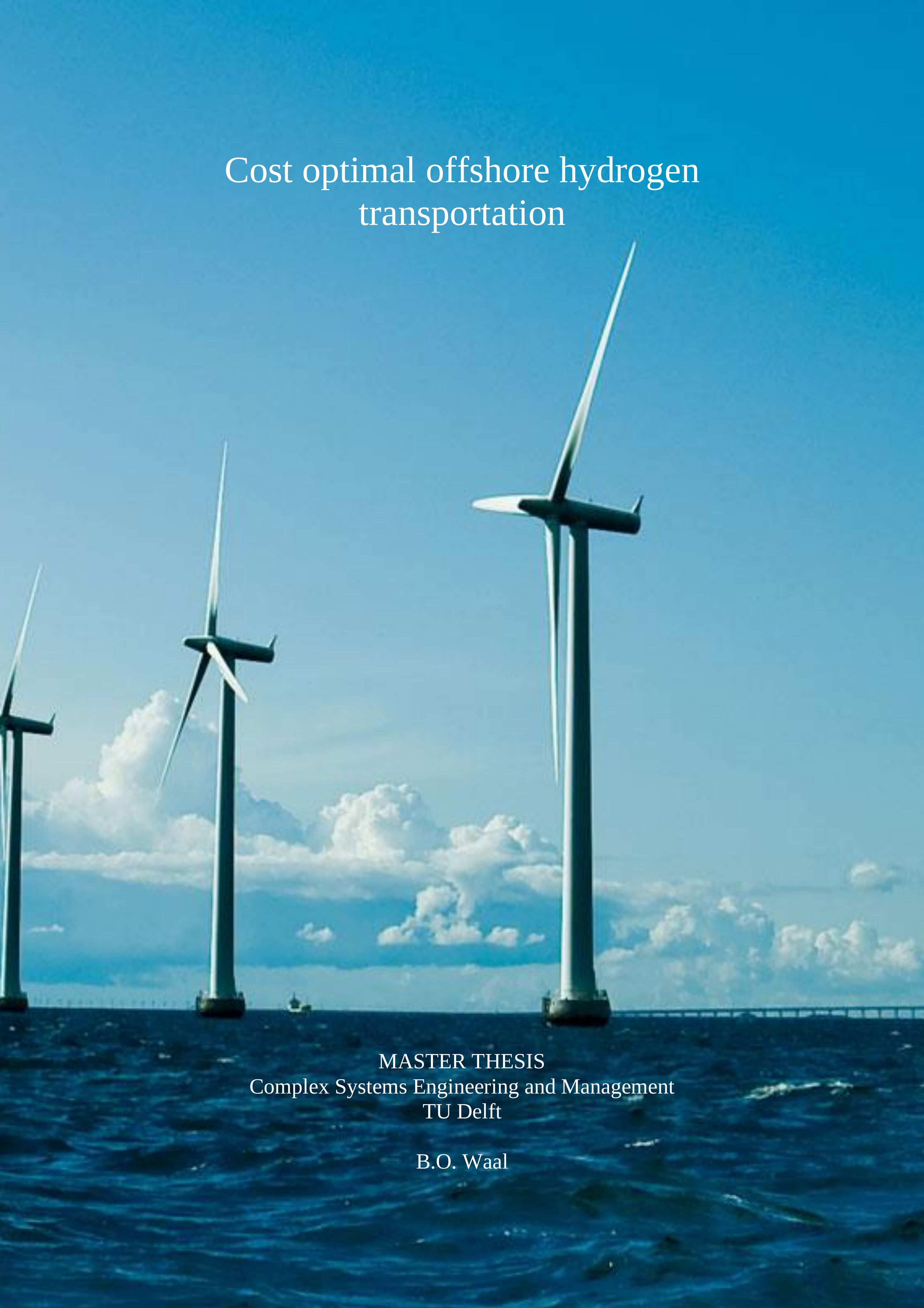

Cost optimal offshore hydrogen transportation

MASTER THESIS
Complex Systems Engineering and Management
TU Delft

B.O. Waal

Cost optimal offshore hydrogen transportation

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

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This report represents the conclusion of my Master thesis, and with it my time as a student at Delft University of Technology.

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Completing this thesis and with it my studies has been an exceptionally educational experience. Looking back I feel a sense of accomplishment, and a sense that my studies have prepared me well for what lies ahead.

Boris Waal

Executive summary

In order to help reach the climate goals set in the Paris agreement, the Dutch government has ordered Gasunie to build a hydrogen pipeline network in the Netherlands. The hydrogen itself is to be produced at offshore wind farms in the North Sea by electrolysis. How the produced hydrogen is to be transported to shore however, has not been decided due to concerns from producers and potential consumers regarding the resulting purity of hydrogen being transported through the onshore network. These concerns stem from the fact that the hydrogen specifications of the network have not been decided. Hydrogen produced via electrolysis has a purity of 99.99%. If these specifications include a lower purity than the hydrogen produced on the North Sea, the hydrogen may be polluted leading to a need to purify the hydrogen. The resulting extra costs of purification beg the question if transportation using pipelines is the cost optimal system configuration, considering the uncertainty of future demand and supply for hydrogen. To answer this question four alternative system configurations are selected for further analysis. These are 1) a pipeline network with onshore storage in salt caverns, 2) a pipeline network with offshore storage in the form of compressed hydrogen at electrolysers, 3) ship transportation using ammonia as hydrogen carrier, 4) ship transportation using the liquid organic hydrogen carrier dibenzyl toluene (LOHC).

To model these different system configurations, graph theory is selected as the best fit. For the modelling of the pipeline alternatives, the optimal network layout tool (Heijnen, 2023) is utilised. This tool allows to find cost optimal network considering multiple producers and consumers of energy over multiple timesteps, with the possibility of including storage. While for the shipping alternatives a Python model is designed. The problem this Python model is designed to solve can be described as a variation of the traveling salesman problem. Another layer of complexity handled in the Python model, is that the ships have a fixed capacity. Meaning that the wind farms where the hydrogen is to collected need to be clustered both on the basis of distance, and on the amount of supply they produce so as not to breach the ship capacity. This problem can be described as a capacitated clustering problem.

In order to measure the performance of the different system configurations, a set of demand and supply scenarios are created. These scenarios contain multiple periods, as they are phased from 2030 to 2050 to be able to judge the performance of the system configurations over time. The supply scenarios contain the level of wind capacity installed in the years 2030, 2040, and 2050. With these capacities the potential electrical surplus that can be used to produce hydrogen, is determined using the Energy Transition Model (ETM). The resulting output is the hydrogen production potential on a hourly basis over the course of a year. From this output, two representative weeks are selected in order to reduce the time complexity of using the dataset.

The output of the ONLT consists out of the cost optimal network layout with the required capacities of the edges, and the amount of hydrogen stored at each time step. Whereas the output of the Python model consists out of the cost of collecting the hydrogen via ships. From these outputs the further system costs and

performances are determined in an excel model. Aside from the costs, the performance of the system configurations is also measured on the basis of the amount of hydrogen delivered, compared to the totally available hydrogen.

From the results it becomes clear that the ammonia transportation configuration is not feasible, as it consistently has the highest cost. Furthermore it involves two processes in which hydrogen losses occur, leading to the highest losses in hydrogen. The final results of the analysis are that in general the total system cost are the lowest for LOHC system configuration. Furthermore the LOHC system configuration includes no processes in which hydrogen losses occur. However the pipeline network with onshore storage in salt caverns will eventually be able to yield a lower cost per kilogram of hydrogen delivered, even though some hydrogen losses occur due to purification requirements after storage in salt caverns. In some of the scenarios the pipeline with offshore storage configuration also beats the LOHC system in terms of cost, however in certain scenarios this system configuration becomes extremely expensive. Due to the uncertainty this offers, the final recommendation of this thesis is to adopt a hybrid solution for the time being. With the LOHC system being used in the short term, as it has relatively low CAPEX requirements. When there is more certainty on future supply and demand, an offshore pipeline network with onshore storage in salt caverns will however become the cost optimal solution. The LOHC system can then still be used for the import of hydrogen.

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1. Problem introduction

In order to combat global warming, countries around the world have pledged to reduce their carbon emissions under the Paris agreement (United Nations, 2015) and be carbon neutral in 2050. One form of energy that holds great potential to help accomplish this is hydrogen, as it has a broad range of applications for usage as feedstock, energy transportation, energy storage, and usages in energy intensive industry (European Commission, 2020). This broad applicability combined with the fact that it can be produced sustainably without carbon emissions is why the European Commission sees hydrogen as an important energy carrier of the future (European Commission, 2023).

Currently about 2% of EU's energy need is satisfied by hydrogen, which is projected to grow to 14% in 2050 (European Commission, 2020). However precise levels of demand are hard to determine as most of the hydrogen used today is generated onsite for industry uses. Most of this hydrogen currently is generated using fossil fuels. Hydrogen produced in this way is often referred to as 'grey' hydrogen, and as 'blue' hydrogen if use is made of carbon capture and storage technologies. The production of this grey hydrogen results in a release of 70-100 million tonnes of carbon annually in the EU. In order to change this, the European Clean Hydrogen Alliance was launched in 2020, which plans to create a network specifically for the transportation of green hydrogen for industry, transportation and other sectors by 2030 (European Commission, 2023) in multiple countries in the EU. Green hydrogen is hydrogen produced using renewable energy sources.

One of the projects is being undertaken by Gasunie in the Netherlands. Their plans are to use wind turbines in the North-Sea for the offshore electrolysis of hydrogen (Gasunie, 2023). This hydrogen will then be transported to the ports of Rotterdam, IJmuiden and Eemshaven in the Netherlands (Gasunie, 2022), where it will be distributed to industrial clusters in the Netherlands. Any excess supply will be stored in empty salt caverns located in the north of the Netherlands, which have a very large storage capacity (Gasunie, 2024). Due to this large capacity the salt caverns are also suited to use as seasonal storage, to balance the mismatch between hydrogen production over the seasons (Ozarslan, 2012). Gasunie plans to have the hydrogen network in the Netherlands operational in 2027 (Gasunie, 2023). An overview of the proposed system by Gasunie, including the storage facilities and access points to the onshore network can be found in appendix A1. A factor contributing to the feasibility of creating the onshore hydrogen network, is that for a large part existing gas pipelines can be repurposed to transport hydrogen. Whether offshore pipelines can also be repurposed is still under investigation (Gasunie, 2022). There is still uncertainty however on how planned hydrogen production facilities in the North-Sea will be connected to the network.

The reason that this remains uncertain, is that the specifications of the hydrogen gas that is to be transported through the onshore pipelines network have not been decided. These specifications entail the temperature, pressure and the purity of the transported hydrogen. While it has been decided that there will be one single gas specification throughout the entire network, both for entry and exit (Gasunie, 2023b). Additionally, the cost of transporting the produced hydrogen greatly depends on the quantity of the supply, as larger quantities of hydrogen would requires larger capacities of pipelines. But large uncertainty remains here, as the supply of hydrogen from the North-Sea depends on the amount of wind energy available. With the Dutch government's plans being to expand the current installed wind capacity to between 38 - 72 Gigawatts in 2050 (Rijksoverheid, 2023). This large gap in the potential supply of hydrogen, leads to further uncertainty on how the hydrogen should be transported.

With regards to the gas specifications, especially the purity is of importance for both suppliers and end users of hydrogen and will affect how the network will be shaped. The purity of the gas specification of the network is of importance as very pure hydrogen would be polluted in the network if the purity is set lower. Building a network that can guarantee a high purity is however more expensive as extra measures would need to be taken. On the supply side green hydrogen generated through electrolysis of water with renewable energy is generated with a purity of 99,99%, while resulting in zero emissions. Whereas grey and blue hydrogen have a purity of around 95% when generated. On the demand side, certain processes that use hydrogen require it to be of a very high purity of 99,99% or higher, whereas other processes only require around 98%.

To determine what purity level will be allowed on the network, Gasunie has had DNV and KIWA execute an independent analysis. They concluded that the gas specification should be set at 98% as this would result in the overall cheapest system cost (DNV/KIWA, 2022). However many suppliers of hydrogen disagreed with this conclusion, demanding that the purity be set at least at 99,5%. This because their green hydrogen would otherwise be polluted in the network. For certain applications this polluted hydrogen would then need to be purified again by the users of the hydrogen leading to extra costs and losses in hydrogen. Furthermore the use of repurposed gas pipelines, and the storage of hydrogen in salt caverns both lead to pollution of the hydrogen (Caglayan, 2020). The extra costs incurred to purify the hydrogen create a barrier for potential producers and users of hydrogen, leading to a slowing effect on the creation of the hydrogen economy. This slowing effect on the hydrogen economy leads to further uncertainty on future levels of supply and demand of hydrogen.

Furthermore, from these extra cost the question arises if transportation using pipelines is the cost optimal solution considering the whole system. The extra costs could for instance mean that transporting the produced hydrogen from the production site using clean tanker ships instead of pipelines could be a better solution. Due to the complaints from both potential consumers and producers the minister of Climate and Energy has postponed the decision regarding the gas specifications of the network, and ordered further research to be carried out leaving the development of the hydrogen economy with further uncertainties (Ministerie van Economische zaken en Klimaat, 2023).

The aim of this thesis will be to analyse what the cost optimal system configuration will be to transport future hydrogen from the wind turbines in the North Sea, considering the needs of both producers and consumers. In the next chapter the system is analysed in order to formulate how this research will fulfil its aim.

2. Research formulation

In this chapter the problem introduced previously is defined more closely in order to formulate research objectives. To facilitate this, first the scope of the system is defined. Following this is an analysis of the stakeholders, and a literature review on the individual system components. From these the system configurations this research will analyse are defined. Afterwards the research questions this thesis will answer are constructed.

2.1 System scope

The aim of this thesis is to find the optimal system configuration for the offshore transportation of hydrogen. The hydrogen needs to be transported from the electrolysers located at offshore wind farms, to one of the three defined access points of the onshore network (Gasunie, 2022). For the scope of this research the Netherlands will be treated as an isolated system, meaning that there is no import or export of electricity or hydrogen. This is necessary in order to be able to fairly compare the performance of different system configurations.

How different system configurations perform, depends on the quantity of hydrogen the system needs to transport over time. This quantity of hydrogen that needs to be transported depends on the level of supply on the one side, and the level of demand on the other side. The level of supply and demand will therefore be treated as inputs for the system. Meaning that the cost of producing the hydrogen, and the final distribution of the demand to consumers is out of scope for this thesis.

The hydrogen will be assumed to enter the system at the wind farms, and exit the system when it reaches one of the access points of the onshore network and is used to satisfy a demand originating from the onshore network. Any steps in between will be included in the scope of this thesis.

