Hydrogen storage in future Dutch energy scenarios: a comparative analysis

Bachelor's thesis in Physics

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Abstract:

Large-scale implementation of hydrogen as an energy carrier will necessitate petajoule-scale hydrogen storage in the Netherlands. Using the Energy Transition Model, the required storage capacity for six different climate-neutral Dutch energy scenarios is determined. Total capacity in these scenarios ranges from 10 PJ to 198 PJ. It is then shown that, in each case, the required capacity can be constructed domestically in the Netherlands using a combination of above-ground pressurized gas storage tanks, underground storage in salt caverns and underground storage in gas fields.

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1 - Introduction

The Dutch energy system is going through major changes. Since the discovery of the Slochteren gas field in 1959, the Netherlands has been heavily dependent on natural gas to supply energy to heat homes, generate electricity, and fuel high-temperature industrial processes. In 2019, 44% of total energy use in the Netherlands was powered by natural gas. 58% of all electricity was generated in gas-fired power plants, while renewables only accounted for 18% (Energie in Nederland n.d.). The energy system of the future is going to look much different. There are two (rather obvious) reasons for this. Firstly, extraction from the Groningen gas field will be shut down by the end of 2022, because of increasing concerns about the earthquakes it causes (*Rijksoverheid* 2019). But most important is the factor of climate change. The Paris Agreement was signed by 196 countries in 2015, in which they commit to keep global warming to below 2 degrees Celsius. In order for the Netherlands to reach its climate goals, carbon emissions have to be drastically reduced (United Nations Framework Convention on Climate Change 2016). A shift away from natural gas and other fossil fuels towards renewable energy sources is inevitable if the goals are to be met.

Slowly but surely, this energy transition is starting to take shape. Each year, renewable sources account for a larger share of total energy production (Central Bureau for Statistics 2020). Houses are being insulated and electric cars are becoming more much common – 25% of cars sold in 2020 were hybrid or electric ("Isolatiemaatregelen Woningen, 1982-2018" 2018; Wijngaarden 2021). But we are not yet close to a carbon-neutral society, and many crucial decisions will have to be made in the coming years when it comes to the energy system of the future. Perhaps the most important of these decisions is choosing which energy carriers will be assigned key roles in our energy system to replace fossil fuels.

Numerous reports and studies have tried to model or predict the energy system of the future (Detz, Lenzmann, and Weeda 2019; den Ouden et al. 2020; Afman and Rooijers 2017). In most of them, electricity becomes the most important carrier of energy. Many appliances that currently use fossil-based fuels will be electrified in the future. Aside from electricity, another carrier that plays a large role in many scenarios is hydrogen. This gaseous fuel does not produce greenhouse gases upon combustion; only water is produced, making hydrogen a carbon-neutral option if it is produced with renewable electricity. Hydrogen can provide a solution for applications that are not easily electrified, such as high-temperature industrial processes and heavy-duty transportation vehicles, and can potentially also be used to replace natural gas to heat homes.

Hydrogen can be produced through electrolysis of water – if this is done using renewable energy, the hydrogen is called *green hydrogen* (Shiva Kumar and Himabindu 2019). This process can also be reversed: hydrogen fuel cells convert hydrogen and oxygen to water, generating electricity (Dincer and Zamfirescu 2014). Hydrogen can thus be used as a way to store electrical energy, similar to a battery.

Perhaps the most important future application of hydrogen is as a means of energy storage (Gabrielli et al. 2020; Heinemann et al. 2021). In a carbon-neutral society, our energy will be produced by renewable sources such as wind and solar. But these sources do not provide a steady supply of electricity: wind turbines can only produce electricity when the wind blows, solar panels can only produce electricity when the sun shines. At one moment, our renewable electricity sources may produce much more electricity than is needed at that moment, and at another time electricity demand may be much greater than what can be produced. In a renewable energy system, it is thus crucial that there is a way to store excess electrical energy from peak production times. This stored energy can then be used to balance the electricity grid in times when renewable production is low. Hydrogen is a prime candidate for storing electrical energy. During times of peak electricity production, the excess electricity is used to generate hydrogen through hydrolysis. This hydrogen is then stored until electricity is needed to supplement renewable production, when the process gets reversed to generate electricity from the hydrogen, which is then 'sent onto' the electricity grid to ensure power demand can be met (Heinemann et al. 2021).

In a nationwide energy system where hydrogen is implemented at a large scale to balance the electricity grid, to generate heat for industry and homes and to fuel vehicles, storage capacities at the scale of several petajoules will be required, as this study will show.

The aim of this research is to explore how much hydrogen storage capacity will be needed in a carbon-neutral Netherlands. To this end, several scenarios that describe the future Dutch energy system are first compared in Chapter 2. Using the Energy Transition Model (ETM), the required hydrogen storage capacity for each of these scenarios is determined. Next, different methods of hydrogen storage are introduced in Chapter 3. It is then described how the required storage capacities of the different scenarios could be achieved using these methods.

This research aims to provide quantitative figures concerning storage capacities and hydrogen use, as well as a qualitative analysis of the feasibility of realizing the storage volumes required for different energy scenarios. By doing this, I hope to contribute to the understanding of the possibilities and challenges of hydrogen as a major factor in the Dutch energy system.

2 – Background

2.1 – Hydrogen storage options

There are several different techniques that can be used to store hydrogen, some of which are more suitable to seasonal storage than others. Three main techniques for the storage of hydrogen can be discerned: above-ground tanks, underground storage in salt caverns and underground storage in gas fields. The first two are currently already fully developed and in operation around the world, while the latter is still in its research phase.

2.1.1 – Tanks

Currently, most hydrogen is stored above the ground in tanks. It may be stored either as a high-pressure gas or more commonly as a liquid. Since liquid hydrogen must be stored at a temperature of 20K, super-insulated cryogenic storage tanks, known as dewars, are most commonly used (US Department of Energy n.d.). These storage tanks are in use both at hydrogen production facilities and end-use industrial sites. Cryogenic storage dewars are not, however, an ideal candidate for large-scale hydrogen storage to support the energy system. This is because it costs a lot of energy to cool down hydrogen to a liquid state, around 10 kWh per kg (Connelly et al. 2019). This energy would then have to be supplied through some other route, meaning that the total energy content stored in the hydrogen is less than the total energy used to produce and store the hydrogen (Jasminská et al. 2014). This makes liquid hydrogen storage an inefficient method of storing very large quantities of hydrogen with the purpose of energy storage.

High-pressure gaseous storage of hydrogen in tanks is thus the preferred way of storing hydrogen in tanks, though also not perfect. Pressurization of hydrogen costs less energy than cooling it to 20K, but storage of hydrogen in gaseous instead of liquid form requires much larger storage tanks. Above-ground hydrogen storage in tanks usually does not happen at pressures higher than 100 bar; at this pressure, the volumetric energy content of hydrogen is 936 MJ/m^3 (Andersson and Grönkvist 2019). Seasonal storage of hydrogen at a scale of several petajoules thus requires a large number of very large tanks to be built, which comes at a significant cost. Underground storage options become much more cost-efficient at large scales and are thus preferred for large-scale, seasonal hydrogen storage.

Figure 11 - Cryogenic liquid hydrogen tanks. Source: (US Department of Energy n.d.)

Storage of hydrogen in above-ground tanks certainly has a role in the future energy system, but only for short-term on-site use, for example at industrial sites and at fueling stations. Long-term, large-scale storage will have to be realized underground, for example with salt caverns.

2.1.2 – Salt caverns

Salt caverns are man-made underground cavities that are constructed in existing salt bed deposits. The caverns are constructed by drilling a well to a certain depth into the salt formation, and then pumping water into this well. The water dissolves the salt and is pumped back to the surface as brine, leaving behind a cavity. This process is continued until the cavern has reached the desired size. These salt caverns are very well suited for gas storage, as the gas cannot permeate through the cavern walls (Mokhatab, Poe, and Mak 2019).

Salt caverns are already being used to store natural gas as well as hydrogen. For example, in the United States and United Kingdom, as a buffer for industrial feedstock demand (Juez-Larré et al. 2019). The technology is thus already fully realized, but would need to be scaled up significantly to accommodate petajoule-scale seasonal storage. According to an assessment commissioned by the Ministry of Economic Affairs and Climate, 321 salt caverns could be constructed at suitable locations in the Netherlands (Juez-Larré et al. 2019). A single salt cavern can contain up to 45 million m^3 of hydrogen at a pressure of 180 bar (roughly 180 times atmospheric pressure), which equals 0.48 PJ of hydrogen. As a result, the maximal total storage capacity that can be realized with salt caverns in the Netherlands is 14.5 billion m^3, which corresponds to 155 PJ of hydrogen.

The salt pillars in which these caverns could be constructed are located in the northeastern Netherlands, in Friesland, Groningen, Drenthe and Overijssel, see Figure 2. If hydrogen is to be stored mainly in salt caverns in these regions, additional investments must be made to develop infrastructure that can quickly transport the hydrogen from these caverns to the rest of the country. If hydrogen is used to generate electricity, it would be advisable to build power plants close to the salt caverns.

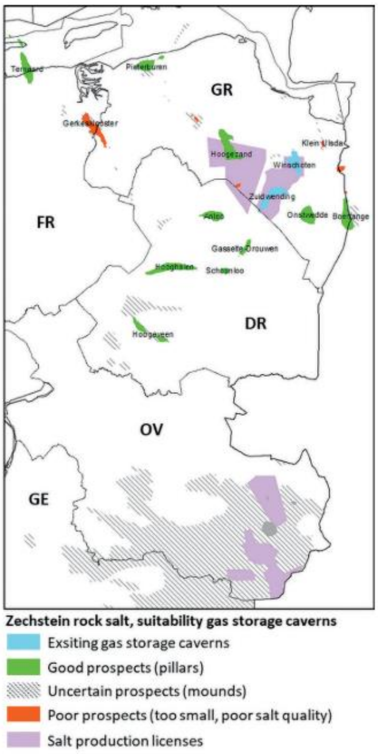

Figure 2 - Map of rock salt formations suitable for construction of gas storage salt caverns in the Northeastern Netherlands. Source: (Juez-Larré et al. 2019)

One potential problem that has to be taken into consideration when building salt caverns is the possibility of surface subsidence above the caverns. Salt mining in Groningen salt pillars has already caused surface subsidence, which has caused damage to homes in a similar way gas extraction has (*RTV Noord* 2019). This a potential source of public resistance and negative PR when plans for salt cavern construction are presented.

