmott, C. J. Barnhart, and S. M. Benson, “Hydrogen or batteries for grid storage? a net energy analysis,” *Energy & Environmental Science*, vol. 8, no. 7, pp. 1938–1952, 2015. [Online]. Available: https://doi.org/10.1039/c4ee04041d

[57] “‘the effects of hydrogen injection in natural gas networks for the dutch underground storages’,” Netherlands Enterprise Agency, Final report RVO-079-1701/RP-DUZA, July 2017.

[58] “Eems ccgt power plant netherlands.” [Online]. Available: http://globalenergyobservatory.org/geoid/44495

[59] T. Christiansen, “Orsted’s first dutch offshore wind farm fully commissioned,” November 2020. [Online]. Available: https://orsted.com/en/media/newsroom/news/2020/11/448070886682487

[60] Svevind, “Onusberget – part of markbygden phase 3,” February 2021. [Online]. Available: https://svevind.se/en/portfolio-items/onusberget/

[61] C. solar, “Largest solar park in the netherlands is now operational,” April 2019. [Online]. Available: https://www.chintsolar.nl/en/news/largest-solar-park-in-the-netherlands-is-now-operational/

[62] D. THOMAS, “Large scale pem electrolysis: technology status and upscaling strategies,” October 2019.

[63] “Capacity densities of european offshore wind farms,” Deutsche WindGuard GmbH, Tech. Rep., 2018.

[64] M. van Defensie, “Netherlands boundaries in the north sea,” Mar 2021. [Online]. Available: https://english.defensie.nl/topics/hydrography/maritime-limits-and-boundaries/netherlands-boundaries-in-the-north-sea

[65] N. S. Energy, “Energy atlas.” [Online]. Available: https://north-sea-energy.eu/en/energy-atlas/

[66] H. Mijnlieff, A. Obdam, J. van Wees, M. Pluymaekers, and J. Veldkamp, “Doubletcalc 1.4 manual,” TNO, Tech. Rep., 2014.

[67] B. Rasmus, R. Knud, W. Anna-Kathrin, and L. Silke, “Capacity densities of european offshore wind farms,” *Deutsche Wind Guard GmbH, Germany*, 2018.

[68] G. R. Energy, “Haliade 150-6mw offshore wind turbine,” 2021.

[69] A. P. Dion, “Public acceptance of offshore wind farms in the netherlands: testing and adjusting the public acceptance models for a better wind of change,” Master’s thesis, University of Twente, 2019.

[70] E. Taibi, H. Blanco, R. Miranda, and M. Carmo, “Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°c climate goal,” 2020.

[71] “Biomass in balance.” Socio-Economic Council (SER), July 2020.

[72] W. J. Klunne, “Hydropower in the netherlands.” [Online]. Available: http://www.microhydropower.net/nl/index_uk.php

[73] P. Boot, “The netherlands needs a serious discussion on nuclear energy,” January 2021.

[74] F. van de Watering and R. van der Velde, "(environmental) impact of inhibitors applied in the geothermal sector in the netherlands," *European Geothermal Congress*, June 2019.

[75] M. Bošnjaković, M. Stojkov, and M. Jurjević, "Environmental impact of geothermal power plants," *Tehnički vjesnik*, vol. 26, no. 5, pp. 1515–1522, 2019.

[76] M. P. Laban, "Hydrogen storage in salt caverns: Chemical modelling and analysis of large-scale hydrogen storage in underground salt caverns." Master's thesis, Delft University of Technology, 2020.

[77] "Engineering toolbox," 2001. [Online]. Available: https://www.engineeringtoolbox.com

Appendices

A Model verification details

Data relationship correctness

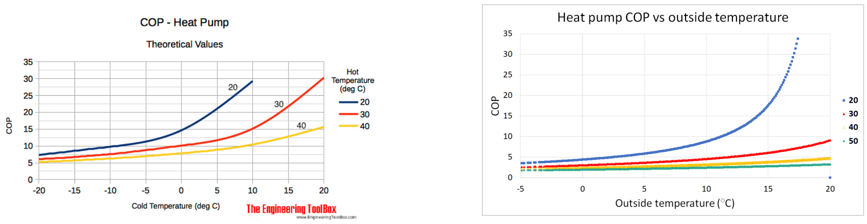
Geothermal heating: In the geothermal heat sheet, the number of doublets and maximum capacity per well can be changed. These should have a linear affect on the produced heat. As the number of doublets and capacity per well approaches zero, the geothermal heating produced approaches zero. This is confirmed through the plot of the heat input NLS compared to the heat output NLS.