On the supply side, the potential hydrogen production is dependent on the capacity of wind energy installed. Due to the intermittent nature of the wind the hydrogen production will therefore be variable over time. Due to this there will be instances in which the supply is greater than the demand and vice versa. In order to balance this mismatch, the system needs to incorporate storage facilities. These storage facilities may be required at multiple stage in the system. Depending on the mode of hydrogen transportation, storage facilities may be required where the hydrogen is produced, as well as onshore in the case there is an excess of supply.

As was found in the introduction, elements of the transportation system can have an influence on the purity of the delivered hydrogen. As the resulting purity is the reason that the system configuration for the offshore transportation system has not been decided, any facilities needed to purify the hydrogen will be included in the analyses.

The resulting system scope is illustrated in figure 1 below. With the hydrogen entering the system after being produced. From there it is either stored onsite, or transported to one of the access points to the onshore network. Depending on the mode of transportation, the hydrogen will then be purified if necessary, or directly leave the system to satisfy a demand. Any excess supply will be stored onshore until there is a demand for it. Depending on the storage technology, the hydrogen will then be purified if necessary, or directly leave the system.

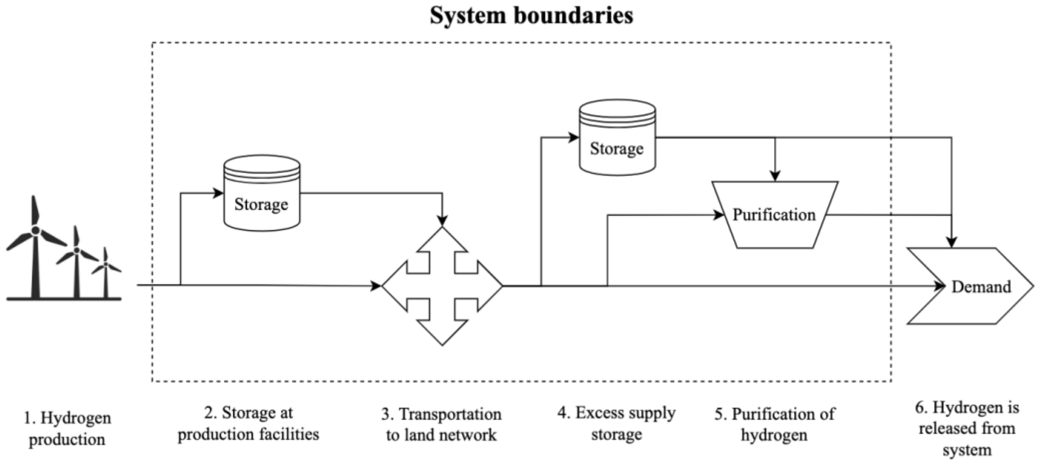

Figure 1: Visual overview of system scope.

2.2 Stakeholder analysis

Now that the scope of the system has been defined, a stakeholder analysis can be conducted in order to find indicators with which the performance of alternative system configurations can be measured.

The system is comprised of six main stakeholders, in the following section the goals from each of the stakeholders will be discussed.

1. Dutch government
2. Gasunie
3. Dutch ports
4. Shipping companies
5. Dutch industry
6. Hydrogen producers

<u>Dutch government</u>

The government of the Netherlands sees hydrogen as an important energy carrier of the future that will help to meet the sustainability goals outlined in the Paris agreement (Rijksoverheid, 2024). As such the government has invested heavily in the development of the onshore hydrogen network that is in development by Gasunie, which is 100% state owned. Furthermore the government stimulates hydrogen projects by creating new policies for hydrogen and by offering subsidies (Rijksoverheid, 2024). With these investments the government wants to position the Netherlands as a key player in future international hydrogen markets. Due to the geographical position and the presence of large ports the Netherlands is uniquely positioned to act as hydrogen hub for importing and exporting hydrogen to neighbouring countries, which the government sees as an economical opportunity (Rijksoverheid, 2024). To solidify this strategic position the government wants to make the hydrogen system as efficient as possible, and create large capacities for the production, import, transportation, storage and export of hydrogen.

Gasunie

Gasunie is executing the development of the hydrogen network on behalf of the government. If an offshore pipeline network were to be realised, Gasunie would also become the transmission operator for that network. Part of the government's plan to meet its sustainability goals is the phasing out of natural gas. As Gasunie is the national transmission operator for natural gas, this would mean the end of its existence. Developing the hydrogen infrastructure therefore is crucial to the future of Gasunie. Gasunie therefore wants as many producers and consumers as possible to connect to its network, to maximize the profitability of the system. In order to succeed in this, Gasunie will want to incorporate the requirements of both hydrogen producers and consumers as much as possible.

Dutch ports

The Dutch port selected by Gasunie as access points to the onshore network see hydrogen an important economic opportunity. With the plans of the government to make the Netherlands in a hub for the import of hydrogen, they are set to become a crucial part of the hydrogen infrastructure. This allows Dutch ports to remain important players in shifting future international energy markets (Port of Rotterdam, 2024). The main goals of the ports is to make a profit. Therefore they will seek to stimulate the further development of production and demand for hydrogen, as this will solidify their position. As the ports will all be connected to the onshore network, and all have the required facilities to handle incoming ships they will likely have little preference in the offshore hydrogen system configuration, aside from seeking to maximize the profitability of the system as this would increase the economic activities in the port areas.

Shipping companies

For shipping companies potential contracts to collect the hydrogen from the North-Sea represent a business opportunity. As these contracts would likely be for long periods of time and entail work on a regular basis. To maximize their profit they will want the system to operate as efficiently as possible to minimize their own costs. To secure their position, shipping companies will want to deliver as much hydrogen as possible, and ensure low losses.

Hydrogen producers

The goal of the producers of green hydrogen is to maximize their profit. The main added value of their product compared to other forms of hydrogen production is its high purity. To maximize their profit they therefore want the transport system to be able to guarantee the high purity they offer. Furthermore they want to be able to satisfy as much demand as possible to increase their profits. Therefore they require the system to have as little hydrogen losses as possible.

Dutch industry

The industry in the Netherlands will be the initial main consumers of the hydrogen, giving them a considerable position of power. The industry also has a need to become more sustainable in order to meet new climate related policies. Currently however, most of the hydrogen used in industry is generated on site (HyWay 27, 2021), meaning that industry players have little urgency to connect to the hydrogen infrastructure on the short term if the product does not suit their requirements. The first requirement industry will have is that enough hydrogen can be supplied to meet their demand. Furthermore the hydrogen needs to be of a high enough quality to fulfil the processes they will be used in. The final need from the industry is that cost of the delivered hydrogen should be low, as it would otherwise be more profitable to produce their own hydrogen.

Performance measures

Overall the goals of the stakeholders can be divided into three categories, which are visualised in figure 2 below. Firstly the stakeholders involved want to maximize their own benefit. Therefore they need the system and the resulting hydrogen to be affordable, and they seek to minimize the costs. The indicators to assess how well a system configuration performs on this goal the investments required for the system configuration, the operational costs associated with the system components, and the cost per kilogram of hydrogen delivered. The second category is that the hydrogen needs to be of sufficient quality. To assess this the total purification requirements of the system configurations will be measured. The final main goal of the stakeholders is the maximization of the supply of hydrogen. Indicators of how well system configurations meet this goal will be the final ratio of the amount of demand delivered, and the amount of hydrogen losses incurred in the system. In appendix A2 more information can be found regarding the role of the stakeholders, and how the goals of the stakeholders are influenced in the system.

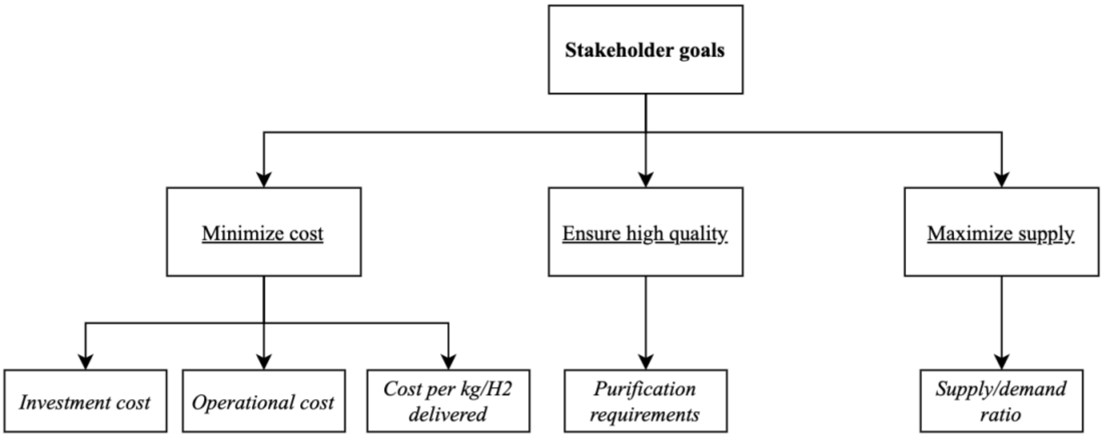

Figure 2: Overview of stakeholder goals and performance indicators.

2.3 Literature review

Offshore hydrogen production

Hydrogen can be produced via electrolysis by introducing an electrical current to the water, splitting it in hydrogen and oxygen (Ibrahim, 2022). This process leads to very high levels of hydrogen up to 99.999% once the process is finished (Abdin, 2020). Another major advantage of using electrolysis is that it can be used to counteract curtailment, which is when a surplus of available renewable electricity is not generated due to the electricity grid being overloaded. This excess electricity can then be used to generate hydrogen (Abdin, 2020). Aside from hydrogen being produced when there is an electrical surplus, it is likely that future wind farms that are located far out of shore, will be dedicated to generating hydrogen (Ibrahim, 2022). Beyond a certain distance energy losses occuring in power lines will make transportation in the form of electricity infeasible, these windfarms will therefore have an electrolyser located inside the turbine to directly produce hydrogen (Ibrahim, 2022). While currently little electrolysis capacity is installed, it is likely that electrolysis will be economically competitive in the near future when the electricity originates from a renewable source (Abdin, 2020). In the EU's hydrogen strategy it plans to realize at least 6 GW of electrolyser capacity paired with renewable energy before 2024.

Transportation alternatives

Ibrahim et al. (2022) identified multiple transportation system configurations for offshore hydrogen production systems. The configurations they proposed are pipeline transportation in gaseous form, ship transportation in liquid form, ship transportation in ammonia, and ship transportation in the form of a liquid organic hydrogen carrier. In all of these configurations they propose a storage facility is located at the electrolyser to store excess supply (Ibrahim, 2022).

Hydrogen can be transported in ships in multiple ways. It can be transported in liquid form , in compressed gaseous form, in the form of an energy carrier such as ammonia or methanol, or it can be transported in a liquid organic hydrogen carrier (LOHC) which entails chemically storing the hydrogen in the form of another molecule (Niermann, 2021). The process of storing hydrogen in another molecule is called hydrogenation, while the process of extracting the hydrogen again is called dehydrogenation.

An added advantage of transporting hydrogen in another molecule, is that it can greatly increase the volumetric hydrogen content compared to transporting hydrogen in liquid of gaseous form (Obara, 2019). Although liquid hydrogen is discussed most often, it is more likely that transportation using in an energy carrier such as ammonia will be more affordable (Salmon, 2021). To make ammonia, dinitrogen is combined with a hydrogen molecule in what is known as the Haber-Bosch process (Rodriguez, 2011).

Over longer distances however, the efficiency of storing hydrogen in the form of an LOHC is superior to other options (Niermann, 2021). Recently one particular LOHC has been most prominent in scientific literature, that is the molecule perhydrodibenzyltoluene (Rao, 2022). The advantage of LOHC's like perhydrodibenzyltoluene is that the hydrogenation and dehydrogenation cycle is completely reversible, meaning that all hydrogen can be extracted again without losses and without pollution (Rao, 2022). Whereas the dehydrogenation of ammonia and methanol do incur some hydrogen loss, and additional purification are required (Salmon, 2021). As the use of LOHC's is a new technology few large scale project using it exist. Recently in the Netherlands however, a company called Hydrogenious has started a LOHC project in collaboration with the port of Amsterdam to import hydrogen using the LOHC dibenzyl toluene (Hydrogenious, 2024).

For short range transportation from offshore locations to onshore, compressed hydrogen yields a lower levelized cost of hydrogen than liquid hydrogen (d'Amore-Domenech, 2023). Yet short range transportation with pipelines yields an even lower levelized cost of hydrogen still (d'Amore-Domenech, 2023). Ship transportation of hydrogen however has other advantages over pipeline transportation, as it is more flexible and does not have fixed endpoints. Furthermore midlife changes in demand are easier to realize for ship transportation than for pipeline transportation (d'Amore-Domenech, 2023). Hybrid solutions using both hydrogen pipelines and ships carrying liquid ammonia might also be an option depending on the end use requirements of the hydrogen (Ibrahim, 2022).

Though the different forms of hydrogen transport all have different advantages, in scientific literature there is no consensus yet on which form of hydrogen transportation forms is optimal (Salmon, 2021). This is due to the fact that analysis of production and transportation cost are rarely paired in scientific work preventing proper assessment of the total cost of the delivered energy (Salmon, 2021).

Purity

For the purification of hydrogen, the most commonly used method is pressure swing adsorption (PSA), which can purify hydrogen to 99.999%. The downside of including purification steps, is that a considerable loss in hydrogen occurs. These losses and the cost of building the required equipment for purification, currently contribute about 50% of the price of hydrogen when produced from fossil processes (Bernardo, 2020).

This is stipulated by Dawood (2020), who stresses the importance of considering both the level of purity produced, and the level of purity required on the demand side when designing hydrogen systems (Dawood, 2020). It is furthermore important to include any costs related to required purification steps in this hydrogen production pathway, even if this happens outside of the production stage (Dawood, 2020). The importance of including the purification costs of hydrogen in economic assessments was also emphasized by Wickham et al. (2022). These costs need to be included so as not to give a skewered view of the total cost of the hydrogen production (Dawood, 2020). However this was identified as a gap in knowledge in scientific literature (Dawood, 2020), seeing as how the cost of purification of hydrogen in production path ways is often missing from economic assessments.

Storage

For the storage of hydrogen there are multiple possibilities. The onshore hydrogen network that is being developed by Gasunie, plans to store hydrogen in compressed gaseous form in empty salt caverns (Gasunie, 2023). Although these caverns offer large capacity at relatively low costs, it creates a need for purification steps to ensure that the hydrogen is of high enough quality (HyWay27, 2021). As outlined in the section above this is important to take into account. Hydrogen can however also be stored in compressed gas form in containers, having the benefit that it is not polluted like in the salt caverns. This type of storage would also be well suited for offshore storage located at electrolysers, as no conversion processes are required. When hydrogen is transported in the form of other molecules like ammonia or LOHC's, it can also be stored in containers in the form of those molecules. This has the advantage of greatly reducing the volumetric storage requirements, and the storage process is less energy intensive compared to compressed hydrogen storage in containers (Obara, 2019).