2.1.3 – Gas fields

The usage of (partially) empty gas fields for hydrogen storage is a technology that is currently being researched. Depleted gas fields have been used to store natural gas for quite some time: in the Netherlands, there are storage facilities in Norg and Grijpskerk, among others (Juez-Larré et al. 2019). Storage of hydrogen in gas fields is much less a proven technology. There are several scientific concerns that need to be addressed before hydrogen storage in gas fields is widely implemented (Heinemann et al. 2021). Firstly, the fluid-dynamical properties of hydrogen under high pressure in porous media need to be better established. Second, more research is needed to understand which chemical reactions could possibly take place between hydrogen and other substances in the gas field. Third, the impact of subsurface microorganisms needs to be clarified, as the presence of hydrogen can trigger the growth of microbes that consume hydrogen. Lastly, it needs to be researched how the repeated pressure changes caused by injection and extraction of hydrogen from the gas field impact the structural integrity of the storage facility and if this causes seismic activity. Experimental research will have to be done to research these issues, so that the obtained knowledge can be used to select gas fields that are suitable for hydrogen storage.

Additionally, it has to be considered that, before a depleted gas field can be used to store hydrogen (or any other gas), so called *cushion gas* has to be injected first. This is a volume of gas that permanently stays in the field in order to maintain enough pressure to support the structural integrity of the field. Depending on the specific field, this cushion gas can amount for up to 70% of the total volume inside the gas field. The remaining 30% is called the working volume of the field. Generally, the same gas as is stored is used as a cushion gas, which means that a large investment needs to be made initially to produce enough hydrogen to serve as cushion gas. This cushion gas can only be recovered once the field is shut down. (Juez-Larré et al. 2019; Heinemann et al. 2021)

Under the condition that future research demonstrates its feasibility, Juez-Larré et al. identify which gas fields within the Netherlands could be used for hydrogen storage. According to this study, a working volume 997 PJ of hydrogen storage could be realized in onshore gas fields and an additional 644 PJ in offshore gas fields in the North Sea for a total of 1642 PJ.

Figure 32 - Computer rendering of possible 'energy island'. Source: (*EngineeringNet* 2017)

The use of offshore fields is especially promising, because a large chunk of future renewable electricity is expected to be generated by offshore wind farms. If excess electricity from these wind parks can be converted to hydrogen and stored on-site, this saves further investments in the electricity grid that would otherwise be needed to transport the electrical energy to the shore. There are currently plans to construct 'energy islands' in the North Sea, artificial islands to which wind parks and the electric grid are connected. On these islands, electrolysis factories are to be built to produce hydrogen. This hydrogen can then be transported to the mainland using the existing gas pipelines (which is cheaper than transporting the same energy electrically through power cables), or potentially stored in depleted gas fields (*Algemeen Dagblad* 2019; Gasunie 2020). In addition, the construction of offshore storage facilities is likely to generate much less public controversy and discontent than that of onshore facilities in regions that have historically been affected by the negative aspects of natural gas extraction. If hydrogen storage in gas fields causes any seismicity, this is a much smaller problem if offshore fields are used.

Having introduced the different options for hydrogen storage, the following section will explain the concept of energy scenarios and introduce the six scenarios for which this research determined hydrogen storage capacity demand.

2.2 – Energy scenarios

It is uncertain exactly how the energy system of the future will look. The specific mix of energy sources and applications, of supply and demand, will be determined by a combination of political choices, market influences and technological developments. In order to provide some insight into how the energy system *might* look in the future, several institutions and research groups have published energy scenarios. Usually, these scenarios sketch a picture of what the energy system of the future will look like based on certain assumptions. Detz et. al. distinguish two types of scenario: the model and the vision. A modelled scenario uses a computational method to determine the energy system of the future based on certain boundary conditions and input variables; it might, for example, calculate a cost-optimized system or a system that reaches a specific CO2 reduction target. These scenarios take political and economic considerations into account and thus have a high level of realism. A vision-based scenario takes a different approach: these studies are usually more idealistic and attempt to give a vision of a future energy system based on a certain storyline. For example, a vision-based study exploring the feasibility of nuclear energy in the future energy mix might describe a scenario in which nuclear power becomes the main source of energy. The point of such a study is not to describe how the future *will look*, but rather to explore how the future *might look* if different choices are made.

In this research, six different energy scenarios are compared. They are introduced in the following subsections. First, it is important to clarify that four of them – the II3050 scenarios – are models, and two – the Urgenda and TKI Nieuw Gas scenarios – are visions. That is to say, the II3050 study provides four separate scenarios that each represent the modeled outcome of a different set of basic assumptions, while the Urgenda scenario was made with a specific sociopolitical outcome in mind and the TKI Nieuw Gas scenario intentionally pushes the use of hydrogen to an extreme to explore the implications. Despite the fundamental differences between the scenarios, it is in line with the goal of this research to compare them: each scenario assigns a different role to hydrogen in the energy mix and thus requires a different hydrogen storage capacity to be realized. If it turns out that a certain scenario requires a hydrogen storage capacity that cannot be realized within the Netherlands, this discredits the feasibility of the scenario and indicates that the foreseen energy mix might have to be reevaluated – after all, there is little use in presenting a vision that is fundamentally not attainable. Conversely, if this study shows that the needed storage capacity of a certain scenario can be realized, that further affirms the scenario's feasibility.

2.2.1 – Integral Infrastructure exploration 2030-2050 (II3050)

In March 2020, researchers from consultancy firms Berenschot and Kalavasta published the report "Climate neutral energy scenarios 2050" (den Ouden et al. 2020). This report is part of the Integral Infrastructure exploration 2030-2050 project, abbreviated to II3050. II3050 is a joint project that is being carried out by several stakeholders in the energy transition, notably energy grid operators Gasunie and TenneT, and the Ministry of Economic Affairs and Climate. This project is part of the national Climate Agreement and serves to provide a frame of reference for future infrastructural development and investments by private parties. The report serves as the conclusion of the first phase of this project and presents four distinct scenarios that model the energy system of 2050 depending on different assumptions regarding regulation and policy.

The difference between the scenarios lies in the level of government at which climate and energy is regulated. This makes a concrete difference in the type of policy that is enacted, the possibility of importing and exporting hydrogen, the scale at which renewables are implemented domestically, et cetera. Thus the energy system will look different in each case. The first scenario models the energy system in 2050 when the energy transition is handled mostly by Dutch regional governments. The second scenario considers the situation when the national government takes control. In the third scenario, the national government only loosely regulates the energy system and emission reductions are achieved through a EU-wide CO2 tax. The fourth scenario concerns a future in which climate regulations are enacted at a worldwide, international level. The four scenarios are introduced in the next four subsections.

2.2.2 – II3050, Regional governance

As mentioned, the Dutch government decentralizes control of the energy transition in this scenario. Local and regional governments are given the responsibility of becoming carbon neutral and sustainable. Concretely, this means that there is a focus on smaller-scale renewable energy generation through local onshore wind and solar panels on roofs, a reduction of private energy demand and an expectation that consumers will demand sustainable products, forcing market and industry to shift without government intervention. Large-scale renewable energy projects, which require large monetary investments, are less common in this scenario, because local governments often lack the required space and financial means.

2.2.3 – II3050, National governance

In this scenario, the national government of the Netherlands actively takes a leading role in the energy transition. The government aims for a self-sufficient, sustainable national energy system. There is a focus on large-scale projects coordinated by the government, and less focus on local initiatives. Large offshore wind parks and solar farms play a key role in this scenario to ensure self-sufficiency, and the government will force industry to become more sustainable, both in its energy consumption and its usage of feedstocks and materials.

2.2.4 – II3050, European governance

The key factor that will lead to a decrease in carbon emissions in this scenario is an EU-wide CO2 tax. This tax is instated in 2030 and increases progressively until 2050. The goal of this tax is to make carbon emissions economically unviable within the EU. The focus of this scenario is on a regulated European market; the national government takes much less of leading role than in the previous scenario. Renewable energy sources are realized at the locations where it is economically most desirable, so the Netherlands relies strongly on import of electricity and hydrogen.

2.2.5 – II3050, International governance

In the final II3050 scenario, environmental regulations are made at an international level. Thorough climate laws are instated at a global scale, and a global free market leads to global trade in renewable energy and energy carriers. Advanced international infrastructure is constructed to accommodate this. Renewable energy is generated where it is most economically viable, and as such The Netherlands is heavily dependent on import for its energy supply.

2.2.6 – Urgenda: 100% Sustainable Energy in 2030

In June 2020, Dutch environmental organization Urgenda published the latest version of their vision for a climate-neutral Dutch society (Urgenda 2020). Urgenda achieved international publicity when they successfully sued the Dutch government, alleging that not enough action was being taken to combat serious climate change and meet the Paris Agreement goals (Urgenda n.d.). With this report, they propose an alternative scenario in which the Dutch energy supply is completely climate neutral in 2030. According to this report, a fully sustainable energy supply is possible if the following steps are taken. Firstly, all buildings in the built environment must be made energy neutral. All cars and 90% of heavy transport is fully electric, with the remaining 10% of heavy transport being powered by hydrogen. Industry achieves energy savings of 40% by 2030 and uses renewable electricity and geothermal energy for heat. All energy is generated through solar, wind or geothermal means.

2.2.7 – TKI Nieuw Gas

TKI Nieuw Gas is a consortium of stakeholders from the Dutch gas sector, which aims to contribute to the introduction of new gas-based energy carriers to replace natural gas ("TKI Nieuw Gas" n.d.). TKI Nieuw Gas has conducted studies on hydrogen and green gas to assess the future possibilities offered by these gaseous energy carriers. In 2018, they published a 'Hydrogen Roadmap' which explores the potential of hydrogen across several sectors (Gigler and Weeda 2018). Also included in this roadmap is a vision for a hydrogen-based energy system in which hydrogen is utilized to the largest possible extent in each sector. The aim of the TKI Nieuw Gas report is not to give a realistic picture of what the future energy system will look like, but rather to give an indication per sector of the limit to which hydrogen consumption could theoretically be pushed. Still, the TKI Nieuw Gas vision is relevant for this study, because it is of interest to find out whether such an extreme scenario could be realistically accommodated in terms of storage. If it turns out that this is possible, that might be a reason to consider more intensive hydrogen use in the future. If it turns out that it is not, this is a sign that the factor of storage has to be seriously considered whenever ambitious plans for hydrogen are created.