Hydrogen CCGT: The electricity generated by CCGT was determined by considering the shortage of electricity to balance the demand. Therefore, it is dependent on the electricity input NLS at this point.

The 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, electrolyser efficiency and maximum capacity. Electricity consumption and hydrogen production total is determined by consumption/production single unit times number of units.

Event validity

Heat pump: Similarly to previous research, the relation between the COP and the difference between the outside temperature and the hot water temperature were compared to a reference plot [7]. The plots are shown in figure A.1. From this it can be confirmed that the calculations were correctly implemented in the model.



(a) Reference plot

(b) Model plot

Figure A.1: 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 [77].

As the Carnot correction factor and the temperature of inserted hot water were increased and their data correctness relationship have been confirmed, then the daily pattern of energy consumption of the heat pump can also be verified from the previous event validity [7].

Renewable energy sources: For the wind turbines and solar PV sheets, the Dutch energy production can be compared with the model results data obtained using StatLine results [1] In 2020, 4159 MW onshore wind capacity was installed to produce 8960 GWh. In comparison, when 4159 MW was installed in the model, 6574 GWh was produced. This is about 73% of the measured production from StatLine. However, the weather pattern used in the model is from 2015. In 2015, 3034 MW was installed to produce

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[1] `https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610NED/table?ts=1582731738506`.

5882 GWh. In comparison, 4796 GWh is produced in the model. This is about 82% of the value which is closer to the real value. Meaning that the weather pattern could be a factor.

Extreme condition test

For geothermal heating, if the production rate or volumetric heat capacity is set to zero, then no heat is produced. The same goes for when the number of doublets or the efficiencies are set to zero. Hence, no heating is produced from geothermal heating in the extreme condition that its inputs are set to zero.

B Surplus geothermal energy

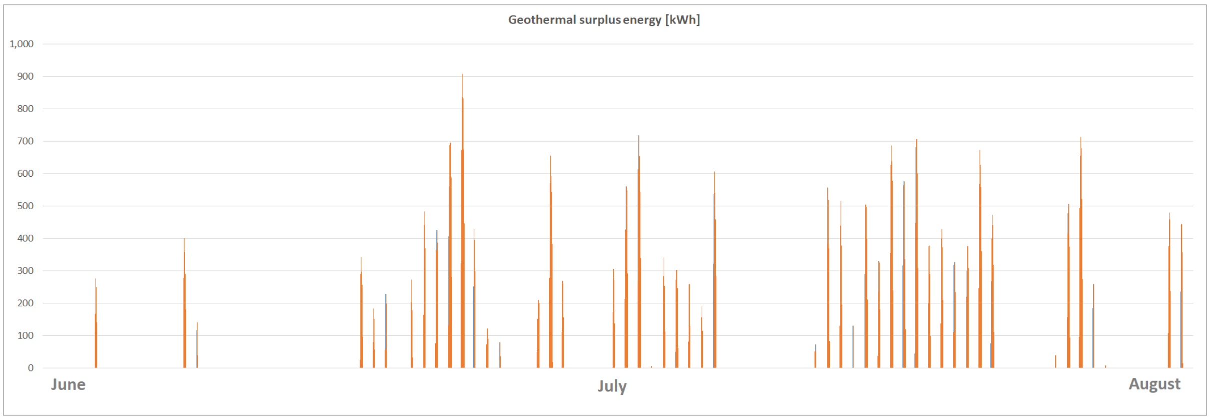

Figure B.1: Surplus geothermal energy from domestic heating. The total surplus energy was 70 GWh in some hours of the summer only.

C NLD curves

The NLDC of electricity and hydrogen gas was separately graphed for the different scenarios: without geothermal, without hydrogen storage, without electrolysers, and without CCGT.