Synthesis

From the literature studied for the scope of this research, it becomes clear that offshore electrolysis in the seems a feasible strategy. Furthermore it became clear that it is important to take into account what level of purity of hydrogen is required when designing the supply chain, stressing that possible purification costs need to be included in the overall economic assessment so as not to give a skewered view. This is identified as a knowledge gap however, as the literature about the transportation of hydrogen neglected the purity requirements of the analysed systems and the resulting purification costs.

From the literature there is no consensus on what the optimal system configuration is to transport the hydrogen. Both the transportation of hydrogen using a pipeline network as well as using ships are discussed in the literature, with both having different advantages under different circumstances.

In the next section, alternative system configurations will be selected based on the information of the literature review. These system configurations will be expanded upon, and an overview of their respective system components will be given.

2.4 Alternative selection

In order to find the cost optimal system configuration four alternatives will be selected from the literature review for further analyses. To allow comparisons to be drawn between the main mode of transportation, two of system configurations will use pipelines for transportation and two will feature transportation using ships. The difference between the pipeline configurations will be that one features onshore storage in salt caverns, while the other features offshore storage located at the electrolysers. The possibility of repurposing old offshore gas pipelines is not considered in this thesis, due to a lack of available data on pipelines that will become available for repurposing in the future. The difference between the ship transportation alternatives is that one configuration features the use of ammonia as hydrogen carrier, while the other features the LOHC dibenzyl toluene.

From the stakeholder analyses it became apparent that the purity of the delivered hydrogen is an important requirement, therefore all system configurations that involve processes that can pollute the hydrogen will include a purification process before leaving the system. Furthermore the importance to maximize the supplied hydrogen came forward from the stakeholder analysis. To this end the design decision is made that in all system configurations, all produced hydrogen needs to either directly satisfy a demand or be stored in the case of an excess of supply. Below the selected configurations are explained, and an overview of all system elements is given.

Pipeline network with onshore storage in salt caverns

The first system configuration to be analysed is the one proposed by Gasunie, in figure 3 below is a schematic overview of all system components. The hydrogen produced at the wind farms is transported to the ports that Gasunie has selected as the access points to the onshore network. From there it will leave the system if there is a demand at that time step, any excess supply will be stored in salt caverns. The costs of transferring the hydrogen to the salt caverns is out of scope for this thesis. Therefore the assumption is made that the hydrogen enters the salt caverns directly. If there is a shortage of supply, the hydrogen is extracted from the salt caverns and purified using pressure swing adsorption. After the purification process, the hydrogen is released from the system to satisfy the demand.

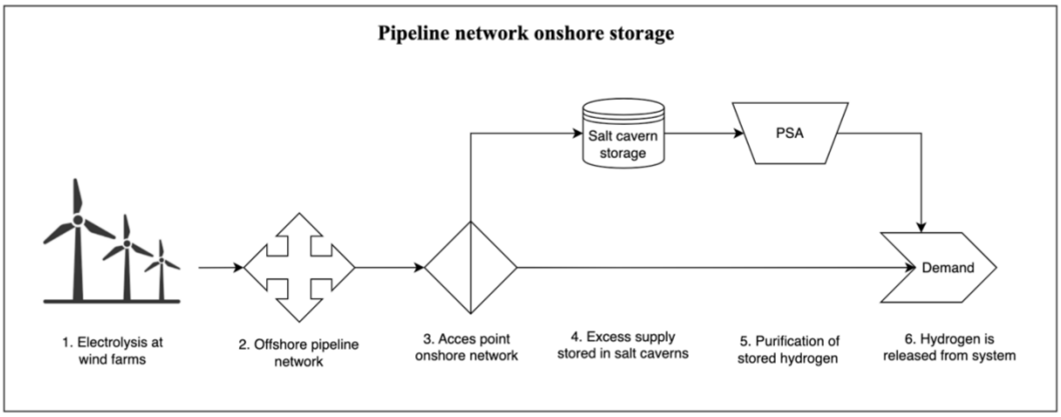

Figure 3: System overview pipelines with onshore salt cavern storage configuration.

Pipeline network with offshore compressed hydrogen storage at electrolysers

The second system configuration that uses pipelines, is inspired by one of the configuration outlined by Ibrahim et al. (2022). In it the produced hydrogen is either directly transported to one of the access points of the onshore network where it leave the system to satisfy a demand, or in the case of excess supply the hydrogen is stored in containers in a compressed gaseous state. This type of storage requires no additional purification. Therefore, at times there is a shortage of supply the hydrogen is extracted from the storage and transported to one of the ports where it will be released from the system. In figure 4 an overview of the system is illustrated.

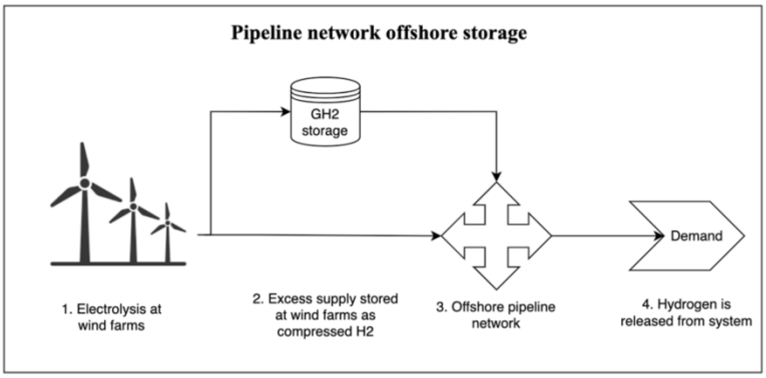

Figure 4: System overview pipelines with offshore compressed hydrogen storage configuration.

<u>Ship transportation using ammonia as hydrogen carrier</u>

The first shipping system configuration will transport hydrogen in the form of ammonia. Ammonia is selected as it is a widely available molecule and the technologies required for the hydrogenation and dehydrogenation are fully matured (Rodriguez, 2011). To transport the hydrogen as ammonia, a hydrogenation facility will be present at the electrolysers where nitrogen will be synthesized into ammonia. The ammonia will then be stored in containers at the location of the electrolysers. From there it will be collected by ships visiting all wind farms on a regular basis, and transported to one of the ports. At the port, part of the ammonia is transferred directly to a dehydrogenation facility to satisfy a demand. After the dehydrogenation, the hydrogen is purified at a PSA facility and then released from the system. The remainder of the ammonia is transferred to an onshore storage facility, from where it is gradually extracted to be dehydrogenated and purified before leaving the system. In figure 5 a schematic overview of this system configuration is illustrated.

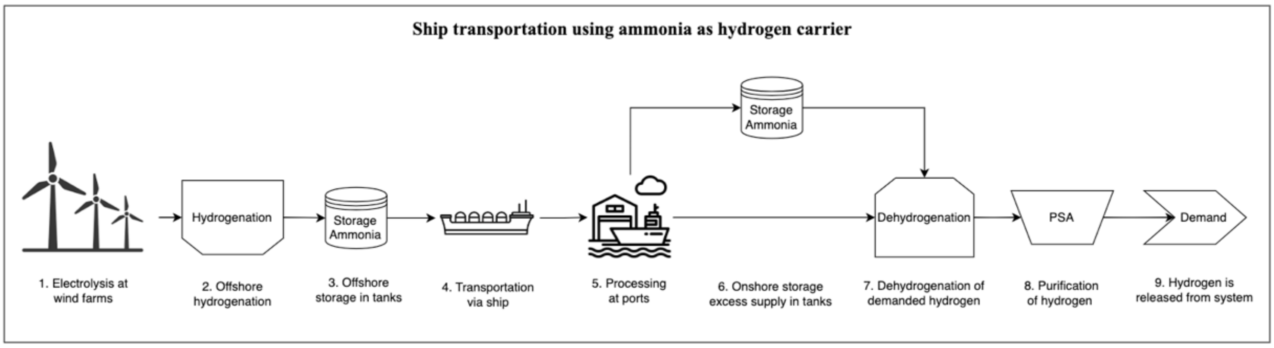

Figure 5: System overview ship transportation using ammonia as hydrogen carrier configuration.

<u>Ship transportation using the LOHC dibenzyl toluene as hydrogen carrier</u>

The final system configuration utilizes the LOHC dibenzyl toluene. This LOHC is selected as the literature review showed it benefits from no losses during the de/hydrogenation cycle and requires no purification. It is of further interest as this is the compound which will be used for the hydrogen importation project in the Port of Amsterdam as mentioned in the literature review. In the system the produced hydrogen will be stored in the LOHC in a hydrogenation facility located at the electrolysers. From there it will be collected by a ship and transported to one of the ports. At the port part of the LOHC will be directly dehydrogenated to satisfy a demand and leave the system. The remainder will be stored onshore in containers, and gradually extracted for dehydrogenation before being exiting the system and satisfying a demand. In figure 6 a schematic overview of this system configuration is given.

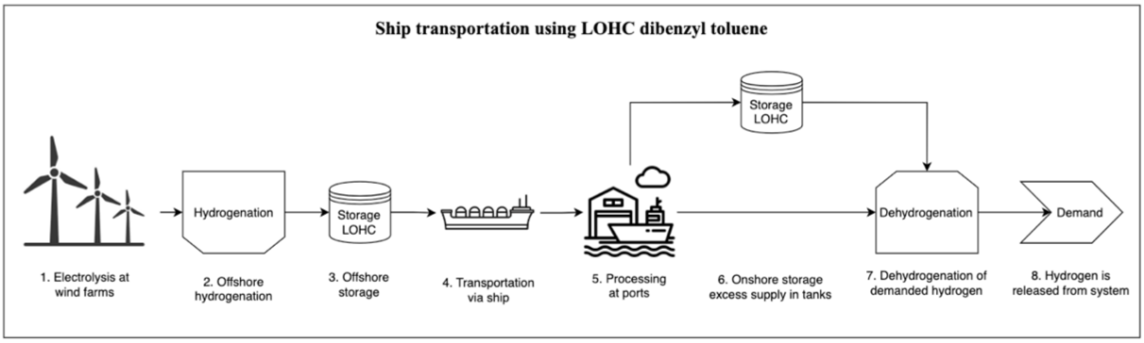

Figure 6: System overview ship transportation using the LOHC dibenzyl toluene configuration.

<u>Additional remarks</u>

It should be noted that there is an inherent difference between the system configurations that transport the hydrogen using pipelines and those using ships. The pipelines are able to continuously transport the produced hydrogen, whereas the ships transport the hydrogen in batches. Therefore a design decision was made on the required capacities of certain system components, which is outlined below.

Due to the continuous transportation of the pipeline configurations, the capacities required for the pipelines and the purification facilities will match the highest level of supply if there is a shortage of supply, or the highest level demand if there is an excess of supply.

In the ship transportation configurations, the dehydrogenation and PSA capacities also match the highest level of demand in the case of excess supply. If there is a shortage of supply however, the dehydrogenation and PSA capacities should be exactly high enough to process the delivered hydrogen batch in the time it takes for a new batch to arrive. Otherwise these facilities would remain unused for large amounts of time, which is not in line with the stakeholder goal that investment cost should be as low as possible.

This inherent difference between the two types of transportation is however compensated to some extent, due to the fact that the pipeline configurations in general will require less storage as they continuously deliver hydrogen. Whereas the shipping alternatives need to store all supply offshore at the electrolysers, and most of the supply onshore at the ports.

2.5 Research objective

Now that the system boundaries and alternative system configurations have been defined, the research question this thesis aims to answer can be formulated:

What is the cost optimal system configuration to transport hydrogen from the North-Sea to shore under uncertain levels of future supply and demand, and considering the resulting purity?

To aid in answering this research question, the following sub questions are defined:

1. *How can a set of scenarios be constructed that cover the uncertainty of the future hydrogen supply and demand?*
2. *What technical and economic inputs are required to model the transportation alternatives?*
3. *How can the transportation alternatives be modelled?*
4. *What is a suitable methodology to optimize the pipelines transportation configurations?*
5. *What is a suitable methodology to optimize the ship transportation configurations?*
6. *How can the performance of the system configurations be measured?*

2.6 Report structure

The remainder of this thesis is structured as follows. In chapter 3 more information surrounding the case is gathered. Using this information the first two sub questions are answered. Chapter 4 aims to answer the third sub question by reviewing scientific literature on network design problems. Chapter 5 applies the lessons learned in chapter 4, to develop a methodology to model the system configurations and answer the fourth, fifth and sixth sub questions. In chapter 6 the results of the applied methodologies are presented. Followed by a discussion of the result in chapter 7, and the conclusion of this research in chapter 8.

3. Data operationalisation

The aim of this chapter is further define the case introduced at the start of this thesis, and to determine all necessary inputs for the various models. In doing so, the following sub questions will be answered:

1. *How can a set of scenarios be constructed that cover the uncertainty of the future hydrogen supply and demand?*
2. *What techno-economic inputs are required to model the transportation alternatives?*

In the following sections, the locations and capacities of current and future wind farms are discussed. Following this, the supply and demand scenarios are quantified. Afterwards the resulting hydrogen potential will be determined from the installed wind capacities of the supply scenarios. Finally the values for the required technical inputs for the different system configurations will be determined, along with the costs related to the system components.

3.1 Wind farm locations

The first required data, are the locations and capacities of the wind farms whose potential hydrogen production this thesis analysis. For the year 2030, these are based upon the '*Routekaart Windenergie op zee'* (Rijksoverheid, 2023) which can be found in appendix B1. The sum of the capacity planned in the map is 22.9 gigawatt (GW).

For the windfarms to be built after 2030 there is more uncertainty. This is due to the fact that some of the planned wind farms for 2030 are still to be built, and no concrete plans have been set out for the expansion of the wind capacity beyond 2030. Certain areas of the Dutch North Sea have however already been designated as potential locations for windfarms. These designated areas can be seen in figure 7 containing, the "Zoekgebiedenkaart Noordzee" (Rijksoverheid, 2023b) map. As these potential wind farms do not have a planned year of construction, the assumption was made that all the new windfarm areas will start being developed between 2030 and 2040.

Beyond a certain distance out of shore, transporting energy in the form of hydrogen becomes more economically advantageous than transporting electricity due to high losses (Ibrahim, 2022). As these wind turbines currently do not exist yet, they will only be taken included for wind turbines built after 2030. According to Peters (2020) this distance threshold is at 100 kilometres out of shore. Future wind farms over this threshold will therefore be considered dedicated to hydrogen production in this research.