2.2.8 – Selection process for scenarios

The reason precisely these scenarios were chosen for this study, and why others were left out, is as follows. Out of the dozens of scenario studies that have been published in the past decade or so (Detz et. al. compare 7 Dutch scenarios and 17 foreign or international scenarios), the II3050 study is by far the most relevant to the Netherlands today. This is because this study was published after the Dutch climate agreement of 2019. In fact, the II3050 report states explicitly that its purpose is to update older scenarios to take the specific measures of the climate agreement into account. Importantly, the II3050 study also serves as an official document for the

Ministry of Economic Affairs and Climate, which is in charge of the Dutch energy transition. Modelled scenarios dating from before 2019 were thus judged to not be meaningfully comparable to the II3050 scenarios. On the other hand, the Urgenda and TKI Nieuw Gas scenarios are included precisely because they are not models but visions: the outcome of these studies is not made irrelevant by new policy, because they do not serve to predict the outcome of policy. In fact, especially the Urgenda study uses its scenario to plead for *different* policy. By determining and comparing the hydrogen storage capacity needs of each scenario, this study can then serve either as an indicator of how much storage capacity will need to be built (in the case of the II3050 models) or as an indicator of whether the visions are viable alternatives to current policy.

In order to do this research and determine the required storage capacities, the Energy Transition Model (ETM) was used. The following chapter explains the ETM and the way it was used to generate the results relevant to this study.

3 – Methodology: the Energy Transition Model

In order to meaningfully compare the different scenarios and their hydrogen storage needs, the required storage capacity has to be determined in the same way for each scenario. The Energy Transition Model (ETM) was used for this purpose. The ETM is an open-source computational model that allows users to input all sorts of variables concerning the energy system of the future.[1] The ETM then models what the energy system will look like with considerable detail. For example, the user can input energy demand per sector, determine the ways in which this energy is to be produced, and the ETM will output the yearly CO2 emissions and costs, among many other results. Figure 4 illustrates what the ETM's user interface looks like.

Below you can specify how hydrogen will be produced in the future. The ETM offers the following options: electrolysis of wind and solar power from wind/solar farms dedicated to hydrogen production; steam methane reforming (with and without carbon capture); gasification of biomass (with and without carbon capture); import from abroad.

In addition, it is possible to convert excess electricity into hydrogen using 'power-to-gas' (see the power-to-gas slide). You can do this if your scenario has moments where electricity production exceeds demand. Hydrogen for the fertilizer industry can also be produced on-site since this industry already has large hydrogen production plants built (see the fertilizer industry slide).

For more information see our documentation.

input capacity

Offshore wind turbine for H_2 0 MW

Solar PV plant for H_2 0 MW

Steam methane reforming 0 MW

Biomass gasification 0 MW

H_2 import 0 MW

Energy use -35.8%

CO_2 relative to 1990 -98.5%

Energy imports 28.3%

Costs (bln/yr) €55.1

Renewables 95.7%

Blackouts 0 h/yr

Biomass import 7.0%

Figure 4 - example of ETM user interface

3.1 - Hydrogen in the ETM

Crucially relevant for this study is the detail with which the user can specify the application of hydrogen. Hydrogen demand per sector can be specified, as well as the exact methods of hydrogen production. The model then calculates hydrogen production and usage per hour for a whole year and determines how much excess hydrogen can be exported or stored, or how much of a deficit needs to be imported or taken from storage. Based on this information the ETM produces a graph that shows the total energetic value of hydrogen that needs to be stored each day throughout the year. An example of what such a graph looks like is shown in Figure 5. The peak value of this graph thus represents the maximum demand for hydrogen storage and thus the total storage capacity that needs to be realized within the Netherlands to be able to fully accommodate this storage demand domestically.

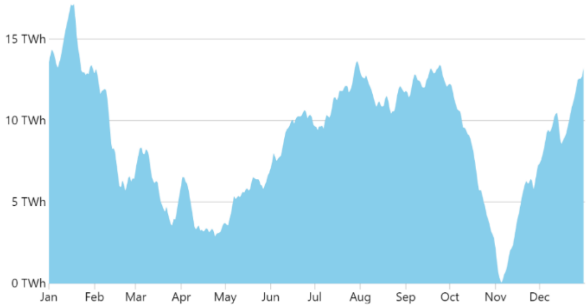

Figure 5 - Example of ETM graph displaying total energetic value of hydrogen stored throughout the year

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[1] The ETM is freely available for anyone to use at energytransitionmodel.com

3.2 - Weather-years

The ETM allows the user to select one of several 'weather-years', on the basis of which it will calculate renewable energy production and energy demand. A weather-year is a year-long meteorological profile corresponding to a certain year in history. It maps wind and solar production as well as heat demand per hour for the entire year. This is of crucial importance to this study. In a future that relies on renewables for its energy generation, meteorological aspects have a large influence on the energy system. As mentioned in the introduction: solar panels only generate electricity when the sun shines, wind turbines when the wind blows. Additionally, energy demand is highest in winter, when buildings need to be heated. This is exactly the time when solar electricity production is at its lowest. If hydrogen storage is to be used as a way to store excess renewables and to produce energy at times of low renewable production, meteorological variations thus play a key role. The storage capacity needs to be prepared for a worst-case scenario, a year with low renewable energy production and a large need for hydrogen to fill the gap.

The ETM allows users to choose one of four different weather-years. The default year is 2015, a relatively warm and sunny year with plenty of renewable production and relatively low energy demand for heating. Users can also select weather-year 1987, a worst-case year with an extremely cold winter and so called 'Dunkelflaute' periods - periods in which it is exceptionally cold, dark and wind-still, so that neither solar nor wind produces a lot of energy. The model shows a sharp increase in demand for energy import and storage in this weather-year, as will become clear later. The two other weather-years are 1997, another cold year with little sustainable production, but somewhat less so than 1987 and with a different temporal profile, and 2004, a year in which renewable production fluctuates heavily between large excesses and large deficits.

3.3 – Energy scenarios in the ETM

For the purpose of this research, each of the energy scenarios introduced in Chapter 2 had to be loaded into the ETM. It should be noted that the ETM was actually used by the II3050 researchers and Urgenda to create their scenarios. This means that the ETM is very well suited to accurately predict hydrogen usage and storage requirements for these scenarios. The ETM models used for the II3050 and Urgenda studies are freely available on the ETM website, and users can import them to look at the models and their results. This was also done for this study. It must be noted that the scenarios were updated in the ETM after the II3050 report (den Ouden et al. 2020) was published: technical updates and refinements were added to the ETM, certain numbers and figures were updated and a further analysis of flexible energy usage was conducted (Afman and Douwes 2020). This means that the numbers presented in the results section of this report will not be equal to those presented in the II3050 report. Instead the updated, newer numbers as available in the ETM are used.

The TKI Nieuw Gas vision was not created using the ETM. Therefore an ETM scenario was made for this vision specifically for this research. Because the TKI Nieuw Gas report only concerns itself with hydrogen and not the rest of the energy transition, the specifics of how well houses are insulated or how non-hydrogen energy demand develops are not discussed. Because these data are in fact required to create a model in the ETM, certain background assumptions had to be made. TKI Nieuw Gas does assume a level of national control of the energy transition. Therefore the II3050 National scenario was used as a basis for the new scenario. All the hydrogen-related variables were then updated to fit the TKI Nieuw Gas report. Weather-year 2015 is used as the reference year, from which demand is calculated for the other weather-years.[2]

3.4 - Methodology

This study compares the hydrogen storage demand for the six different scenarios as follows. First, the scenario is loaded into the ETM. Weather-year 2015 serves as the reference year in which hydrogen usage per sector is input, if the study does not differentiate between different weather-years itself. The model automatically scales hydrogen demand and supply to different weather-years. Hydrogen demand per sector is determined for each weather-year for each scenario. Next, the ETM is used to generate a graph displaying the energetic value of stored hydrogen per day for each weather-year for each scenario. Through analysis and comparison of these graphs, the required total hydrogen storage capacity for each scenario is determined.

The following chapter presents the results obtained using the ETM for each chapter, and discusses how the required storage could be implemented within the Netherlands.

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[2] The ETM scenario that was specifically made for the TKI Nieuw Gas report is available at https://pro.energytransitionmodel.com/saved_scenarios/10754

4 – Results and discussion

The aim of this research is to determine the demand for hydrogen storage in a climate neutral Dutch energy system. Section 4.1 presents and critically discusses the results, generated with the ETM, in order to determine the total hydrogen storage capacity that is needed in each scenario. In section 4.2, an analysis is given for each scenario which describes how the required capacity could be realized within the Netherlands.

4.1 – ETM Results

4.1.1 – II3050, Regional governance

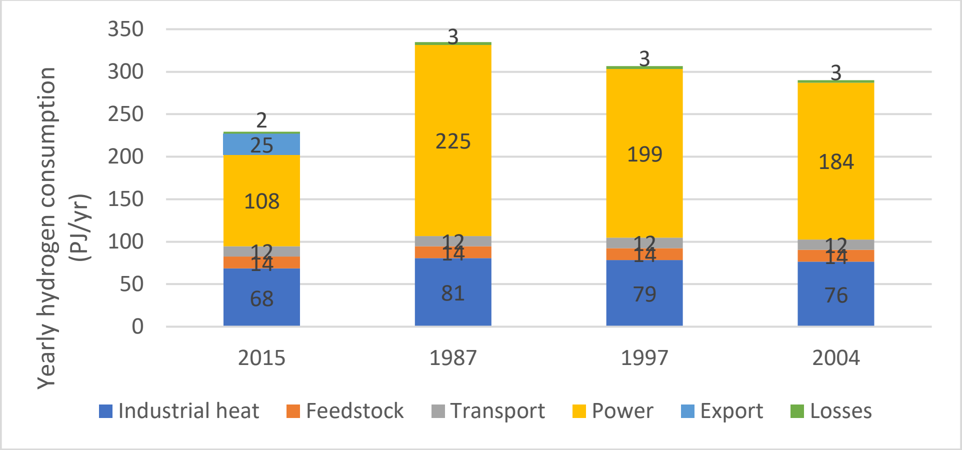

Figure 6 - Yearly hydrogen consumption for each weather-year, II3050 Regional scenario

Figure 6 displays the yearly hydrogen consumption per sector in the different weather-years for this scenario. The largest share of hydrogen is used to generate electricity in hydrogen-based power stations. In weather-year 2015, power accounts for roughly half of all hydrogen consumption and this share increases in size in the other weather-years, because here renewable electricity generation decreases. Because homes are heated mostly using electrical heat pumps in this scenario, hydrogen is not used directly for low-temperature domestic heat. However, because hydrogen is used to generate electricity in cold years, when more electrical energy is needed to heat homes, it could still be said that indirect consumption of hydrogen for heating increases in colder years. This is evident from the noticeable increase in hydrogen consumption for power in colder years. Industrial use for heat and feedstock is roughly stable between weather-years, with a slight increase in industrial heat use in colder years. Hydrogen use for transportation is limited in this scenario, with 12 PJ of yearly consumption. This is because regional governments are expected to prefer electrification of public transport, and in the absence of a national hydrogen fueling network, most heavy transport is also done electrically rather than hydrogen-based.