NLDC electricity

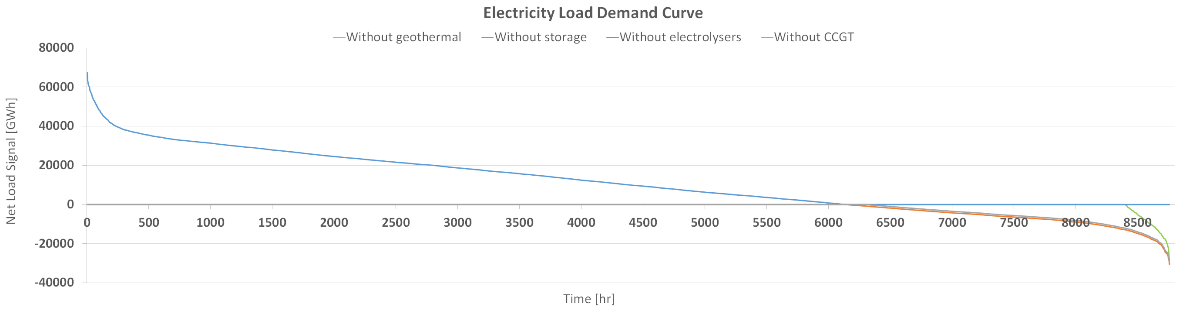

Figure C.1: A graph of the electricity NLDC over every hour in a year. Geothermal seems to have the least effect on the NLDC as there is a deficit in electricity only for a few hours in the year. In contrast, electrolysers seem to have the most effect as the NLDC starts in the overproduction part of the graph and then balances. The NLDC of a scenario without storage of CCGT overlap and show a deficit for over 200 hours.

NLDC hydrogen gas

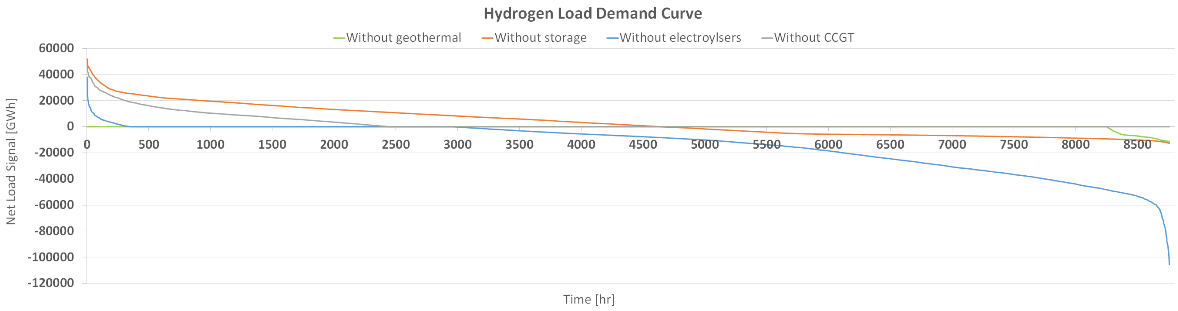

Figure C.2: A graph of the hydrogen gas NLDC over every hour in a year. Similar to the electricity NLDC in figure C.1, geothermal seems to have the least effect while electrolysers have the most effect on the NLDC. However, there is more deviation in this graph from the balanced one. The hydrogen NLDC starts with overproduction in all cases but geothermal and results in demand for all except CCGT.

D Amount of systems required

As it was difficult to estimate the space required for each system, it may be a better indication to look into the number of turbines or solar fields required, for example. This is shown in table 17.

Table 17: The number of technologies required per production, conversion or storage system.

Geothermal heating	Amount of doublets	175	[28]
Offshore wind	Amount of turbines	4000	
Onshore wind	Amount of turbines	2000	
Solar PV	Amount of solar fields	364	
Electrolyser	Amount of electrolysis plants	3380	
Salt cavern	Amount of salt caverns	101	
Hydrogen CCGT	Amount of gas turbines	39	

E Sensitivity analysis details

In the next page, the capacity sensitivity analysis and spatial sensitivity analysis are tabulated by each input variable and output. The orange cells are positive numbers indicating an increase in output while the red cells are negative numbers indicating a decrease in output. The green cells indicate no change in output. All numbers are rounded to 3 significant figures.