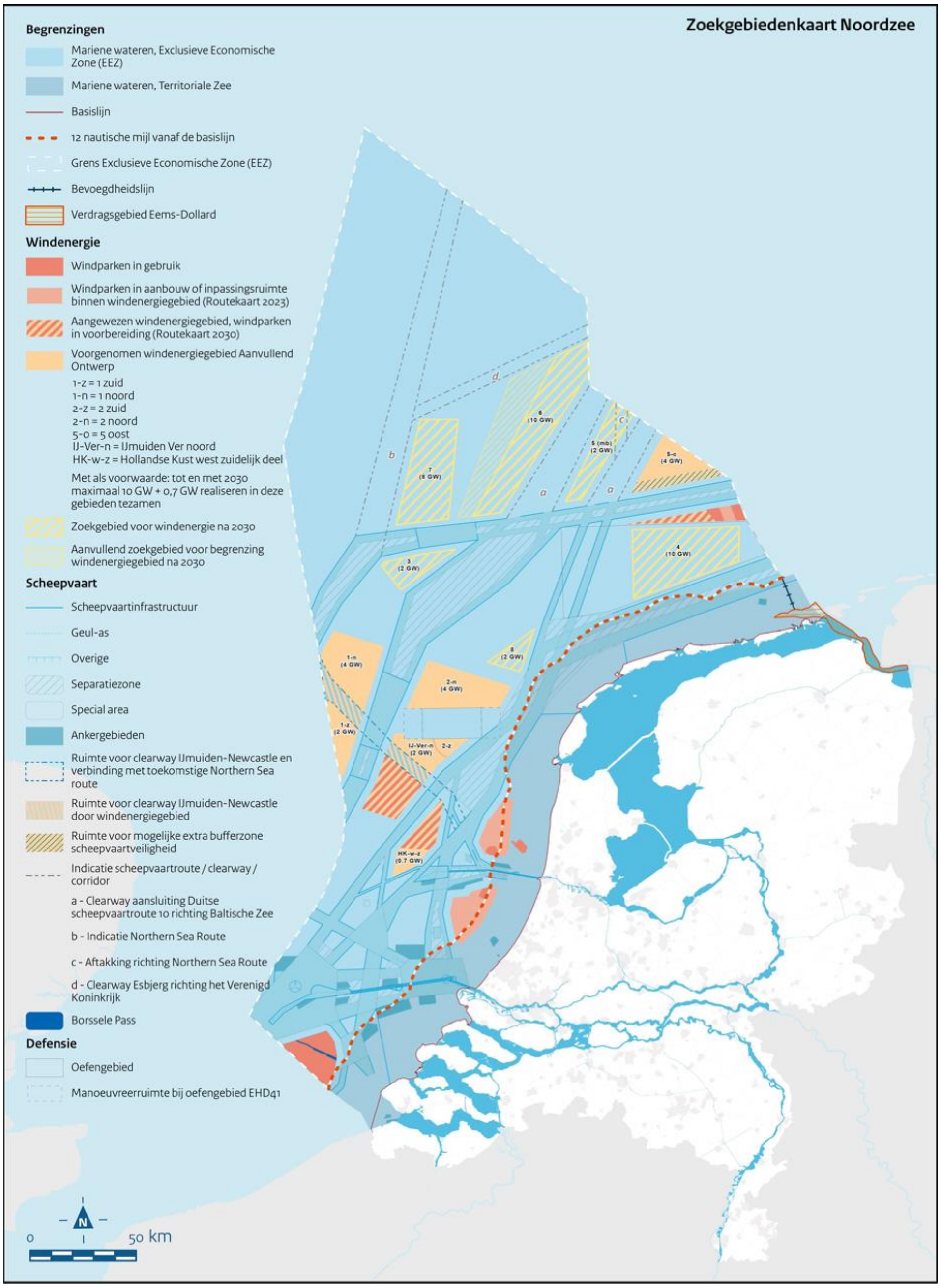

Figure 7: Areas in the North-Sea designated as potential wind farm locations.

To find the coordinates of the wind farms an overlay of the 'Zoekgebiedenkaart Noordzee' was created in Google Earth. The assumption was made here that all wind farms will have one electrolyser, and that each electrolyser can be located at the edge of the wind farm for easy access.

The resulting overlay with the locations of the electrolysers indicated by yellow pins, dedicated wind farms by green pins, and the ports by a red pin can be seen in figure 8.

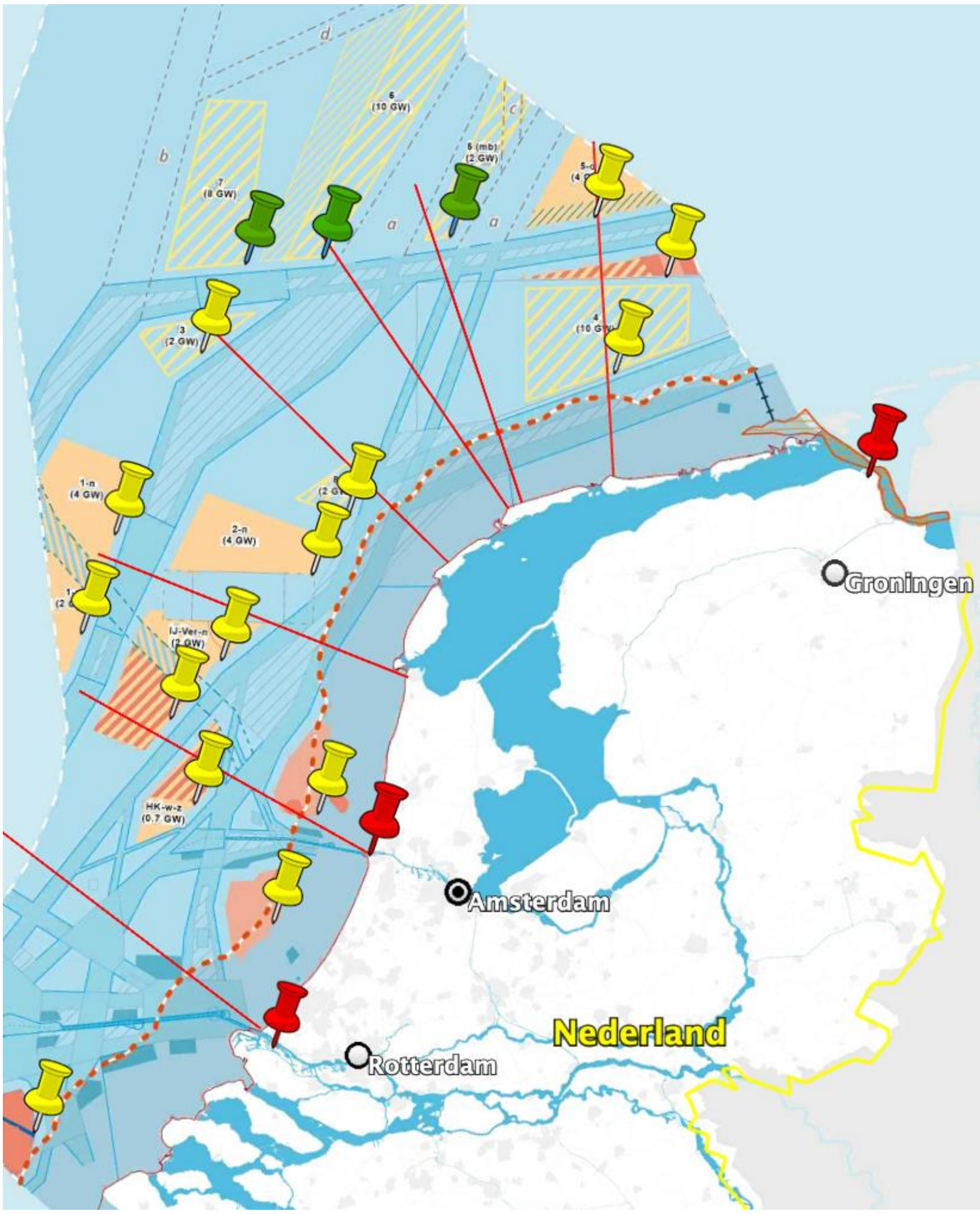

Figure 8: Locations of electrolysers and ports.

The red lines indicate a distance of 100 kilometres out of shore, which is the threshold for future hydrogen dedicated wind farms used in this thesis (Peters, 2020). Due to the ambiguity of whether or not 100 kilometres out of shore will be measured from the islands in the North Sea or from the main land, two wind farms at the top of the map fell partly inside and partly outside of the threshold. Seeing as how both of these wind farms have the same planned capacity, the decision made to select one of these two to be a dedicated hydrogen wind farm. For the dedicated hydrogen wind farms that have an electrolyser inside the turbines, it is assumed all hydrogen produced in the wind farm is transferred to the set location.

3.2 Scenarios

There are two main sources of uncertainty that influence the optimal system configuration. These uncertainties are the level of supply and demand for hydrogen, and their development in the period from 2030 to 2050. To deal with these uncertainties a low, medium, and high scenario is constructed for both the supply and demand. As the hydrogen supply is contingent on the installed wind capacity, the supply scenarios will consist out of different levels of installed wind capacities.

All the scenarios are phased over the years 2030, 2040 and 2050, meaning all scenarios contain three discrete timesteps. These years are assumed to represent an investment moment, meaning that investments required to facilitate the growth in hydrogen production will be made at those moments. For these years, the total cost of the different system configurations will be calculated.

In order to capture the intermittent nature of the wind, the available wind for hydrogen production is calculated on an hourly basis. Modelling the system configurations over the course of all hours in a year however requires an substantial computational effort. Yet the level of supply varies over the seasons due to changes in wind availability. To reduce the computational effort required without losing the seasonal supply patterns, a representative winter and summer week will be selected for all three investment moments, for all scenarios. The hourly wind availability of these weeks will be used as the values for half of the year each.

Combining the supply and demand scenarios leads to a total of nine scenarios. The structure of the combined scenarios is illustrated in figure 9 below.

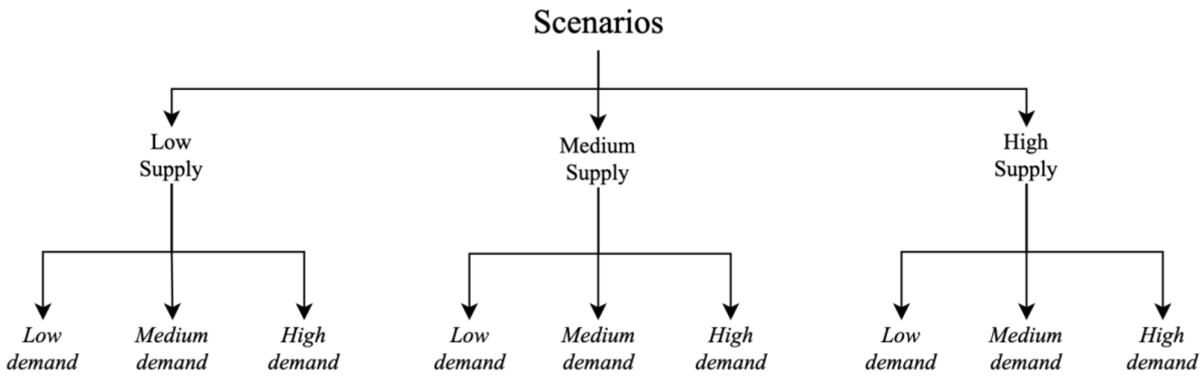

Figure 9: Visual overview of supply and demand scenarios.

In reality further combinations of the scenarios could be possible, if for instance the demand would start low for the year 2030 but then rapidly increases to values of the high demand scenarios in 2040 or 2050. This possibility of crossover however is not considered for this research, as the current set up is designed to analyse how the alternative system configurations perform under the different demand and supply circumstances. Including this possibility would obscure scenario specific outcomes, leading to less specific insight in the performance of the alternatives under the different circumstances.

Supply scenarios

The potential hydrogen supply depends on the amount of offshore wind power that will be installed in the coming years. The total planned offshore wind power capacity for 2030 is 22.9 GW, with plans to expand this to between 38 and 72 GW by 2050 (Rijksoverheid, 2023). Since the hydrogen production potential is contingent on the amount of electrical surplus, an increase in installed wind power has a dual impact on hydrogen production. Firstly, more installed power increases the frequency of surplus occurrences. Secondly, it increases the hydrogen generation capacity during surplus periods. Given this context the supply scenarios will vary the future installed wind capacity.

As explained in the methodology, each scenario is phased over the years 2030, 2040 and 2050. As the plans for the wind capacity of 2030 are quite concrete, all supply scenarios will start with the same wind capacity of 22.9 GW. In the low and high supply scenarios this will be scaled to 38 and 72 GW in 2050 respectively, following the plans of the Dutch government. The assumption is made that half of the required increase in capacity will be built in 2040, and the remaining half in 2050. As the gap between the projections of the low and high wind scenarios is quite large, the capacities in the medium wind scenario will at the centre of this gap. In table 1 below are the resulting wind capacities for the scenarios over all three timesteps.

Supply	**Low wind**	**Medium wind**	**High wind**
2030	22.9	22.9	22.9
2040	30.5	39	47.5
2050	38	55	72

Table 1: Wind capacity installed in supply scenarios in GW.

Demand scenarios

In 2030, there is considerable uncertainty regarding hydrogen demand. This uncertainty arises from the necessity of a steady supply before demand can materialize. Lower bound scenarios for 2030 anticipate that many large industry players will switch to using hydrogen as feedstock only during their next reinvestment cycle, when current facilities require replacement (TNO, 2023). This strategy would reduce their supply uncertainty while deferring their next substantial capital expenditure (CAPEX) investment. In these lower bound scenarios, hydrogen demand in the Netherlands is estimated at approximately 7.5 Petajoule (PJ) per year (TNO, 2023). Conversely, higher bound scenarios for 2030 envision industry players proactively investing in hydrogen-compatible facilities, resulting in a national hydrogen demand of 75 PJ per year (TNO, 2023). With the scenarios in between the low and high demand leaning towards the high demand projections at 50 PJ (TNO, 2023).

Beyond 2030 the gap between hydrogen demand projections only increases. With lower bound scenarios projecting that the total demand in 2050 will be comparable to the current energy demand of the Dutch industry, around 200 PJ per year (TNO, 2020a). Higher bound scenarios typically forecast demand at approximately 500 PJ per year, with the highest estimates reaching up to 1600 PJ per year if potential demand from the shipping and aviation industries is included (TNO, 2020a). However the potential demand from these sectors is excluded in this research to avoid increasing the uncertainty of the high demand scenario, as the technologies to use hydrogen in these sectors are not yet available (TNO, 2020a) . Furthermore, it is estimated that at a demand level of 500 PJ, approximately 70% of the hydrogen demand will need to be met through imports (Jepma, 2019).