In weather-year 2015, there is so much production of hydrogen from excess renewable electricity, that the ETM expects 25 PJ of hydrogen to be exported, as yearly hydrogen production exceeds yearly demand. Instead of export, this hydrogen could also be stored strategically to anticipate periods in future years where hydrogen demand exceeds production. In this case, this 25 PJ should be added on top of the maximum storage capacity derived by the ETM.

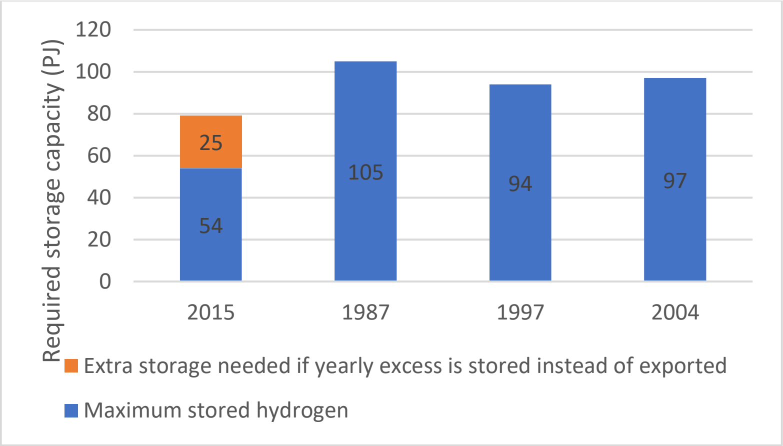

Figure 7 - Hydrogen storage capacity that needs to be realized per weather-year, II3050 Regional scenario

From Figure 7 we can see that in this scenario, required storage capacity varies between 54 PJ in weather-year 2015 and 105 PJ in worst-case weather-year 1987. In weather-years 1997 and 2004, the numbers are 94 PJ and 97 PJ respectively. If the decision is made to strategically store the excess 25 PJ of hydrogen produced in weather-year 2015, the required storage capacity goes up to 79 PJ.

How much storage capacity should be constructed if this energy scenario is to become reality? At a first glance, the obvious answer is 105 PJ; if this much storage capacity is realized, the storage facilities will be able to handle even the most extreme case, and therefore also the other weather-years. Of course, this is a possible course of action. But governments might hesitate to construct expensive storage facilities just so enough capacity is available in the very worst case possible, which might only happen once every decade or more. Such governments might want to know if there is a reasonable, lower capacity that would still provide enough storage almost all of the time.

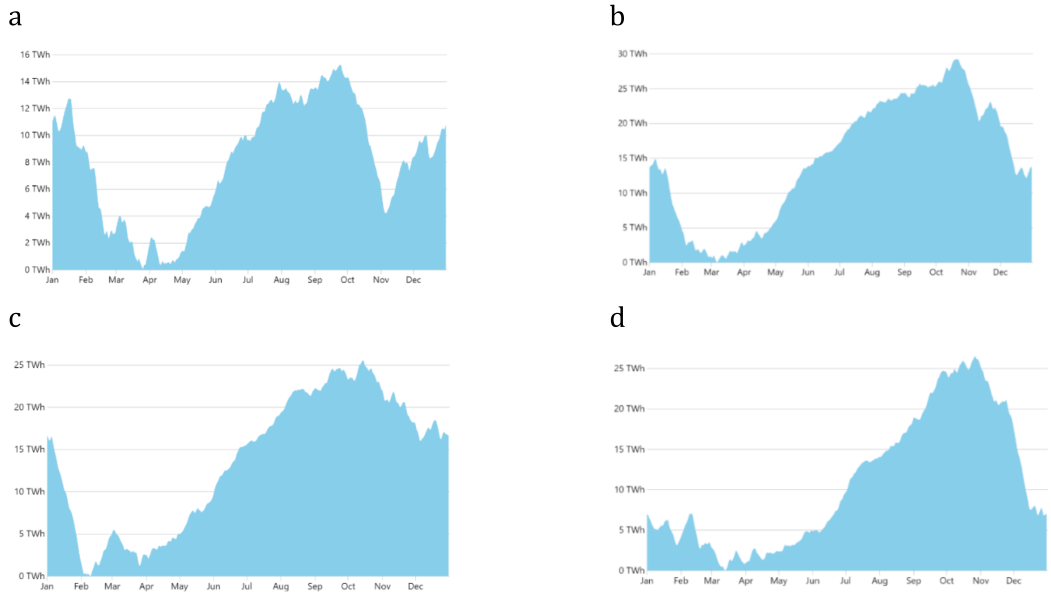

Figure 8 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), II3050 Regional scenario

Closer examination of the yearly storage capacity graph for weather-year 1987 in this scenario (Figure 8b) shows that the maximum value of roughly 29TWh ~ 105 PJ occurs for a short time during the month of October. During the rest of the year, the total energetic value of stored hydrogen does not exceed 26TWh ~ 94 PJ. Similarly, the total stored volume in weather-year 2004 only reaches its absolute peak of 27 TWh ~ 97 PJ for a few days (Figure 8d). It would be a reasonable conclusion to say that constructing a total storage capacity of 94 PJ will provide ample hydrogen storage for all weather-years except those with somewhat higher peaks like 1987 and 2004. In these extreme cases, where excess hydrogen is still being produced for a few weeks or days per year while the storage facilities are completely full, this hydrogen could be exported. Furthermore, constructing a storage capacity of 94 PJ means that in the standard weather-year of 2015, there is plenty of space left over to strategically store the excess 25 PJ of hydrogen instead of exporting it, which could be considered an added benefit. 94 PJ is thus the preferred total hydrogen storage capacity for this scenario.

4.1.2 – II3050, National governance

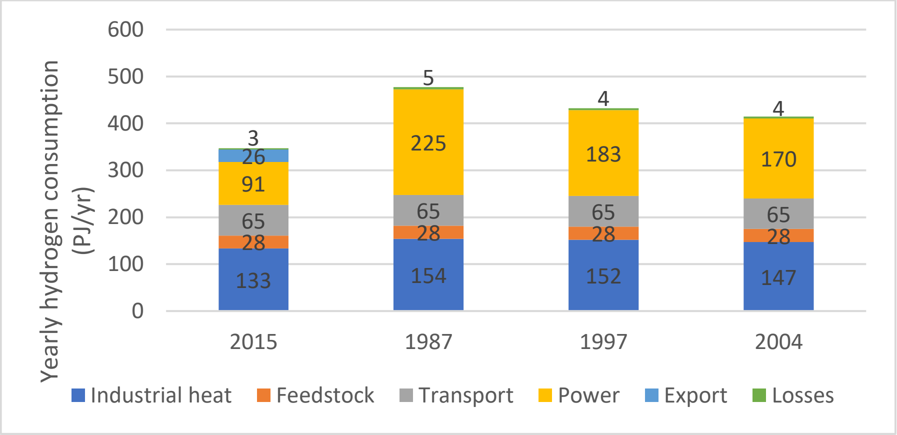

Figure 9 - Yearly hydrogen consumption for each weather-year, II3050 National scenario

Total hydrogen use is higher in this scenario than in the regional scenario in every weather-year. We can see in Figure 9 that hydrogen usage increases in every sector. Notably, much more hydrogen is used in the transport sector. This is because, in this scenario, half of heavy transport uses hydrogen as a fuel. This is made possible because, due to the national governance of the energy transition, a network of hydrogen fueling stations is realized. Use of hydrogen for industrial heat roughly doubles compared to the regional scenario. This is due to stricter, national laws that force industry to decarbonize, leaving hydrogen as one of the key fuels for high-temperature processes.

The usage of hydrogen for power generation is a different story, however. In each weather-year except 1987, this actually decreases compared to the previous scenario. This is due to the fact that, in the national governance scenario, more large-scale renewable energy sources are developed, leading to a larger overall supply of renewable electricity. Hydrogen is needed to 'fill the gap' about as often, but more total hydrogen is produced through electrolysis, which is then applied in other sectors than power generation – industry and transport. This thus leads to a greater overall yearly consumption of hydrogen, but comparable hydrogen consumption in the power sector.

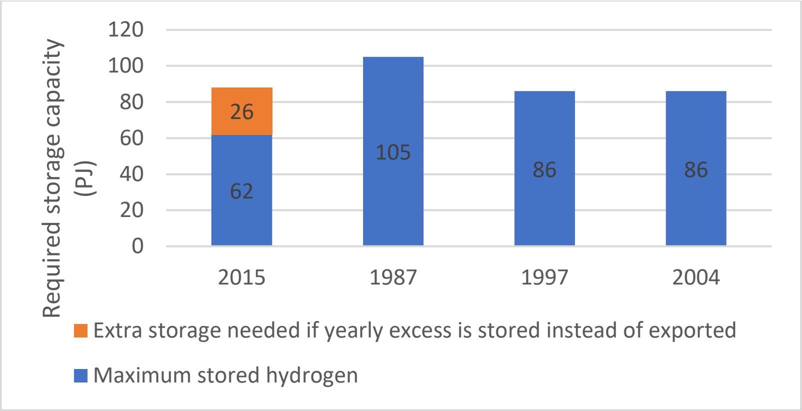

Figure 10 – Peak energetic value of stored hydrogen per weather-year as computed by the ETM, II3050 National scenario

Just like in the regional governance scenario, there is some excess hydrogen produced in weather-year 2015, which the ETM then designates for export. Again, this 26 PJ of hydrogen could also be strategically stored. Figure 10 shows that, despite the strong increase in hydrogen consumption in this scenario compared to the previous one, the need for hydrogen storage actually does not change very much, ranging from 62 PJ in weather-year 2015 to 105 in weather-year 1987. Storage demand increases slightly in 2015, stays equal in 1987 and decreases slightly in 1997 and 2004, both at 86 PJ. Why does the need for storage not grow with total hydrogen consumption in this case? This can be explained by the fact that most of the consumption growth happens in the industrial and transport sectors. These sectors have a more or less steady demand for hydrogen throughout the year, and therefore the hydrogen used by these sectors does not need to be stored to wait for a certain time of the year when demand peaks. The hydrogen is simply transported to factories and fueling stations immediately where it is directly consumed.