SHEET	Variable	Original value	Change in output compared to original Total electricity consumed		Change in output compared to original Total electricity produced		Change in output compared to original Total hydrogen consumed		Change in output compared to original Total hydrogen produced		Change in output compared to original Shortage in hydrogen		Change in output compared to original Shortage in hydrogen [hours]		Change in output compared to original Surplus geothermal energy	
			+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
Electricity demand	Electricity demand savings	75%	-0,038	0,047	0,000	0,000	0,163	-0,150	-0,038	0,047	-0,364	0,406	-0,351	0,517		
Heat demand	Heat demand savings	77%	-0,027	0,035	0,000	0,000	0,111	-0,105	-0,027	0,035	-0,249	0,294	-0,264	0,344		
	Gas-to-heat efficiency	88%	-0,023	0,031	0,000	0,000	0,097	-0,092	-0,023	0,031	-0,215	0,261	-0,227	0,314		
Gas demand	Gas demand savings	40%	0,004	0,004	0,000	0,000	0,000	0,000	0,004	0,004	-0,597	0,645	-0,598	0,750		
Electric heat pump	Carnot factor	0,3	0,021	-0,018	0,000	0,000	-0,060	0,076	0,021	-0,018	0,179	-0,166	0,233	-0,167		
	Temperature outside	-	0,137	-0,118	0,000	0,000	-0,391	0,500	0,137	-0,118	**1,127**	**-1,000**	**1,181**	**-1,000**		
	Temperature space heating water	50	-0,016	0,024	0,000	0,000	0,069	-0,069	-0,016	0,024	-0,149	0,202	-0,158	0,253		
Offshore wind	Wind pattern per hour	-	0,181	-0,203	0,126	-0,144	-0,189	0,266	0,181	-0,203	**1,137**	**-1,000**	**1,239**	**-1,000**		
	Installed capacity	60000	0,144	-0,135	0,094	-0,088	-0,056	0,067	0,144	-0,135	0,808	-0,765	0,733	-0,745		
	Power output turbine	10	0,004	0,004	0,003	0,003	0,000	0,000	0,004	0,004	0,024	0,024	0,035	0,035		
	Turbine efficiency	100%	0,144	-0,135	0,094	-0,088	-0,056	0,067	0,144	-0,135	0,808	-0,765	0,733	-0,745		
	Hub height turbine	140	0,017	-0,012	0,012	-0,008	-0,016	0,018	0,017	-0,012	0,112	-0,075	0,159	-0,077		
	Heigh measurement location		-0,011	0,020	-0,008	0,014	0,017	-0,019	-0,011	0,020	-0,073	0,131	-0,075	0,187		
	Roughness location	0,0002	0,005	0,002	0,004	0,002	-0,001	0,002	0,005	0,002	0,032	0,015	0,057	0,017		
Onshore wind	Wind pattern per hour	-	0,008	-0,007	0,005	-0,005	-0,009	0,005	0,008	-0,007	0,049	-0,044	0,073	-0,037		
	Installed capacity	4000	0,007	0,000	0,005	0,000	-0,002	0,002	0,007	0,000	0,045	0,003	0,068	0,006		
	Power output turbine	5	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		
	Turbine efficiency	100%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		
	Hub height turbine	110	0,005	0,003	0,003	0,002	-0,001	0,001	0,005	0,003	0,031	0,018	0,053	0,021		
	Heigh measurement location		0,002	0,006	0,001	0,004	0,002	-0,003	0,002	0,006	0,014	0,038	0,013	0,063		
	Roughness location	0,03	0,001	-0,001	0,001	0,000	-0,001	0,001	0,001	-0,001	0,005	-0,004	0,006	-0,002		