Again the scenarios are phased over the years 2030, 2040 and 2050. The low and high demand projections of 7.5 and 75 PJ in 2030 are scaled to the projections of 200 and 500 PJ in 2050 respectively. Whereas the medium demand scenario starts at 50 PJ, and is scaled over the years to the centre of the gap from the low and high scenario to 350 PJ in 2050. In table 2 below is an overview of the demand values over the time steps of the scenarios.

	Low demand	**Medium demand**	**High demand**
2030	7.5	50	75
2040	103.75	200	287.5
2050	200	350	500

Table 2: Demand scenarios in PJ per year.

The input for the models used in this thesis require the values of the supply and demand on an hourly basis, yet the further allocation of the demand is out of scope for this research. Therefore the demand is assumed to be constant at all time.

3.3 Hydrogen potential

Using the installed wind capacity of the supply scenarios, the hourly production of hydrogen can be derived. The potential hydrogen production on the North Sea depends on multiple factors. Firstly it depends on how often there is a surplus in the electricity supply of the Netherlands. This is when the total supply of must-run electricity plants and renewable energy is greater than the total electricity demand at a certain time. The supply of these must-run plants and renewable energy are deciding for the surplus, as in the energy market the energy generated by these facilities are sold first, as they have the lowest marginal cost. Must run electricity plants are plants that either take a long time to start up meaning that they need to run constantly for economic reasons, or combined heat and power plants that do not primarily run to generate electricity but also satisfy a heat demand. If the supply of these must run electricity plants and the renewable energy sources is greater than the hourly electricity demand, the part of the electrical surplus that is generated by the offshore wind turbines will be available for the production of hydrogen. For the dedicated wind farms the hydrogen potential only depends on the installed capacity and the available wind at each time step.

In order to find the hydrogen production in the scenarios, the Energy Transition Model (ETM) is utilised (Quintel Intelligence, n.d.). The ETM is an open source energy model in which energy scenarios can be created for countries, in which the demand and supply sources can be altered. The model makes use of real data collected over multiple years, making it capable of generating reliable output. The output of the ETM consists of an hourly overview of all sources and demand of electricity over the course of an entire year. This output is used in an excel model to find the potential hourly hydrogen production for the scenarios.

The full steps of coming to the potential hydrogen production capacity are outlined below:

1. Within the ETM the offshore wind capacities of the supply scenarios is entered. For the purpose of this thesis the possibility of import and export of electricity to other countries is excluded, as including this makes the ETM balance the system by selling the surplus to neighbouring countries. The ETM uses wind data from the year 2012 to give accurate output profiles of the electricity generated by offshore wind farms for each hour of the year. For the years 2040 and 2050 in which hydrogen dedicated wind farms are included, their corresponding capacity is not entered in the ETM as offshore wind capacity as this would give a skewered view of the amount of times there is an electrical surplus. Instead their hydrogen production is calculated later using outputs of the ETM.

2. The output of the ETM is an excel file containing an hourly overview of all sources of demand and supply in the system over the course of an entire year. The ETM uses the hourly electricity demand of the year 2020, so the first step in the excel model is to incorporate the electricity demand growth for the corresponding year of the scenario. This yearly increase in the electricity demand is estimated at 1.1% per year for the period of 2020-2050 (McKinsey&Company, 2010). Other electricity sources are assumed to remain stable until the year 2050. Now within the excel model the hourly

surplus can be calculated by subtracting the corrected hourly demand from the hourly supply of electricity.

3. Now within the excel model the hourly surplus can be calculated by subtracting the corrected hourly demand from the hourly supply of electricity. As only the part of the surplus that is generated by offshore wind farms is of relevance to the potential hydrogen production, its share of the surplus is derived next.

4. This is done by comparing the hourly surplus to the hourly offshore wind energy production. If there is an hourly electrical surplus, but it is lower than the hourly offshore wind production, the electrical potential for hydrogen production is equal to the surplus. Conversely, if the hourly surplus is greater than the hourly offshore wind energy generation, the electrical potential for hydrogen production is equal to the offshore wind electricity generation at that time. Next the hydrogen production of the dedicated hydrogen wind farms is calculated. This is done by finding the ratio between normal wind farms and dedicated hydrogen wind farms in the scenario. This ratio is then multiplied with the hourly offshore wind electricity generation, to find the potential electricity available for direct hydrogen production.

5. The next step in the excel model is to compile the hourly potential for hydrogen production, into average hourly supply on a weekly basis. This is done as the inputs for the models will be the hourly supply of a representative week of winter and summer, as stipulated in the methodology. From the weekly averages, the seasonal averages are derived. Note that the seasonal averages are for the winter and autumn, and summer and spring weeks combined. The two weeks whose average hourly hydrogen production are closest to the seasonal average are then selected to use as input for the models. After analysis of the database it was concluded that the weeks selected to represent the seasons, do not necessarily need to fall within that season. This analysis can be found in appendix B2.

For all supply scenarios an overview of the resulting hourly hydrogen production of the selected weeks can be found in appendix B3.

3.4 Technical data

In this section all relevant technical data will be discussed for all system components.

Electrolyser

With the locations of the electrolysers decided upon, there is a need to define the technical parameters on the hydrogen that can be produced with the available wind energy. As the aim of this research is to analyse the cost optimal way to transport the potential hydrogen, the costs of the electrolysers will not be taken into account as this has no influence on the transportation of the hydrogen. The following techno economic values are used in this thesis:

Capacity	*1 MW*
Production	*450 kg/day*
Efficiency	*75%*

These values are based upon the technical specifications of the H-TEC ME450 electrolyser (H-TEC, 2024). H-TEC is a leading electrolyser developer, and the capacity and output of the electrolyser can be scaled evenly.

Pipeline data

For pipelines the parameter values below are used in this thesis. All these values are based upon the HyWay 27 report by the Ministry of Economic affairs and climate (HyWay27, 2021).

Operating pressure:	50 bar
Flow speed	60m/s
Lifetime	50 years

Ship data

For the ships the following technical parameter values are used:

Capacity	47-280 million kg
Lifetime	20 years

These figures are based upon the fact that 47 million kilogram capacity is the capacity of the average tanker ship in the Netherlands (Stratelligence, 2023), while the 280 million kg is the capacity of the ship used by Hydrogenious, a company that plans to import hydrogen in the form of LOHC to the Port of Amsterdam (Hydrogenious, 2024).

Storage facilities

For the storage facilities used in the different system configurations, the expected life time is required. The following value have been used in this thesis.

Storage type	**Lifetime**	**Source**
Salt caverns	30 years	Hyway 27, 2021
Compressed H2	20 years	Hyway 27, 2021

LOHC	30 years	Abdin, 2022
Ammonia	30 years	Abdin, 2022

Furthermore the capacity is required for the salt caverns, along with the amount of hydrogen that can be stored per m3 of LOHC and ammonia.

	Capacity	**Source**
Salt caverns	4166 tonnes/cavern	HyWay 27, 2021
LOHC	54 kg/m3	Hydrogenious, 2024
Ammonia	121 kg/m3	Obara, 2019

De/hydrogenation facilities

For the hydrogenation and dehydrogenation facilities lifetime, the following values were used.

	Lifetime	**Source**
De/hydrogenation LOHC	20 years	Reuß, 2017
De/hydrogenation ammonia	20 years	Reuß, 2017

Another important factor is the amount of hydrogen that can be recovered in the dehydrogenation process, the values used in this thesis are the following:

	Recovery rate	**Source**
LOHC	100%	Rao, 2022
Ammonia	77.60%	Jackson, 2019

PSA

The technical parameters required for the PSA installations are the lifetime, and the hydrogen recovery rate. The following values have been used in this research.

Lifetime	*20 years*
Feed pressure	*25 bar*
Recovery rate	*80%*

These values are based upon the work of Luberti (2022) and Kalman (2022).

3.5 Cost data

In table 3 on the next page, all relevant investment (CAPEX), fixed costs (FC), and operational costs (OPEX) are outlined for all system configurations and their components.

After the cost table the next chapter of this thesis is presented. In it a theoretical basis on which to model the various system configurations is sought through a review of relevant literature.

Pipelines onshore storage	Specific cost	Value	Source
Investment cost	Pipeline CAPEX:	€10 million/km (36 inch)	Stratelligence, 2023
	Storage CAPEX:	€107 million/0.5 PJ	HyWay27, 2021
Operational cost	OPEX pipelines:	1% of CAPEX	HyWay27, 2021
	OPEX storage:	2% of CAPEX	Reuß, 2017
	FC storage:	€7.5 million per salt cavern	HyWay27, 2021
Pipelines offshore storage			
Investment cost	Pipeline CAPEX:	€10 million/km (36 inch)	Stratelligence, 2023
	Storage CAPEX:	€644,000/tonne H2	Abdin et al. 2021
	PSA CAPEX:	$6242000 ∗ (m3/h /22424.9)	Wang, 2012
Operational cost	OPEX pipelines:	1% of CAPEX	Stratelligence, 2023
	OPEX storage:	2% of CAPEX	Reuß, 2017
	OPEX PSA:	€0.34 per kg H2	
Ship LOHC			
Investment cost	Ship CAPEX:	€40-125 million	Self-study
	CAPEX hydrogenation:	€1.91 million/Tonne/H2/day	Abdin, 2021
	CAPEX dehydrogenation:	€100,000/Tonne/H2/day	Abdin, 2021
	Storage CAPEX:	€41,000 per tonne H2	Abdin, 2021
Operational cost	Cost per km:	€80-240 depending on size	Stratelligence, 2023
	FC ship:	€12.9-60 million depending on size	Stratelligence, 2023
	FC hydrogeneration:	4% of CAPEX	Scherer, 1998
	OPEX hydrogeneration:	5% of CAPEX	Scherer, 1998
	FC dehydrogenation	4% of CAPEX	Scherer, 1998
	OPEX dehydrogenation:	5% of CAPEX	Scherer, 1998
	OPEX storage:	2% of CAPEX	Reuß, 2017
Ship Ammonia			
Investment cost	Ship CAPEX:	€40-125 million	Self-study
	CAPEX hydrogenation:	€1.94 million/Tonne/H2/day	Abdin, 2021
	CAPEX dehydrogenation:	€2.125 million/Tonne/H2/day	Abdin, 2021
	Storage CAPEX:	€43,000 per tonne H2	Abdin, 2021
	PSA CAPEX:	$6242000 ∗ (m3/h /22424.9)	Wang, 2012
Operational cost	Cost per km:	€80-240 depending on size	Stratelligence, 2023
	FC ship:	€12.9-60 million depending on size	Stratelligence, 2023
	FC hydrogeneration:	4% of CAPEX	Scherer, 1998
	OPEX hydrogeneration:	5% of CAPEX	Scherer, 1998
	FC dehydrogenation:	4% of CAPEX	Scherer, 1998
	OPEX dehydrogenation:	5% of CAPEX	Scherer, 1998
	OPEX storage:	2% of CAPEX	Reuß, 2017
	OPEX PSA:	€0.34 per kg H2	Kallman, 2022

Table 3: Complete cost table for all system configurations and components.

4. Theoretical framework

This chapter aims to answer the third sub question:

3. *How can the transportation alternatives be modelled?*

To achieve this scientific literature is reviewed to create a theoretical basis on which the methodology for this research can be build. The system configurations selected previously can all be described as network design problems. The three main approaches to solving such problems, identified by Heijnen et al. (2019) are: geometric graph theory, mixed integer (non-) linear programming (MILP), and agent based models.

Agent based models consist out of autonomous entities that interact and behave in according to specified rules (De Marchi, 2014). For analysing network design problems specifically, ant colony optimization (ACO) models are used (Heijnen, 2019). ACO takes inspiration from the foraging behaviour of social insects (Dorigo, 2006) and has been applied to find solutions to the classical shortest path problem (Blum, 2005). The MILP approach relies on formulating mathematical models including an objective function and a set of constraints. The MILP approach has been used extensively for the purpose of network optimization analyses (Kantor, 2020). Furthermore, using the MILP approach makes it possible to make the model spatially explicit (Moreno, 2017), making it well suited to handle network design problems. The final approach for studying network design problems is the use of geometric graph theory. The term geometric graph theory refers to the body of scientific literature related to graph that are defined by their geometric means (Pach, 2013). Geometric graph theory consists out of heuristics and algorithms from geometry and graph theory that are designed to analyse networks. Due to its rather simple structure, yet broad range of applications and possibilities, using graphs to model network design problems is the most commonly used method (André, 2013).

Due to the simple main structure of using graph theory, this methods seems more flexible compared to MILP and ACO. Furthermore geometric graph theory is designed specifically to analyse networks, whereas agent based modelling and MILP are designed to be used for multiple applications. As this thesis aims to analyse multiple system configurations, the flexibility geometric graph theory offers combined with the fact it is specifically designed to analyse networks, makes it the best fit for the purpose of this research.

Graph theory is used in network design analyses by describing the network as a set of points (*Nodes*) and the connections between them (*Edges*). The graph G is then defined as $G = (N, E)$. In figure 10 below is an illustration of a simple graph, in this case containing four nodes and four edges.

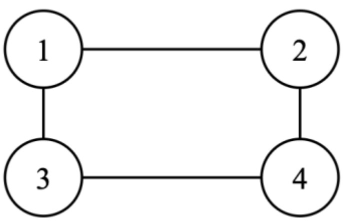

Figure 10: Simple graph with four nodes and four edges.

When using graph theory to model new energy networks one of the main goals is to connect sources to sinks, with the sources being producers and the sinks being consumers in the network (Heijnen, 2014). In figure 11 below is a simple example of a new network with several sources and sinks that need to be connected.

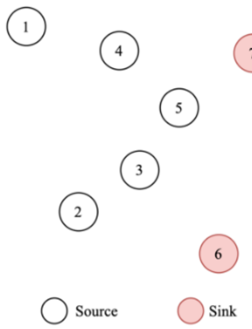

Figure 11: Example of network to be connected with multiple sources and sinks.

The cost optimal way to connect such a network results in a tree topology. Meaning that the graph contains no loops or cycles, so that there is exactly one path from each node to each other node (Heijnen, 2014). The cost of the edges is determined by their weight, which represent characteristics such as their length and capacity. When only the length of the edges is taken into account the resulting network is the Euclidean minimal spanning tree (MST), representing the network with the minimal length. In figure 12 below is the resulting MST of the example introduced above.

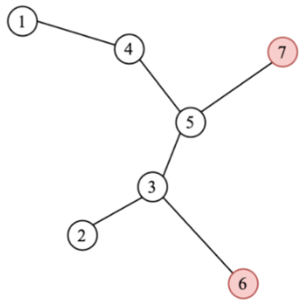

Figure 12 : Euclidean minimal spanning tee of example network.