Figure 11 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), II3050 National scenario

How much total storage capacity should be constructed if this scenario became reality? Once more, inspection of the yearly storage capacity graph for weather-year 1987 (Figure 11b) shows that there is a sharp peak during the month of October, where the total energetic value of stored hydrogen reaches 29 TWh ~ 105 PJ for a week or so. Apart from this month-long period, not more than 25 TWh ~ 90 PJ of hydrogen is ever stored. In the other weather-years, total storage needs do not exceed 90 PJ, also in the case in weather-year 2015 if 26 PJ of excess hydrogen is strategically stored. A total capacity of 90 PJ would provide enough storage in any case except for one month in the most extreme weather-year. During this month, any excess hydrogen produced when storage facilities are full could be exported. In this scenario, a total storage capacity of 90 PJ is thus preferred.

4.1.3 – II3050, European governance

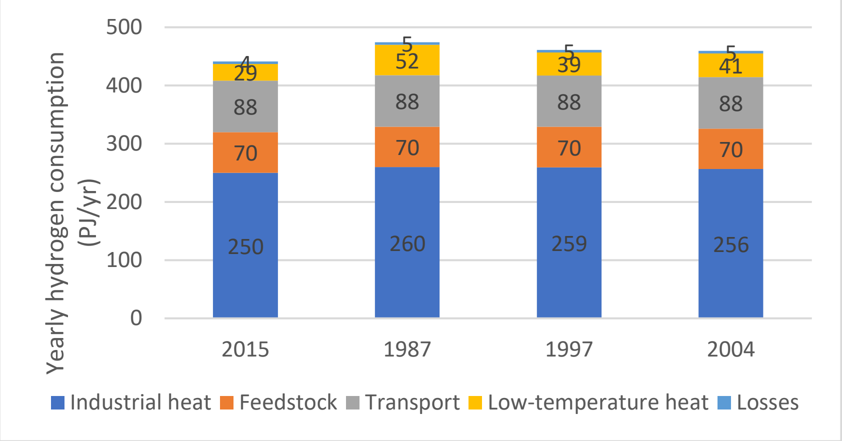

Figure 12 - Yearly hydrogen consumption for each weather-year, II3050 European scenario

The hydrogen consumption pattern in this scenario looks markedly different from those of the regional and national scenarios. Figure 12 shows that industrial hydrogen use for heat and feedstock accounts for a large majority of all consumption. The focus in this scenario on a competitive European market allows for industry to grow significantly, while the CO2 tax means that industry must look for carbon-neutral alternatives. This leads to a notable increase in industrial hydrogen consumption.

In this European scenario, the Netherlands does not attempt to be self-sufficient in its energy use. Only very little hydrogen is generated using excess electricity, most of it by far is imported instead. A further result of this European integration is that hydrogen is not used to generate power in this scenario – a large difference with the previous scenarios where power generation accounts for up to half of all hydrogen consumption. Hydrogen is simply not needed to back up the power system, as electricity is imported from other places in Europe instead. There is no export of hydrogen in this scenario. We notice an increase in hydrogen consumption in the transport section, because the CO2 tax leads to an increase in hydrogen-fueled vehicles both for cars and heavy transport. In Figure 12 we see a new category that hadn't been part of the hydrogen mix of the previous two scenarios: low-temperature heat. This is hydrogen usage to heat homes and buildings, through hybrid hydrogen-fired heat pumps and regional heat networks.

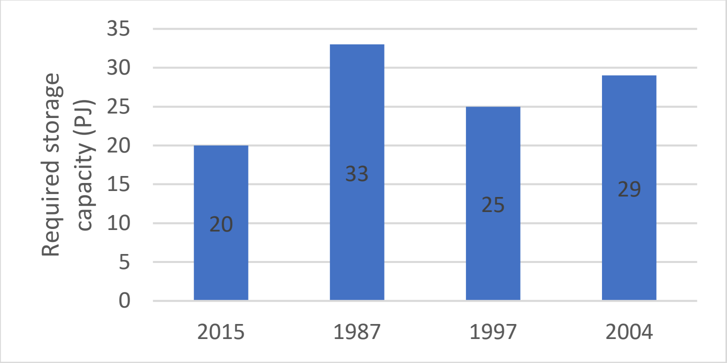

Figure 13 - Peak energetic value of stored hydrogen per weather-year as computed by the ETM, II3050 European scenario

Because hydrogen is used largely in industry, which requires less storage as it consumes hydrogen immediately and at a steady rate throughout the year, total hydrogen storage capacities turn out much lower in this scenario compared to the previous two. The maximum required storage capacity ranges from 20 PJ in weather-year 2015 to 33 PJ in weather-year 1987.

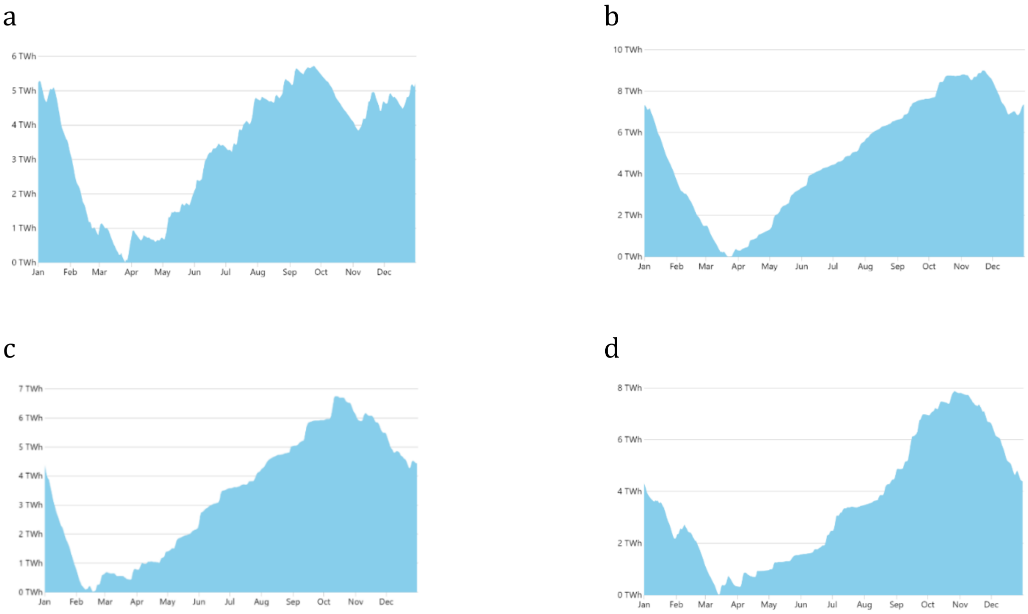

Figure 14 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), II3050 European scenario

Inspection of the yearly storage graphs (Figure 14) shows that the peak in storage capacity required in October of weather-year 1987 is less sharp in this scenario, with the maximal required capacity of approximately 9 TWh ~ 33 PJ lasting for nearly two months during October and November. For the rest of the year, the total energetic value of stored hydrogen does not exceed 8 TWh ~ 29 PJ. Because the extra 4 PJ of storage needed to accommodate the peak is not that much, and 33 PJ is relatively little capacity in the first place, it could be decided to build 33 PJ of storage to be prepared for the worst. The other choice is to build 29 PJ and have appropriate storage for any case except those two months in the most extreme weather-year. This is a political decision, and something can be said for either option. 33 PJ of storage will be taken as the indicative value for this scenario going forward.

4.1.4 – II3050, International governance

Global trade in renewable energy is very important in this scenario. Because hydrogen is well-suited as a carrier to import energy, further augmented by the advanced transport infrastructure, hydrogen plays an important role. As visible in Figure 15, total hydrogen consumption is much higher than in the other II3050 scenarios. It is important as one of the major carriers used for the import of electrical energy; a large amount of hydrogen is used yearly to generate power. Furthermore, the focus on international trade in this scenario means that industrial hydrogen demand continues to grow, both for heat and feedstock. Hydrogen is widely used in the transport sector, as a fuel for cars as well as heavy transport, and also implemented to generate low-temperature heat for homes and buildings.

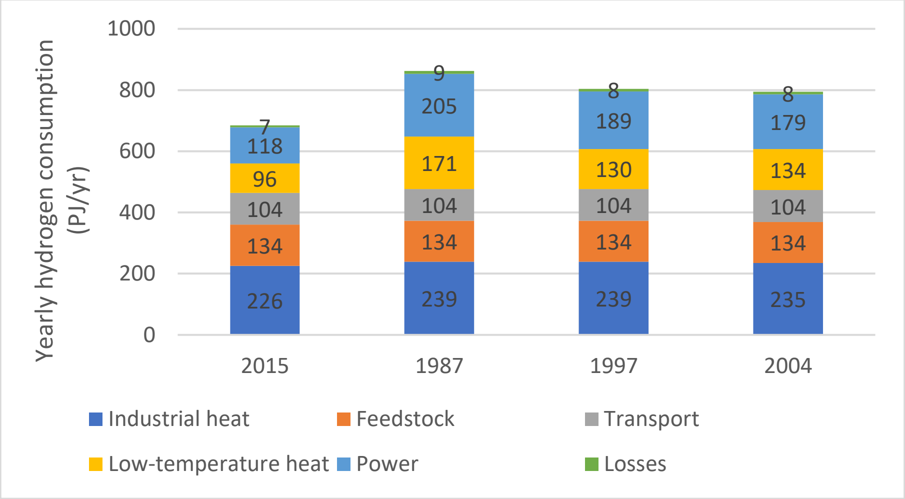

Figure 15 - Yearly hydrogen consumption for each weather-year, II3050 International scenario

As one might expect, the intensive and widespread usage of hydrogen in this scenario leads to a relatively large demand for storage. As shown in Figure 16, the maximum energetic value of stored hydrogen ranges from 69 PJ in weather-year 2015 to 130 PJ in weather-year 1987.

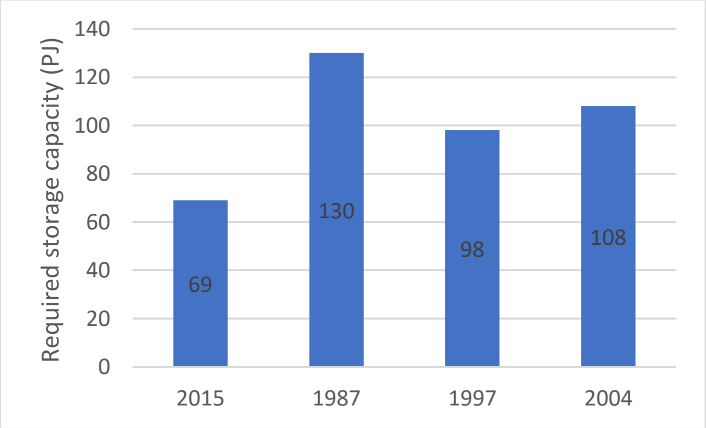

Figure 16 - Peak energetic value of stored hydrogen per weather-year as computed by the ETM, II3050 International scenario

In Figure 17 the yearly storage graphs are presented. As was the case with the previous scenarios, storage demand peaks around October in each weather-year. However, the peaks are not as sharp and a high capacity is required for several months in the fall of weather-year 1987. Storage demand exceeds 30 TWh ~ 108 PJ, the peak value of weather-year 2004, for this extended period of time. 108 PJ of total storage capacity thus seems like the absolute minimum that would need to be constructed in this scenario, and a choice would have to be made whether further investments are made to construct an additional 22 PJ of storage to accommodate peak demand during weather-year 1987. This is a political choice like the one described for the European scenario; there are viable arguments for either choice, or perhaps a total capacity higher than 108 PJ but less than 130 PJ. The upper value, 130 PJ, will be used in the rest of this research.