Solar PV	Solar irradiance pattern per hour	-	0,009	-0,008	0,007	-0,007	-0,021	0,023	0,009	-0,008	0,067	-0,068	0,115	-0,060		
	Installed capacity	17500	0,009	-0,008	0,007	-0,007	-0,021	0,023	0,009	-0,008	0,067	-0,068	0,115	-0,060		
	Power output panel	420	-0,008	0,010	-0,006	0,008	0,021	-0,023	-0,008	0,010	-0,062	0,074	-0,057	0,124		
	Solar panel efficiency	22%	0,039	-0,037	0,030	-0,031	-0,079	0,121	0,039	-0,037	0,287	-0,317	0,408	-0,307		
	Inverter efficiency	96%	0,009	-0,009	0,007	-0,007	-0,021	0,024	0,009	-0,009	0,070	-0,071	0,118	-0,062		
	Surface area per panel	1,88	0,009	-0,008	0,007	-0,007	-0,021	0,023	0,009	-0,008	0,067	-0,068	0,115	-0,060		
Electrolyser	Plant capacity	20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		
	Electrolyser efficiency	86%	0,000	0,000	0,000	0,000	0,000	0,000	0,116	-0,116	0,603	-0,603	0,543	-0,554		
Storage	Storage capacity	34600	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	-0,064	0,064	-0,064	0,078		
	Max. charge power	0,42%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	**-1,000**	**-1,000**	0,000	**-1,000**		
	Max. discharge power	0,42%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	**-1,000**	**-1,000**	**-1,000**	**-1,000**		
	Charge efficiency	99%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,384	-0,470	0,485	-0,465		
	Discharge efficiency	99%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,325	-0,398	0,420	-0,388		
	Depth of discharge	100%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	**1,104**	0,000	**3,200**	0,000		
	Self-discharge	0%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	**-1,710**	**13336,943**	**-1,000**	**4,895**		
	Start state	50%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,129	-0,129	0,147	-0,128		
H2 CCGT	Turbine capacity	800	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000		
	Turbine efficiency	64%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,143	-0,195	0,209	-0,207		
Geothermal	Number of doublets	175	0,004	-0,004	0,000	0,000	-0,016	0,016	0,004	-0,004	0,037	-0,038	0,058	-0,050	**1,102**	-0,689
	Production rate	360	0,004	-0,004	0,000	0,000	-0,016	0,016	0,004	-0,004	0,037	-0,038	0,058	-0,050	**1,102**	-0,689
	Production temperature	95	0,007	-0,007	0,000	0,000	-0,024	0,025	0,007	-0,007	0,059	-0,060	0,085	-0,071	**1,959**	-0,885
	Volumetric heat capacity	3,92	0,004	-0,004	0,000	0,000	-0,016	0,016	0,004	-0,004	0,037	-0,038	0,058	-0,050	**1,102**	-0,689
	Injection temperature	35	-0,002	0,002	0,000	0,000	0,009	-0,009	-0,002	0,002	-0,022	0,022	-0,035	0,037	**1,715**	0,586
	Pumps efficiency	70%	0,006	-0,006	0,000	0,000	-0,022	0,023	0,006	-0,006	0,053	-0,054	0,079	-0,064	**1,715**	-0,846
	System efficiency	98%	0,004	-0,004	0,000	0,000	-0,016	0,016	0,004	-0,004	0,038	-0,039	0,058	-0,051	**1,128**	-0,698