When a new network is built however, shorter networks may be found by adding Steiner points when two edges are both directed towards the same node. The resulting network is then called a Steiner minimal tree. When the capacities of the edges are different, the locations of the Steiner points may be slightly different if that results in lower costs. If the capacities are taken into account the network is then called the generalized Steiner minimal tree (Heijnen, 2014). In figure 13 below the Steiner minimal tree of the example network is illustrated.

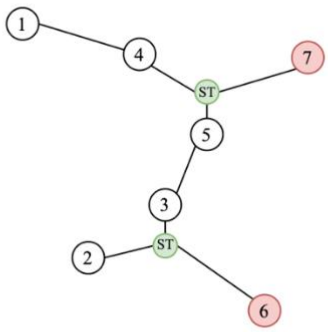

Figure 13: Steiner minimal tree of example network.

For the system configurations in which hydrogen will be transported with ships, no networks will be build. Therefore instead of find a minimal cost network, the route with the shortest distance has to be found. This route should start at a sink, visit all sources exactly once and then return to a sink to deliver the hydrogen. This is a version of the well-known traveling salesman problem (TSP) (Hoffman, 2013). The solution to such a problem is often referred to as a Hamilton circuit. As there are no direct costs associated with such a circuit, the circuits are evaluated on the basis of the sum of the lengths of all edges (Applegate, 2006). In figure 14 below a simple example of a Hamilton circuit.

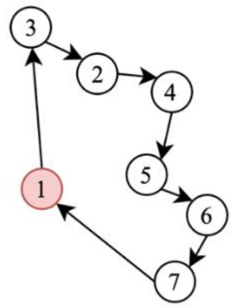

Figure 14: Simple example Hamilton circuit.

Due to the geographic span of this research however, visiting all source nodes in one circuit may not be optimal. Instead finding multiple circuits with fewer nodes may yield a solution with a shorter total distance. Furthermore ships have a limited capacity, which may make visiting all nodes unfeasible depending on the level of supply.

To facilitate this the source nodes can be divided amongst clusters. This clustering process entails the identifying of natural groupings (clusters) within multidimensional data on the basis of a similarity measure (Omran, 2007). Clustering is used in many different disciplines, and as such there are many different clustering techniques (Omran, 2007). In general these techniques can be divided in two categories, hierarchical clustering and partitional clustering (Madhulatha, 2012). In hierarchical clustering techniques the number of clusters changes during the clustering, as indices in the clusters are relocated. Whereas in partitional clustering techniques, all clusters are determined simultaneously (Madhulatha, 2012). The advantages of using hierarchical techniques is that the results are independent of the initial conditions, and that the number of clusters does not need to be specified in advance. Their drawbacks are however that they are computationally expensive, and once an item has been assigned to a cluster it can’t be relocated (Omran, 2007). Partitional clustering techniques on the other hand work faster and take a more iterative approach, allowing items to switch between clusters if that improves the result. Due to these advantages partitional clustering techniques are most commonly used (Jain, 2000), and seem most fruitful for the scope of this research.

Amongst the partitional clustering techniques, the most widely used is the K-means algorithm. This is due to the fact that the algorithm is easy to implement, and finds solutions quickly. It is important to note that the end result depends on the initial conditions, which may result in local optimum solutions (Omran, 2007).

The K-means function is iterative, and its objective function minimizes the intra-cluster distance (Hamerly, 2002). Meaning that it attempts minimize the total distance of the elements within clusters to each other. The algorithm works by first initializing K centroids, one for each of the required clusters. One by one the elements in the dataset are then assigned to the cluster centroid closest to them. The centroids are then recalculated as the centre of all elements in it. The last two steps of this process are iteratively repeated until the change of the centroids values is smaller than a user specified value, or a set number of iterations is completed (Omran, 2007). To decrease the dependency on the initial conditions of the K-means algorithm, the centres can be initialized using the K-means++ algorithm. This algorithm works by choosing the first centroid at random from the elements in the dataset, the subsequent centroids are then selected using a probability function that spreads them uniformly over the span of the dataset (Arthur, 2006). The K-means++ algorithm was found to both increase the speed and the accuracy of the results. In figure 15 below an illustration of resulting clusters, and the hamilton circuits of the previous example.

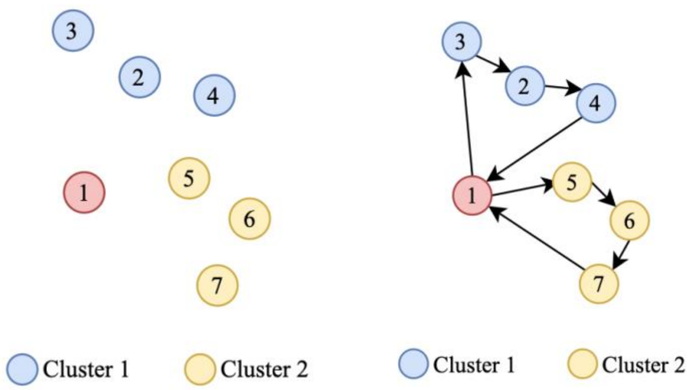

Figure 15: Clustering of example network

As mentioned earlier however minimizing the distance of the Hamilton circuits is not the only reason that clustering is needed. The ships collecting the hydrogen have a limited capacity, meaning that the sum of the produced hydrogen of all nodes in a cluster has to be lower than the capacity. This problem is known as the capacitated clustering problem (CCP) and was first formulated by Mulvey and Beck (1984). Since it was first formalized, multiple algorithms have been proposed to solve it. However the CCP is known to be at least NP-hard (Negreiros, 2006), with some sources calling it NP-complete (Geetha, 2009). This entails that no algorithm can guarantee the optimal solution.

5. Methodology

In this chapter the proposed methodology of this research is laid out by building upon the theoretical framework laid out in the previous chapter. In doing so, this chapter answers the fourth, fifth and sixth sub questions:

4. *What is a suitable methodology to optimize the pipeline transportation configurations?*
5. *What is a suitable methodology to optimize the ship transportation configurations?*
6. *How can the performance of the system configurations be measured?*

5.1 Pipeline configurations

In the previous chapter, graph theory was selected as the best fit to model the transportation alternatives. To model the pipeline alternatives this research makes use of the Optimal Network Layout Tool, a graph theoretical tool developed in Python (Heijnen, 2023). This tool is selected as it is specifically build to find optimal energy networks with multiple sources and sinks under varying levels of supply and demand. Additionally the tool includes the possibility of adding storage facilities in the network to handle excess supply. Considering that the difference between the pipeline alternatives is the location of the storage facilities, this makes the tool an excellent fit.

The primary input of the tool consists of the location of all sources and sinks in the network, and their respective supply and demand for each time step. In order to include the intermittent nature of wind energy, and thus hydrogen production the supply and demand is entered on an hourly basis. As the scenario data will be made up of one week of winter and summer, the number of time steps the model takes is equal to the number of hours in a week. Furthermore the location of the storage facilities needs to be specified, including their capacity and the amount of hydrogen that is stored at the start.

The tool makes use of several algorithms and heuristics to find an optimal minimal cost network. The model consists out of following steps:

1. Determine minimal spanning tree
2. Determine minimal-cost spanning tree
3. Determine minimal-cost Steiner tree

In the first step the model derives the Euclidean minimal spanning tree, which is the network with the lowest total length, with capacities that can satisfy the highest flow required over the edges over all time steps. This flow can be to satisfy a demand, or to transport remaining supply to the nearest possible storage. In figure 13, the left image is the output of this step for an example network. In the second step the model takes into account the capacity cost of the edges, and tries to find cheaper networks by iteratively switching edges. In figure 16, in the middle is the output of this step for the same example. The final step the model takes is to find splitting points to reduce the total cost of the network. The output for this step of the example can be seen in the figure on the right.

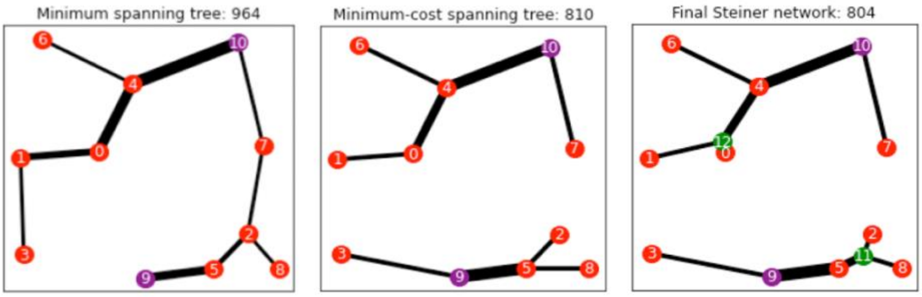

Figure 16: Example output of model steps 1,2 and 3 (Heijnen, 2023).

5.1.1 Model adaptation and output usage

Super-sink

Normally in the input of the model each sink has its own specific demand, and the model will optimize the network to satisfy these. The scope of this thesis however is purely focused on transporting all produced hydrogen from the wind farms to the ports, not on the further allocation of the demand. Therefore, in order to avoid having to specify the demand of each sink separately, a super-sink is created. This super-sink represents the source of all demand in the network, while the regular sinks the hydrogen is transported to have a constant demand of 0.

To facilitate this super-sink, a feature of the model was used that allows the user to specify existing connections in the network without increasing the cost of the network. This feature was used to create edges with extremely large capacities between the sinks and the super-sink. By placing the super-sink far away from the sinks, the model is tricked into optimally distributing the hydrogen to the sinks along the shore. This works because the model will never create new edges to the super-sink, as using the existing connections will always be cheaper. In figure 17 below, the usage of the super-sink is illustrated.

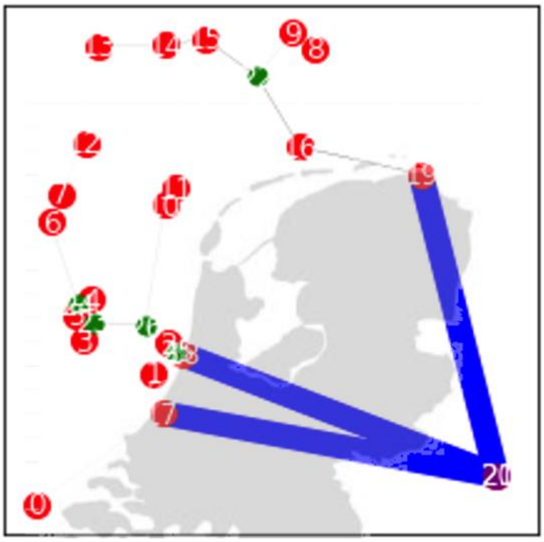

Figure 17: Illustration of arbitrary network with super sink.

Output Usage

The output of the model consists of the final networks with their edges and respective capacities, and the amount of storage used at each time step.

Cost function

The model assesses the quality of found networks using the following cost equation:

$$C(G) = \sum_{e \in E_n(G)} l_e q_e^{\beta}$$

In which $E_n(G)$ represents all edges in network G, l_e is the length of edge e, and q_e is the capacity of the edge. β is the capacity cost component, indicating how expensive it is to scale the capacity of an edge. This cost function is not completely realistic, but is only used to asses and compare the quality of the different network topologies. For the final cost calculations another formula is used. To facilitate this switch between the cost formulas the value β in the model was adjusted to 0.5, as this value offers the best fit with the new cost formula.

A more accurate function to calculate the cost of hydrogen pipelines including for their capacity was found by Parker (2004). Who compiled cost data of numerous pipelines projects to come to this general cost function specifically for hydrogen pipelines:

$$C_{H2} = \tau * L * (924.5D^2 + 12040D + 260280)$$

In which τ is a terrain factor, L is the length of the pipeline in miles, and D is the diameter of the pipelines in inches. Even though the formula is relatively old, it is still regularly used in scientific literature. The cost function is calculated in year 2000 US dollars, so to use it inflation and currency exchange have to be taken into account. Using this cost function on the output of the model it is possible to obtain a more reliable cost value for the network.

Storage

In order to find the required storage capacity for the different scenarios, the system configuration with central onshore hydrogen storage in salt caverns on land was modelled first. The salt caverns were placed at the super-sink in the model, as their precise location onshore is out of scope for this thesis. These salt caverns have a very large capacity, and there are around 300 of them available for use (HyWay27, 2021), meaning they have a virtually infinite capacity for the scope of this system. The resulting required storage capacity, was used as input for the required storage capacity for the same scenario for the decentral offshore storage system configuration.

For the central onshore storage scenarios, the maximum flow out of the salt cavern storage is of importance as well. As the flow out of the salt caverns need to be purified before leaving the system, and the maximum flow out of the storage dictates the purification capacity that is required.

In the event that there is an excess of supply on the basis of the total week analysed, this excess of supply needs to be multiplied by 26 in order to represent the excess over the course of half a year. This excess hydrogen is stored as seasonal storage.

If there is a shortage of supply during the other season, the seasonal storage can be emptied to accommodate this.

Scenario analysis

When building the resulting networks in 2030 and 2040, the final network of 2050 should be taken into account. This to ensure that pipelines build in earlier time steps have sufficient capacity for the years to come. Therefore a backwards reasoning will be applied, in which pipelines build in 2030 and 2040 should have sufficient capacity to satisfy the supply of 2050. Furthermore as new wind farms emerge over the years, pipelines should be built to accommodate them even if the wind farm does not yet exist in the timestep. For the storage and purification facilities a forward reasoning is applied, in which investments or reinvestments for required capacity can be made at each time step. In the final section of this chapter, the methodology of this economic assessment will be expanded upon.

5.2 Ship configurations

From the theoretical framework it became apparent that modelling the system configurations using ships to collect and transport the hydrogen, is a version of the traveling salesman problem. The solution to the traveling salesman problem is a Hamilton circuit that starts and ends at the same port and visits wind farms in between. A requirement for this circuit is that the supply of the wind farms it visits, should be below the ship capacity. Leading to the capacitated clustering problem explained in the theoretical framework. To solve this combination of existing problems, a Python model utilizing graph theory was developed for this thesis. The steps this model takes to find the optimal capacitated clustering and resulting Hamilton circuits are outlined below. The full code can be accessed through: https://github.com/Boriswaal/Capacitated-clustering-model.

Step 1: Reading input data and creating initial graph

The model starts by reading the input file containing the coordinates of the ports and windfarms, and hydrogen production levels of the windfarms. The model then constructs a graph with the ports and windfarms as nodes.

Step 2: Initial clustering of nodes

Next the number of required clusters is determined dynamically. This is done by summing the supply of all wind farms, and dividing it by the ship capacity which is multiplied with a factor of 0.8. This is done as there are a limited amount of wind farms, which may make it impossible to find combinations in which all clusters fall within the ship capacity if there is a too small margin. The ship capacity is a variable whose value can be set manually to allow ships of different sizes to be used. The wind farms are then clustered using the K-means algorithm, with K-means++ centre initialization. In figure 18 below the resulting initial clusters can be seen for an arbitrary example. Note that the cluster centres, indicated by the red dots are distributed over the geographic span of the dataset due to the K-means++ centre initialization.