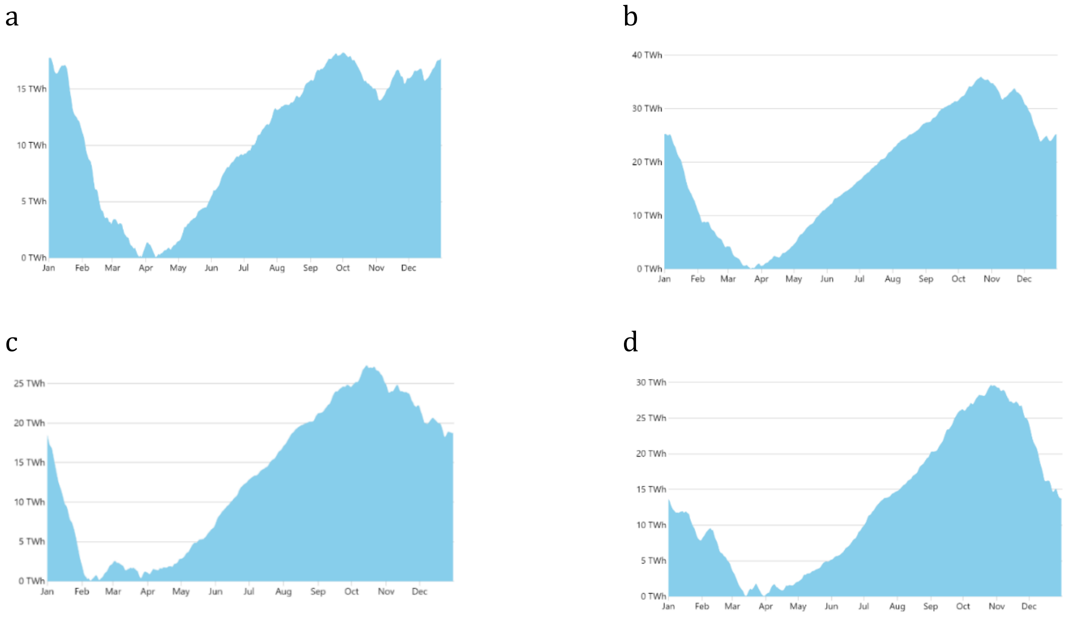

Figure 17 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), II3050 International scenario

4.1.5 – Urgenda: 100% Sustainable Energy in 2030

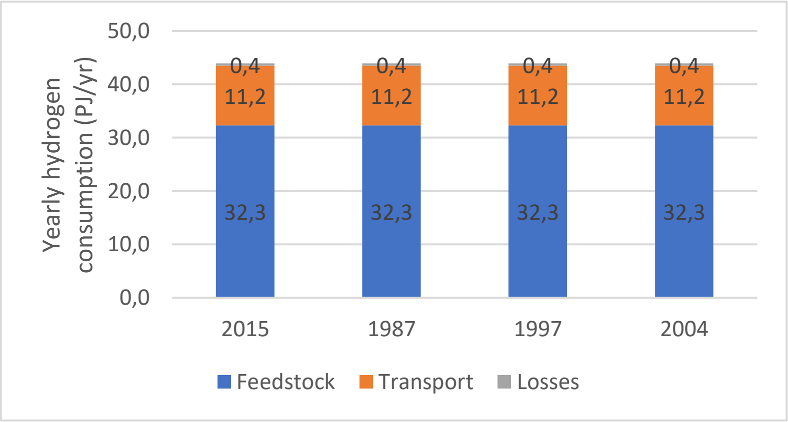

Figure 18 - Yearly hydrogen consumption for each weather-year, Urgenda scenario

Because Urgenda strives for a much faster energy transition, achieving a climate-neutral energy system in 2030, very different choices are made compared to the other scenarios. This becomes evident when looking at hydrogen usage in this scenario (Figure 18). Hydrogen is not implemented on a large scale, because construction of the necessary infrastructure to enable widespread hydrogen use would simply take too long and not be finished before 2030. Hydrogen is only used in heavy transport and as a feedstock in industry. Consumption rates in these sectors do not depend on the weather, and therefore we see that consumption is invariant across weather-years, with a total yearly hydrogen demand of 43,9 PJ.[3] Hydrogen is produced largely from excess electricity generated by the ample renewable sources in this scenario, supplemented by import.

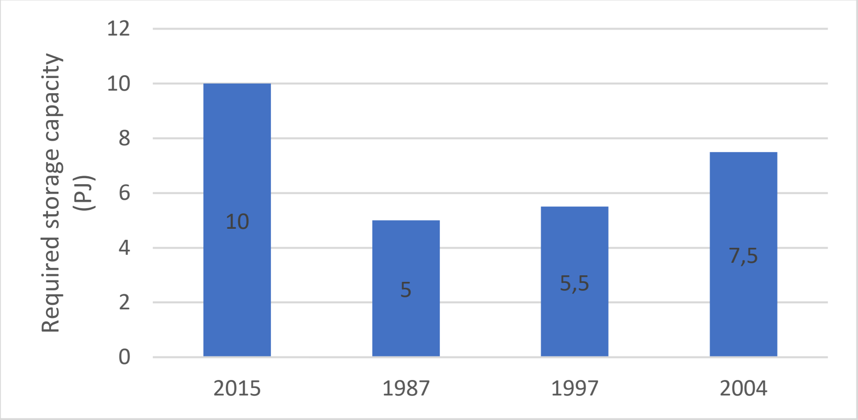

Figure 19 - Peak energetic value of stored hydrogen per weather-year as computed by the ETM, Urgenda scenario

Figure 19 shows the peak energetic values of hydrogen stored in each weather-year. The values range from 5 PJ in weather-year 1987 to 10 PJ in weather-year 2015. A marked difference with the other scenarios is visible here: in the Urgenda scenario, maximum storage demand is largest in 2015, the warmest, sunniest year. In the II3050 scenarios, we saw storage demand increase in the cold weather-years, not decrease. This can be explained by the fact that hydrogen consumption remains stable across all weather years, but hydrogen production changes. In a weather-year like 2015, renewable electricity production is higher than in the other weather years. This means that more hydrogen is produced through electrolysis using excess electricity and less is imported. In weather-years with less excess renewable electricity, more hydrogen is imported. If hydrogen is imported, this usually happens at the same rate that it is used, meaning that the imported hydrogen is consumed immediately and does not require storage. Hydrogen produced using excess electricity needs to be stored, because hydrogen production does not line up exactly with hydrogen demand. Thus we see in this scenario that more storage capacity is required in warmer, sunnier weather-years.

Because the need for hydrogen storage is lower in the more extreme weather-years, storage should be constructed to be sufficient for the reference weather-year, 2015. Since the 10 PJ of storage required in this weather-year is relatively little, there is no need to compromise in the way that was done for the earlier scenarios. 10 PJ of hydrogen storage is the final capacity that should be constructed if the Dutch government suddenly made the radical choice to take climate change seriously and commit to Urgenda's plans.

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[3] Note that hydrogen consumption is given with decimal accuracy for the Urgenda scenario so that the 0,4 PJ yearly losses are not rounded to zero.

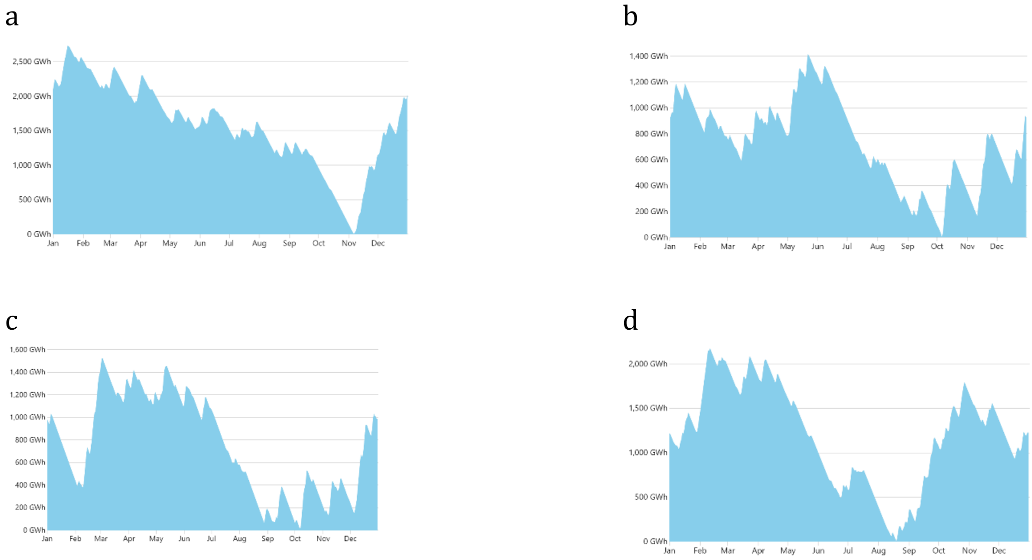

Figure 20 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), Urgenda scenario

4.1.6 – TKI Nieuw Gas

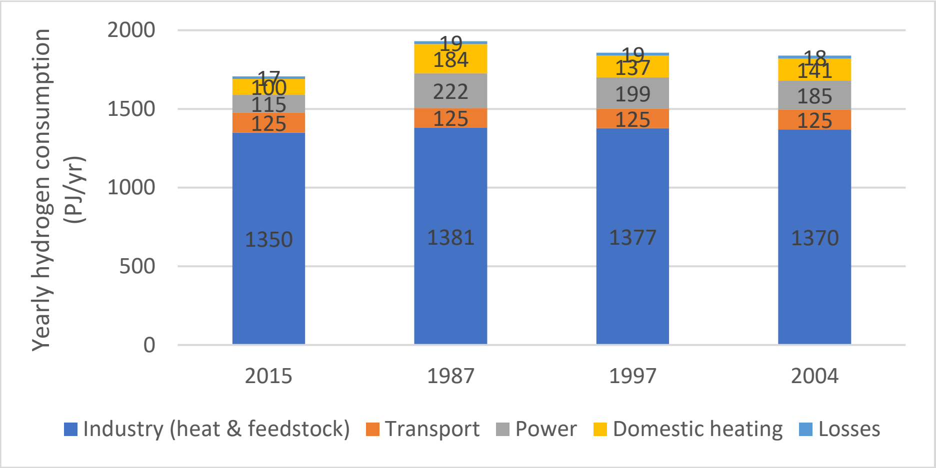

Figure 21 - Yearly hydrogen consumption for each weather-year, TKI Nieuw Gas scenario

Figure 21 shows the yearly hydrogen consumption in this scenario for each weather-year. We can see that these numbers are enormous – up to five times more than the other scenarios. Especially in industry, hydrogen demand is very large. TKI Nieuw Gas foresees a large growth in Dutch industrial activities, with hydrogen as the only provider of high-temperature heat and as the most important feedstock for industrial processes. Hydrogen is also widely used to generate power and domestic heat, and is a common fuel for both cars and heavy duty transport.