SHEET	Variable	Original value	Change in output compared to original Space required total		Change in output compared to original Space required specific tech		Change in output compared to original Amount of electrolysers		Change in output compared to original Amount of salt caverns		Change in output compared to original Amount of CCG turbines	
			+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
Electricity demand	Electricity demand savings	75%	0,053	0,020	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Heat demand	Heat demand savings	77%	0,035	0,003	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Gas-to-heat efficiency	88%	0,028	-0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Gas demand	Gas demand savings	40%	0,087	0,062	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Electric heat pump	Carnot factor	0,3	-0,004	0,023	0,000	0,000	0,000	-0,006	-0,105	0,263	-0,051	0,077
	Temperature outside	-	0,000	-0,007	0,000	0,000	0,000	0,000	0,000	0,053	0,000	0,000
	Temperature space heating water	50	0,018	-0,005	0,000	0,000	-0,006	0,003	0,263	-0,126	0,051	-0,051
Offshore wind	Wind pattern per hour	-	0,087	0,132	0,000	0,000	0,012	-0,009	**1,284**	**1,947**	0,000	0,000
	Installed capacity	29925	0,183	0,018	0,154	-0,154	0,091	-0,091	**1,358**	**1,589**	0,000	0,000
	Power output turbine	10	-0,053	0,065	-0,091	0,111	0,000	0,000	0,000	0,000	0,000	0,000
	Turbine efficiency	100%	0,044	0,065	0,000	0,000	0,058	-0,061	0,642	0,947	0,000	0,000
	Hub height turbine	140	-0,003	0,006	0,000	0,000	0,000	0,000	-0,042	0,084	0,000	0,000
	Heigh measurement location		0,006	-0,005	0,000	0,000	0,000	0,000	0,084	-0,074	0,000	0,000
	Roughness location	0,0002	-0,003	-0,001	0,000	0,000	0,000	0,000	-0,042	-0,011	0,000	0,000
Onshore wind	Wind pattern per hour	-	0,004	0,029	0,000	0,000	0,027	-0,058	0,053	0,421	0,000	0,000
	Installed capacity	22275	0,038	-0,031	0,182	-0,182	0,042	-0,042	-0,084	0,200	0,000	0,000
	Power output turbine	5	0,000	0,000	-0,091	0,111	0,000	0,000	0,000	0,000	0,000	0,000
	Turbine efficiency	100%	-0,004	0,008	0,000	0,000	0,021	-0,024	-0,053	0,116	0,000	0,000
	Hub height turbine	110	-0,002	-0,001	0,000	0,000	0,006	-0,009	-0,032	-0,011	0,000	0,000
	Heigh measurement location		0,002	-0,002	0,000	0,000	-0,012	0,006	0,032	-0,032	0,000	0,000
	Roughness location	0,03	-0,003	0,000	0,000	0,000	0,003	-0,006	-0,042	0,011	0,000	0,000
Solar PV	Solar irradiance pattern per hour	-	-0,002	0,013	0,000	0,000	0,030	-0,033	-0,021	0,189	0,000	0,000
	Installed capacity	253125	-0,003	0,003	0,044	-0,044	0,012	-0,015	-0,042	0,053	0,000	0,000
	Power output panel	420	0,012	-0,002	-0,091	0,111	-0,030	0,033	0,200	-0,053	0,000	0,000
	Solar panel efficiency	22%	0,034	0,078	0,000	0,000	0,112	-0,139	0,495	**1,147**	0,000	0,026
	Inverter efficiency	96%	-0,004	0,013	0,000	0,000	0,030	-0,033	-0,063	0,189	0,000	0,000
	Surface area per panel	1,88	-0,005	0,013	0,000	0,000	0,030	-0,033	-0,074	0,189	0,000	0,000
Electrolyser	Plant capacity	20	0,000	0,000	0,000	0,000	-0,091	0,109	0,000	0,000	0,000	0,000
	Electrolyser efficiency	86%	0,029	0,049	0,000	0,000	0,009	0,000	0,432	0,726	0,000	0,000
Storage	Storage capacity	34600	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Max. charge power	0,42%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Max. discharge power	0,42%	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Charge efficiency	99%	0,019	0,043	0,000	0,000	0,000	0,000	0,274	0,632	0,000	0,000
	Discharge efficiency	99%	0,011	0,055	0,000	0,000	0,000	0,000	0,158	0,811	0,000	0,000
	Depth of discharge	100%	0,000	0,162	0,000	0,000	0,000	0,000	0,000	**2,379**	0,000	0,000
	Self-discharge	0%	**-1,000**	**-1,000**	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
H2 CCGT	Turbine capacity	800	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	-0,077	0,128
	Turbine efficiency	64%	-0,013	0,028	0,000	0,000	0,000	0,000	-0,189	0,411	0,000	0,000
Geothermal	Number of doublets	175	0,006	-0,006	0,100	-0,100	0,000	-0,003	-0,029	0,045	0,000	0,000
	Production rate	360	-0,002	0,003	0,000	0,000	0,000	-0,003	-0,029	0,045	0,000	0,000
	Production temperature	95	-0,003	0,005	0,000	0,000	0,000	-0,003	-0,040	0,083	0,000	0,026
	Volumetric heat capacity	3,92	-0,002	0,003	0,000	0,000	0,000	-0,003	-0,032	0,042	0,000	0,000
	Injection temperature	35	0,001	-0,001	0,000	0,000	0,000	-0,003	0,011	-0,011	0,000	0,000
	Pumps efficiency	70%	-0,004	0,002	0,000	0,000	0,000	-0,003	-0,053	0,042	0,000	0,026
	System efficiency	98%	-0,002	0,003	0,000	0,000	0,000	-0,003	-0,028	0,042	0,000	0,000