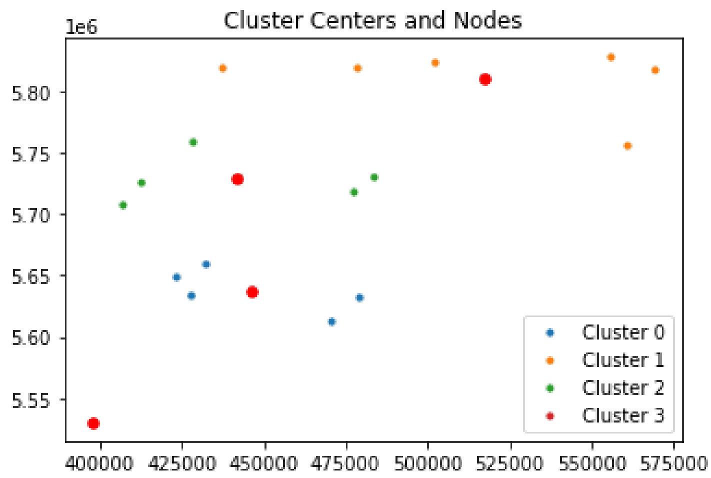

Figure 18: Scatter plot of initial clustering with cluster centres in red.

Step 3: Reassigning nodes

The next step is to ensure that the sum of the supply of the windfarms in the resulting clusters does not breach the capacity of the ships. To facilitate this, a method developed by Heijnen (2023a) is used to reassign the nodes to clusters.

In it the code creates a list containing the distance of all nodes to all cluster centres, and sorts it so that the shortest distances are the first entries. One by one the nodes are then reassigned to the cluster centre closest to them that has enough capacity left over.

Step 4: Check if all nodes are in their closest cluster

The next step of the code is to recalculate the centres of the clusters. Afterwards the code checks to see if all nodes are assigned to the cluster centre closest to them, and if the supply of all clusters falls within the ship capacity.

If all nodes are in the cluster closest to them, and none of the clusters breach the capacity constraint, no further reassignment is needed. In this case the code will find the shortest Hamilton circuit for all clusters using the simulated annealing heuristic. To decide from what port the clusters should be serviced, the code finds the Hamilton circuits for all ports and selects the circuit with the shortest distance.

Step 5: Final optimization

If not all nodes are in their closest cluster, or there are clusters that breach the capacity constraint, further optimization steps are taken to improve the clustering and reduce the costs. The optimization steps taken are outlined below.

1. *Check if moving a single node to another cluster reduces the total cost.*

In the first step the function looks at all nodes, to see if moving any of them to any other cluster reduces the total cost. To do this it first checks if moving the node does not breach the capacity constraint for the new cluster. If this is not the case, the code temporarily assigns the node to the new cluster and calculates the new cost of servicing both clusters using the cluster cost function. If the sum of the new cluster costs is less than the sum of the old cluster costs, it reassigns the node to the new cluster.

2. *Check if swapping a single node from one cluster, with a single node from another cluster reduces the total cost.*

The second step again looks at all nodes, but now checks if swapping any one node from a cluster with any one node from another cluster reduces the total cost. An important distinction is that the code now checks both clusters to see if the capacity constraint is not breached by swapping the nodes. Again if this is not the case, the code calculates the new costs, and if they are lower than the previous total cost the code reassigns the nodes to the new cluster.

3. *Check if swapping multiple nodes from one cluster, for multiple nodes from another cluster reduces the total cost.*

In step three again all possible combinations are considered, this time however for multiple nodes being swapped with multiple nodes. The further logic is equal to step two.

4. *Check if swapping a single node from one cluster, for multiple nodes from another cluster reduces the total cost.*

Equal logic.

5. *Check if swapping multiple nodes from one cluster, with a single node from another cluster reduces the total cost.*

Equal logic.

6. *Check if any of the clusters have a total supply above the ship capacity.*

In the final step of the function, the code checks if after iterating through the first 5 steps, there are any clusters that have a higher supply than the ship capacity. If that is the case the code increases the number of clusters by 1 and runs the K-means++ clustering algorithm again. It then proceeds to return to the start of the function to optimize the new clusters again.

If none of the clusters breaches the capacity constraint, the model finds the Hamilton circuits for the final clusters. In figure 19 and 20 the final clusters and their Hamilton circuits are illustrated respectively for the example.

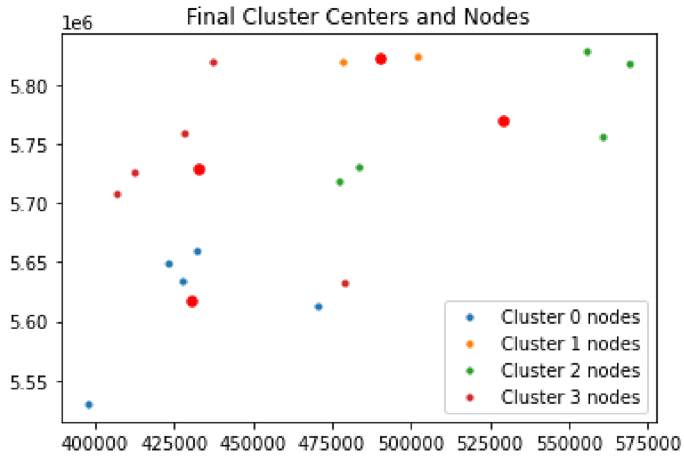

Figure 19: Scatter plot of final clustering with cluster centres in red.

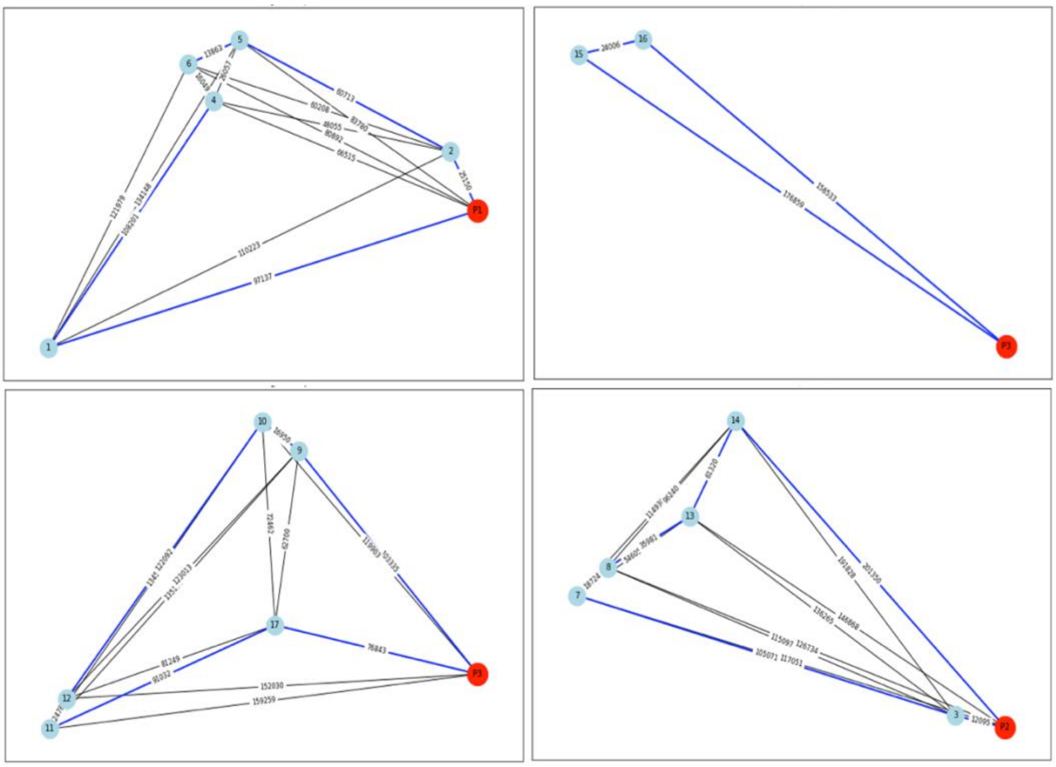

Figure 20: Final minimal cost Hamilton paths for all clusters in example.

5.2.1 Output usage

Cost of shipping

Using the costs of collecting all supply from the wind farms using ships, the total yearly costs of shipping can be calculated using both the summer and winter weeks. Furthermore from the total supply of hydrogen it can also be decided when an investment needs to be made to acquire a larger ship. The model is designed to visit all wind farms once, and all produced hydrogen needs to be collected. As the investment cost in a new ship is far higher than operational cost of shipping, this investment decision should be postponed until necessary. Therefore only when a wind farm has a higher weekly production than the ship capacity, a larger ship needs be acquired.

It should be noted that the model does not take obstacles into account when deciding the shortest paths, while some of the wind farms may not be accessible by the direct routes the model finds. To compensate for this the total distance of the final paths was multiplied by 1.5 in the cost calculations.

Scenario analysis

Unlike the output of the pipelines model, the output of the shipping model is not directly affected by the demand scenarios. As the available hydrogen is decided by the supply scenarios, and again the assumption has been that all generated hydrogen needs to either satisfy a demand or be stored.

The technical differences between storing and transporting hydrogen in either LOHCs or ammonia however do influence how well the system configuration perform in different demand scenarios. Furthermore the two hydrogen carriers have different hydrogenation and dehydrogenation processes that affect how much hydrogen will eventually be usable.

In the case that there is a total excess of supply over an analysed week, this excess will be multiplied with 26 in order to find the required seasonal storage. This is done to incorporate the seasonal mismatch between wind availability in summer and winter. Unlike the pipeline configurations however, this seasonal storage is incorporated in the onshore storage facilities at the ports. This difference stems from the fact the pipeline configurations continuously transport hydrogen, making the amount of stored hydrogen more volatile. Whereas the batched transportation of the ship configuration makes the storage requirements more stable.

5.3 Economic assessment

In order to assess the performance of all four system configurations, the total costs of the systems are derived for all scenarios. These costs include all necessary investment costs (CAPEX), as well operational costs (OPEX) to be able to make a fair comparison between the alternative system configurations.

In the economic assessment, the total costs are calculated for the different system configuration over a 30 year time period ranging from 2030 to 2060. This allows large investments to be spread out over time to give a fair view of the required capital. Furthermore this allows the possibility to include reinvestment required at the end of the technical lifetime of the system components. Any remaining CAPEX at the year 2060 will be spread out over the 30 years to ensure all costs are accounted for.

As found in the stakeholder analysis, an important indicator of the performance of the different system configurations will be the total cost of transporting and storing the hydrogen in €/kg. Following from the total costs of the system configurations, the cost per kilogram is calculated for the years 2030, 2040 and 2050 for all alternatives in all supply and demand scenarios.

Another important performance measure is the ratio of supply/demand, as this will give insight in how much of the available hydrogen can be delivered by the different system configurations.

On the next page, the results chapter is presented. In it the results from the various models will be analyzed, discussing the performance of the different system configurations under the circumstances of the different scenarios.

6. Results

In this chapter the results from the models are presented. Over the supply scenarios, trends can be observed related to the costs of the demand scenarios for all system configurations. To show these trends, one supply scenario will be discussed in detail for each system configuration. For the rest of the supply scenarios, the analysis of the system configuration performance can be found in appendix C. Following this the performance of all system configurations will be compared amongst the different scenarios.

6.1 Pipelines

6.1.1 Pipelines onshore central storage

In the pipelines with central onshore hydrogen storage in salt caverns system configuration, the CAPEX for the required pipelines are equal amongst the demand scenarios for the same supply scenarios. This is due to the fact that the model will transport all produced hydrogen to the access points of the land network, where both the demand and salt caverns are located. The differences in cost between the demand scenarios stems from the amount of hydrogen that needs to be stored at each time step. Furthermore the amount of hydrogen that is extracted from the storage needs to be purified using PSA resulting in extra costs, and a loss in hydrogen.

<u>*Low supply*</u>

Depicted below in figure 21 are the optimal networks to transport all supply for the year 2030 and 2050 respectively. As can be seen the top nodes of the figures are connected using a splitting point in the optimal network for 2050. Even though this node is not yet required in 2030, the edges to it should be built already to facilitate the optimal network in 2050.

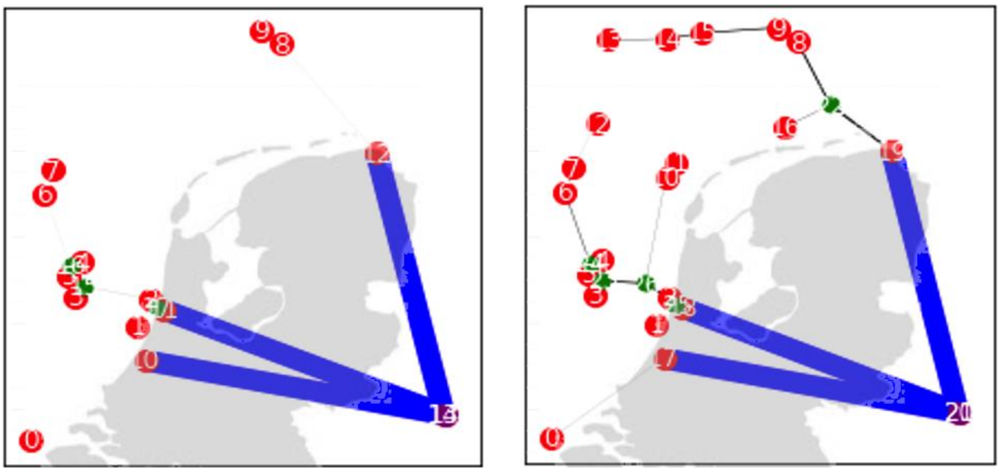

Figure 21: Optimal networks for low supply scenario in 2030 and 2050 respectively.

The total costs for the construction and operation of all required facilities in the period from 2030 to 2060 can be seen in table 4 below for all demand scenarios.

	Low Demand	Medium Demand	High Demand
CAPEX	18.8	15.9	15.6
OPEX	24.4	13.5	13.1
Total cost	31.5	20.5	20.1

Table 4: Cost of low supply demand scenarios in Billion €.

The low demand scenario is clearly the most expensive amongst the demand scenarios. This is due to the fact that in 2030 the supply is higher than the demand, requiring a higher storage capacity. Due to the design choice that all hydrogen needs to either satisfy a demand or be stored, these high extra costs are incurred. This mismatch between supply and demand is so large that for both the summer and winter week additional storage is required. As mentioned in the methodology, this additional storage is labelled seasonal storage as the hydrogen is stored in it for a longer period of time. Whereas the regular storage is used to balance the mismatch of supply and demand over a shorter period of hours to days. This additional storage requirement is also the reason the OPEX of the low demand scenario is considerably higher. In figure 22 below is a complete overview of the CAPEX requirements for all demand scenarios.