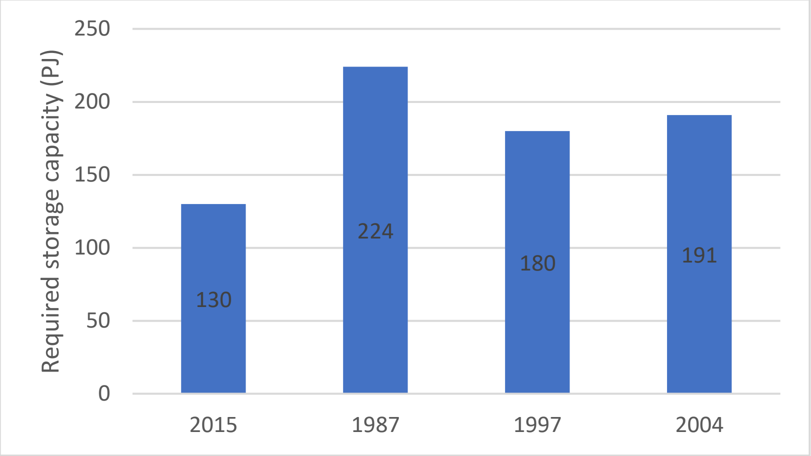

Figure 22 - - Peak energetic value of stored hydrogen per weather-year as computed by the ETM, TKI Nieuw Gas scenario

How much storage capacity is needed to accommodate such widespread hydrogen use? Figure 22 shows the peak energetic value of stored hydrogen for each weather-year as computed by the ETM. Storage demand ranges from 130 PJ in weather-year 2015 to 224 PJ in weather-year 1987. Storage demand varies considerably depending on the meteorological conditions in this scenario. This can be explained by the fact that hydrogen is used intensively for electricity generation as well as low-temperature heat.

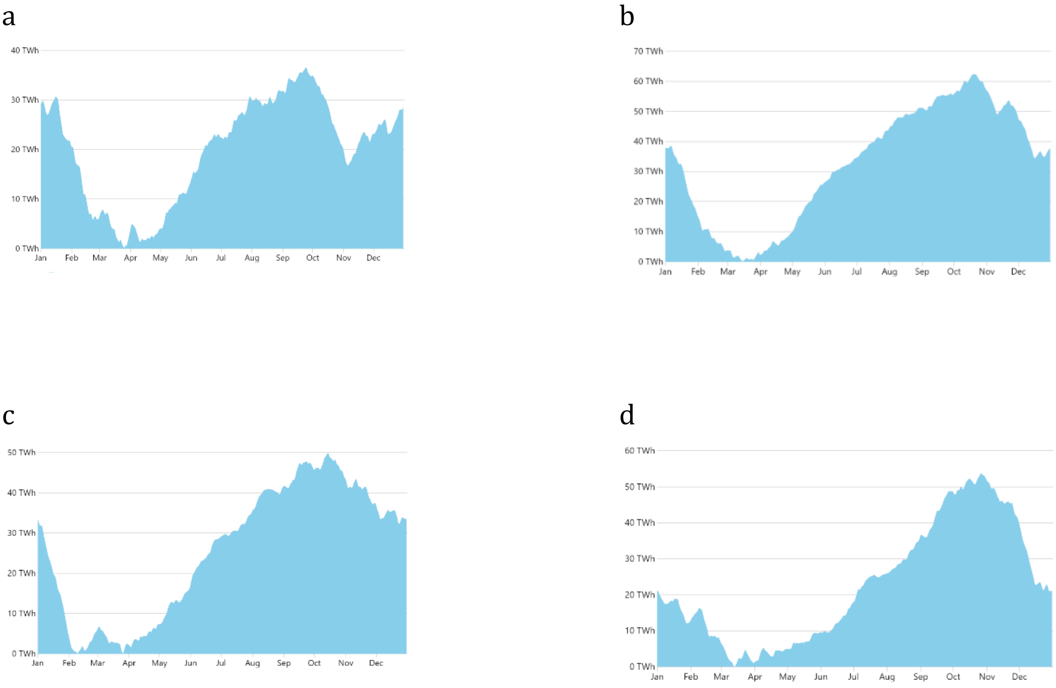

Figure 33 - Total energetic value of stored hydrogen, weather-years 2015 (a), 1987 (b), 1997 (c) and 2004 (d), TKI Nieuw Gas scenario

Figure 23 displays the yearly storage demand in each weather-year. The graph for weather-year 1987, the one with the largest maximum demand, shows a peak in stored hydrogen in the month of October, when it reaches 62 TWh ~ 224 PJ. Aside from this peak, storage demand is below 55 TWh ~ 198 PJ the whole year. The other weather-years always have storage demand lower than

198 PJ too. It is reasonable for the government to elect to construct 198 PJ of hydrogen storage in this scenario, as constructing an additional 26 PJ to meet peak demand in the most extreme year could be very expensive. Hydrogen produced during the month of October in this weather-year could be exported instead of stored.

4.1.7 - Recapitulation and comparison

The six scenarios presented in this section all implement hydrogen in distinct ways. As a result, the demand for hydrogen storage is very different for all of them, and can vary strongly depending on meteorological conditions. Figure 24 recapitulates the yearly hydrogen consumption of each scenario in weather-year 1987, the weather-year with the highest consumption in each case. The differences are stark: total hydrogen consumption in the TKI Nieuw Gas scenario is forty-three times higher than in the Urgenda scenario. The projected yearly hydrogen consumption in the different II3050 scenarios are also quite different from each other, with consumption in the international scenario being more than double that in the regional scenario. Clearly, the Dutch government has to be prepared for a plethora of different outcomes of the energy transition, especially when it comes to hydrogen. The demand for hydrogen storage also varies, though not as widely as the consumption numbers. Figure 25 displays the required storage capacities for each scenario as determined in this chapter.

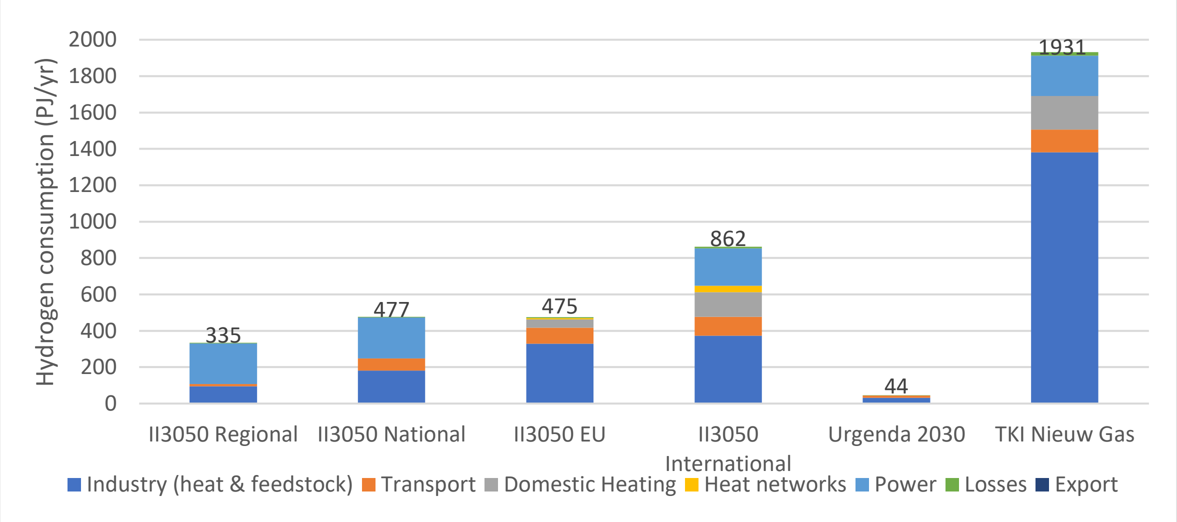

Figure 24 - Yearly hydrogen consumption for each scenario, weather-year 1987

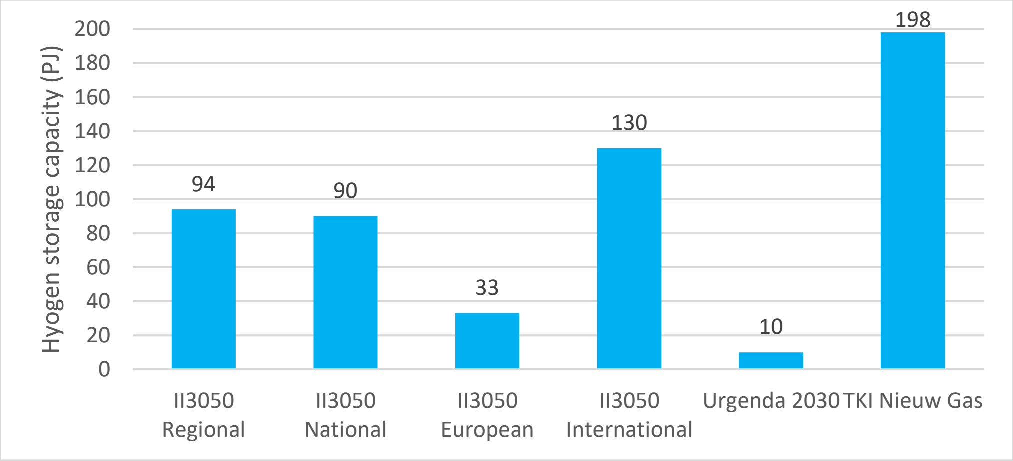

Figure 45 - Storage capacity required per scenario

It is clear that, no matter what happens, large-scale hydrogen storage facilities will have to be developed in the Netherlands. The following section will explore how the required capacity could be achieved in each scenario.

4.2 – Storage implementation in each scenario

Now that the required hydrogen storage capacities for the different scenarios have been determined, this section will explore how this storage could be implemented. The circumstances in each scenario will be taken into account to analyze which techniques should be used, and to what extent.

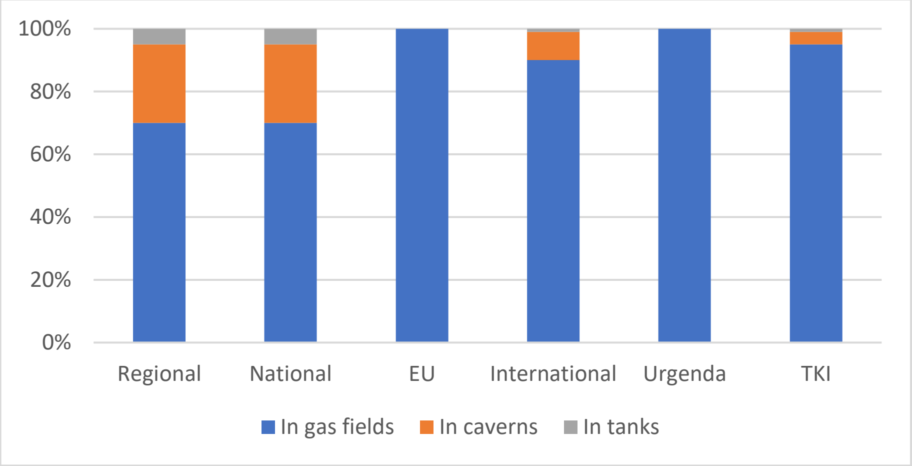

Figure 5 - Possible distribution of hydrogen storage between technologies as suggested in Section 4.2

4.2.1 – II3050, Regional governance

The regional governance scenario of the II3050 study requires a hydrogen storage capacity of 94 PJ, as was shown in the previous chapter. Using the numbers from section 2.1, it can be calculated that it would take 196 salt caverns to provide the required storage volume. 100 million m^3 of storage in high-pressure tanks would also satisfy the demand. The storage capacity could also quite easily be provided using gas fields - 94 PJ is much less than the potential capacity of 1642 PJ -, though the variability in energetic capacity between gas fields makes it hard to say exactly how many fields would be needed. A first conclusion would thus be to say that the required storage capacity could feasibly be realized within the Netherlands. That is already quite a relief, but which methods should be picked?

A look back at the hydrogen consumption per sector in this scenario (Figure 6), reminds us that power generation accounts for a large part of yearly consumption. This means that hydrogen storage demand takes on a very seasonal pattern in this scenario (this can also be seen in Figure 8). Because of this fact, it would be advisable in this scenario to use storage in gas fields as the main technique. This is because the large capacity of gas fields in combination with the proximity of offshore fields to renewable electricity sources make gas fields the best option for seasonal energy storage using hydrogen. As power generation accounts for between approximately half to two-thirds of total hydrogen consumption in this scenario, at least two-thirds of total hydrogen storage capacity should preferably be built in the shape of gas fields. Salt caverns and tanks may be built near end-use sites to provide shorter-term storage. It is possible that, in this scenario, 70% of storage is provided by gas fields, 25% by salt caverns and 5% by tanks. In this case, there is 66 PJ of gas field capacity, 49 salt caverns are constructed and some 5 million m^3 of high-pressure tanks are built.

If, after future research, it turns out that hydrogen storage in gas fields is not a feasible technology, salt caverns should take over the role of gas fields as the main large-scale storage option, as they are much more cost-effective than tanks at large scales.

4.2.2 – II3050, National governance

In this scenario, a total storage capacity of 90 PJ is required, quite a similar figure to the one discussed in the previous case. It would take 188 salt caverns to satisfy this storage demand using only salt caverns, or 96 million m^3 of high-pressure tanks. Once more, the storage could also easily be provided using only gas fields. The hydrogen consumption pattern in this scenario is different from the regional scenario, however.

In this scenario, hydrogen for energy storage and power generation still plays a large role, but less so than in the regional scenario, see Figure 9. We can see that industrial hydrogen consumption plays a bigger role than before. We could thus argue that local hydrogen storage at industrial sites should play a larger role in this scenario. However, we should remember that the national approach in this scenario means that there will be a well-developed nationwide pipeline system for transportation of hydrogen from storage to end-use sites. Since storage at gas fields is the most cost-effective option at very large scales, it is likely that the focus will remain on gas fields as the main storage option. The distribution of storage technologies could again be 70% gas fields, 25% salt caverns and 5% tanks. In that case, there is 63 PJ of gas field capacity, 47 salt caverns are constructed and 4,8 million m^3 of high-pressure tanks are built.

As before, salt caverns take over the role of gas fields in the case that hydrogen storage in gas fields proves not to be a feasible technology.

4.2.3 – II3050, European governance

33 PJ of hydrogen storage is needed in this scenario, equating to 69 salt caverns or 35 million m^3 of gas tanks. The capacity could also be constructed using only gas fields.

In this scenario, hydrogen is not used to back up the power grid. Instead, industry accounts for by far the largest share of hydrogen consumption (see Figure 12). The second largest consumer of hydrogen is the transport sector.

Because of the low total storage demand and the lack of need for seasonal storage to back up power, it is likely that a choice will be made to fully rely on a single technology to construct all of the storage, in order to keep the hydrogen storage system simple. Either salt caverns or gas fields could easily supply enough storage capacity. If hydrogen storage in gas fields turns out to be a feasible technology, it will be the most cost-effective and thus the premier candidate to provide all 33 PJ of storage. If this is not the case, 69 salt caverns will be constructed.

4.2.4 – II3050, International governance

The international governance scenario requires 130 PJ of hydrogen storage capacity. This is equivalent to 271 salt caverns or 139 million m^3 of high-pressure tanks. Again, there is also enough potential capacity in gas fields to supply this demand.

In this scenario, hydrogen is used widely in a variety of different sectors, with no single sector dominating consumption figures (Figure 15). If possible, gas fields will again play a major role in this scenario. The high absolute demand for storage requires gas fields to account for a larger percentage of storage. It is possible that gas fields will supply 90% of all storage, salt caverns another 9% and tanks the final 1%. That means that 117 PJ of gas field capacity is constructed, 24 salt caverns are built and 1,4 million m^3 of storage tank volume is required.

4.2.5 – Urgenda: 100% Sustainable Energy in 2030

In the Urgenda vision, only 10 PJ of hydrogen storage is needed. This could be fully accommodated by 21 salt caverns or 10,7 million m^3 of storage in tanks. In this scenario, hydrogen is only used in industry and for transport. As with the European II3050 scenario, it seems likely that a full commitment is made to a single method of hydrogen storage, either gas fields or salt caverns. Either way, realizing 10 PJ of storage is a relatively simple task, and only a few large scale facilities will be needed.

4.2.6 – TKI Nieuw Gas

This scenario has the highest demand for hydrogen storage: 198 PJ. This is the only scenario in which the required storage capacity could not be constructed using only salt caverns: it would take 413 salt caverns to construct 198 PJ of storage, while the maximum number of caverns that could be constructed domestically is 321 (Juez-Larré et al. 2019). Thus, if this scenario were to become reality, it would be absolutely crucial that storage in gas fields becomes a feasible technology. Otherwise, all the remaining storage would have to be supplied with storage tanks, which would be a very expensive ordeal.

It is most likely that gas fields become the largest storage technology in this scenario, as they are most cost-effective at large scales. Gas fields could possibly account for 95% of storage, with 4% provided by salt caverns and the final 1% by tanks. That would mean 188 PJ of gas field capacity, 17 salt caverns and 2,1 million m^3 of storage tanks.

5 – Conclusion

5.1 - Recapitulation

In this research it was demonstrated that hydrogen has a role in all carbon-neutral future Dutch energy system scenarios. This role is widely variable, however, with yearly hydrogen consumption ranging from 44 PJ to 1931 PJ. Hydrogen storage capacity is necessary in each scenario, with storage demand ranging from 10 PJ in the Urgenda scenario to 198 PJ in the TKI Nieuw Gas scenario.

The different types of possible storage technology were discussed: tanks, salt caverns and gas fields. It was analyzed how these technologies could be employed in order to construct the necessary storage capacity in each scenario. It was demonstrated that, in each of the scenarios, the required capacity can feasibly be realized domestically. If gas field hydrogen storage technology becomes a feasible method, it will most likely be the most widely implemented technique. In that case, salt caverns and tanks play a much smaller role due to their higher costs. In the case that hydrogen storage in gas fields is not tenable, more salt caverns will need to be constructed in order to be able to meet storage demand. The TKI Nieuw Gas scenario is the only scenario in which gas field storage is indispensable, as the total storage demand here greatly exceeds the maximum capacity that can be realized using salt caverns in the Netherlands.

5.2 – Recommendations

This research has shown that reservations concerning the technical possibility of storing hydrogen should not play a role when it comes to political decisions being made concerning hydrogen usage in the future energy system. Only in the most extreme case can storage demand not be met by existing technologies.

Based on the results of this research, I make the following recommendations for future research and policy decisions:

Firstly, it is important that research on hydrogen storage in depleted gas fields continues. If the remaining scientific challenges presented by Heinemann et al. are confronted and solved by research, the potential for hydrogen storage in gas fields in the Netherlands is so large (1642 PJ) that the demand for storage could very easily be met in any scenario, even more extreme ones than discussed in this research.

Second, I recommend that serious work is made by policymakers considering the construction of salt caverns for hydrogen storage. We do not know how long it will take before hydrogen storage in gas fields is a viable technology – this could be a few years, but also a few decades. If we want to start implementing hydrogen into our energy system at a large scale starting from 2030 (as happens in each of the II3050 scenarios, which the government uses for reference), we need some storage capacity to be available at that moment. This could be provided by salt caverns, as we know exactly how this technology works and how reliable it is. But since it takes a while to construct salt caverns, construction should start sooner rather than later.

Third, construction of renewable energy sources like solar and wind should continue on a large scale and preferably be accelerated. If hydrogen is to be widely implemented as an energy source in industry and as a means of seasonal energy storage, it is absolutely crucial that there is enough renewable electricity available to produce all this hydrogen.

With this research, I hope to have contributed to the understanding of the possibilities and limitations of hydrogen in the future energy system and to have shown that underground hydrogen storage is a key component of a green future. In order to decarbonize industry and balance the industry grid, hydrogen can and should be implemented on a large scale, to help us fight climate change and avoid environmental disaster. To quote Marjan Minnesma, the director of Urgenda: it’s possible if we want it!

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