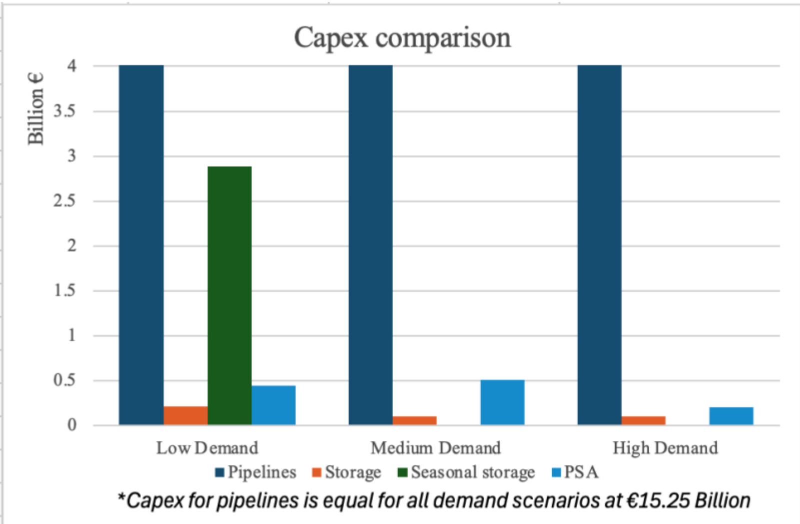

Figure 22: CAPEX comparison demand scenarios.

Another noteworthy observation is that the medium demand scenario requires the most PSA investment. This is due to the fact that the short term storage is filled regularly when the supply is higher than the demand, but when there is a shortage the total flow out of the storage is higher per time step than in the low demand scenario. This flow out of the storage dictates the PSA capacity as its associated CAPEX cost is decided by its feed rate. Whereas in the high demand scenario almost all supplied hydrogen is consumed directly by the demand, only allowing small quantities to be stored. This in turn means that only small quantities can be extracted from the storage, leading to a lower PSA feed rate and CAPEX. The OPEX of the PSA installations is decided by the total amount of hydrogen purified. In figure 23 a cost breakdown of the total yearly cost per demand scenario is illustrated.

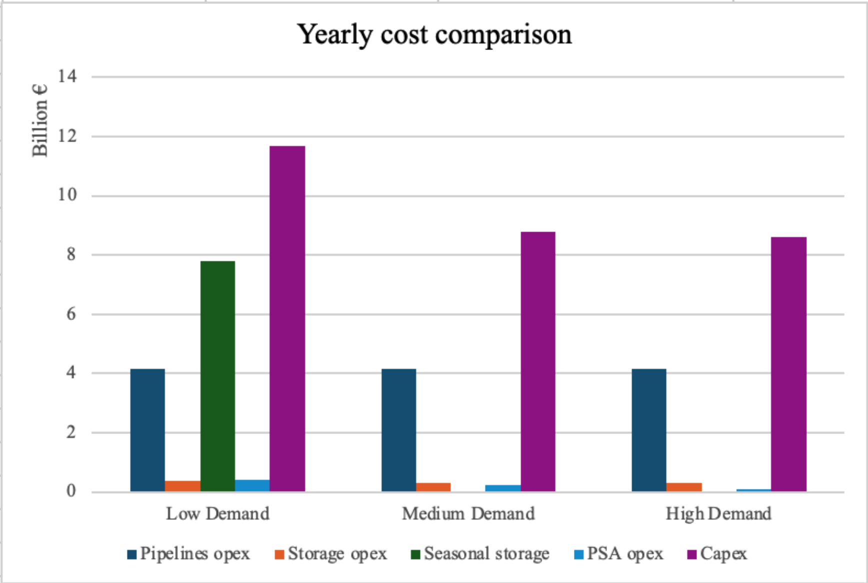

Figure 23: Total yearly cost comparison demand scenarios.

As can be seen the high OPEX of the low demand scenario is mostly associated with the seasonal storage. As it is the only scenario in which this is required, this makes the gap to the others demand scenarios substantial.

Even though the medium demand scenario has the highest PSA capex, in total more hydrogen is purified in the low demand scenario. This is because similarly to the high demand scenario, the total supply is used directly more often than in the low demand scenario. This reduces the total amount of hydrogen that needs to be extracted from the storage and purified in the medium and high demand scenarios.

The usage of PSA has a double effect on the final cost per kg of hydrogen, as there are not only added costs associated with it, but also a loss of usable hydrogen. In figure 24 below the ratio of usable hydrogen versus the totally available hydrogen is shown for the different demand scenarios over the course of the whole years. As can be seen nearly all supply is delivered directly in the medium and high scenario, whereas there are considerable losses in the low demand scenario.

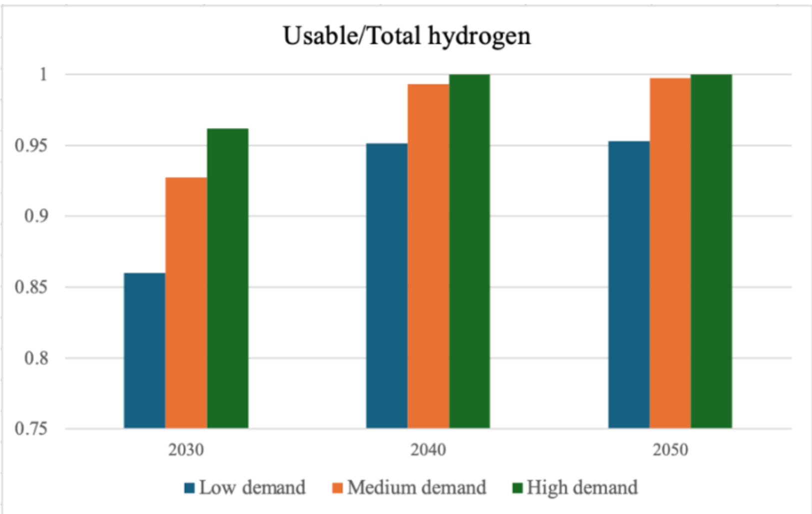

Figure 24: Ratio of usable and total hydrogen in demand scenarios.

This all leads to the final cost per kilogram of hydrogen delivered, these can be seen for the respective scenarios for the years 2030, 2040 and 2050 in table 5 below.

Cost in €/kg	Low demand	Medium demand	High demand
2030	6.33	3.72	3.54
2040	2.41	1.52	1.49
2050	1.57	0.99	0.96

Table 5: Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

There is one final context in which the costs of the demand scenarios should be evaluated, and that is the amount of the demand that can actually be supplied. As seen in the hydrogen potential section, the level of demand is in most cases significantly higher than the level of supply. In the low supply scenario this is especially true. In figure 25 below the ratios of the supply and demand can be seen for the demand scenarios in the different time years.

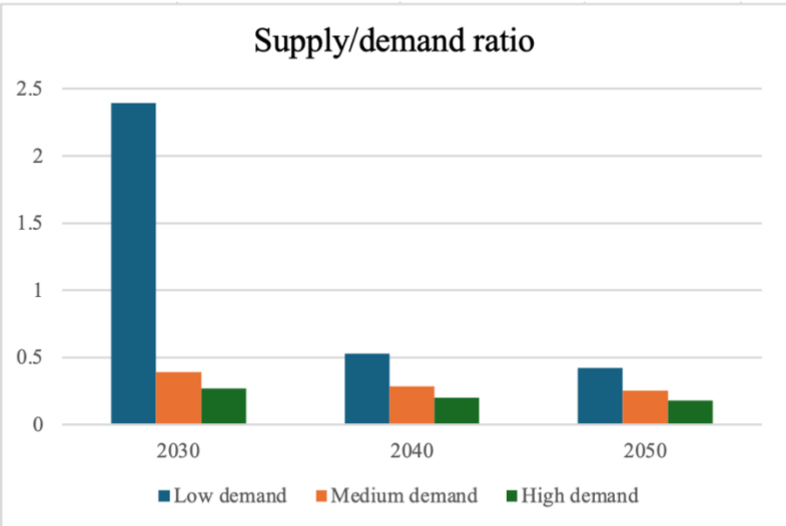

Figure 25: Yearly supply and demand ratios low supply scenario

As illustrated above, only in 2030 can the entire low demand be delivered. This is also the explanation for the high cost additional storage requirements for the low demand scenario, as this is the only occasion in the low supply scenario in which the demand is surpassed.

6.1.2 Pipelines offshore storage

Unlike in the pipelines with central storage system configuration, in the offshore storage configuration the networks found do differ for the different demand scenarios. This is due to the fact the model will try to minimize the costs required to deliver all supply to either the source of the demand or a storage facility if there is an excess of supply. As the storage facilities are now located at the electrolysers instead of at the super-sink together with the demand, the model now finds different networks when different demand are set.

<u>*Low supply*</u>

In figure 26 below are the resulting networks for the different demand scenarios in the low supply scenario. As can be seen three very different topologies emerge under the different demand circumstances.

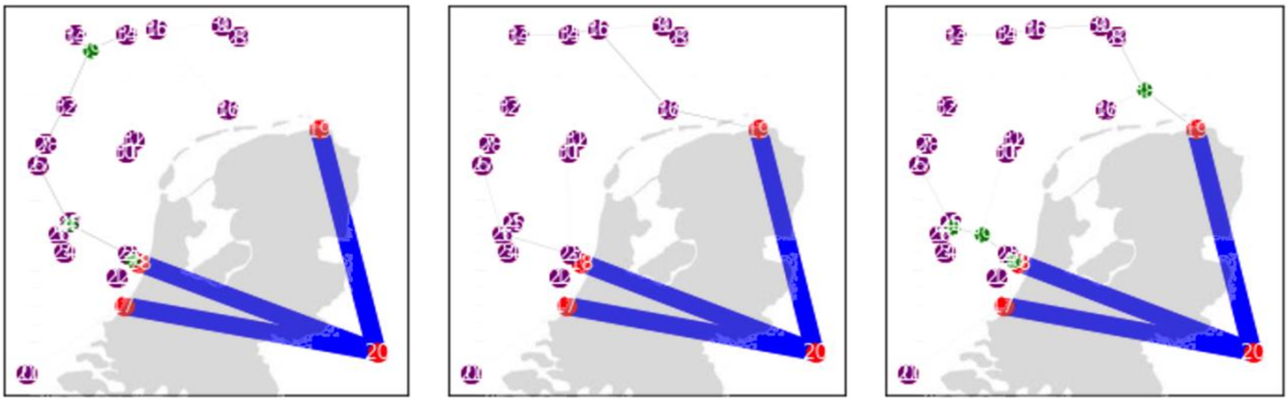

Figure 26: Network topologies demand scenarios low supply.

In table 6 below are the total costs for the different demand scenarios, followed by a breakdown of the CAPEX costs and yearly operation costs in figures 27 and 28 respectively.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	70.7	18.2	15.5
OPEX	86	15.7	12.8
Total cost	95.9	23.4	19.8

Table 6: Cost of low supply scenarios in Billion €.

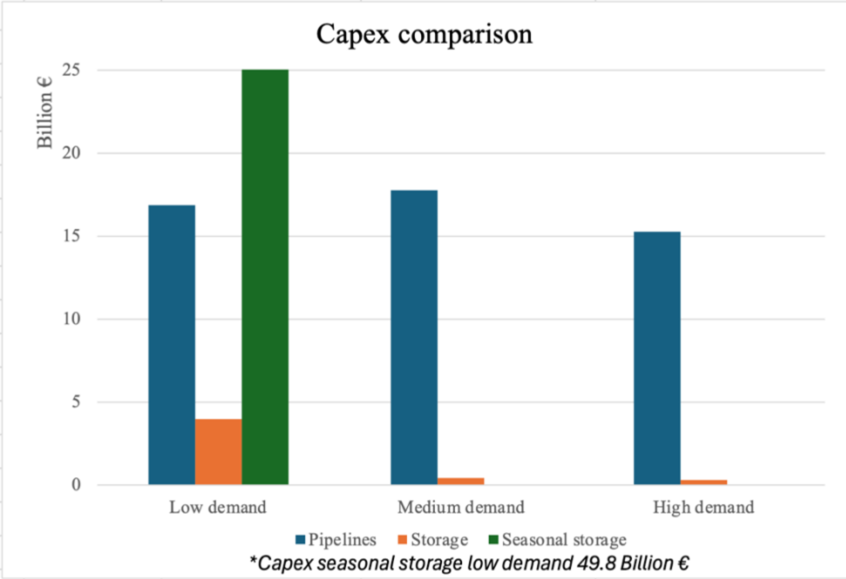

Figure 27: CAPEX comparison demand scenarios.

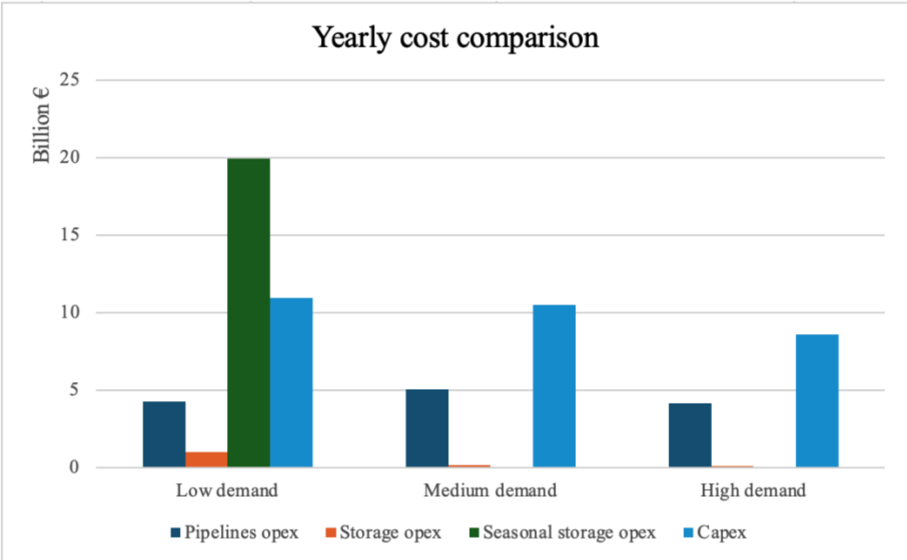

Figure 28: Total costs over all years comparison demand scenarios.

As can be seen from the table and the cost breakdown figures, the total cost is the highest for the low demand scenario. This is due to the extra CAPEX required for seasonal storage caused by the excess of supply. Interestingly, the CAPEX required for the pipelines is lowest in the high scenario, where it converges to the same cost of the network with the onshore storage. While the CAPEX required for the pipelines of the medium demand scenario is the highest, followed by the low demand scenario.

In table 7 the total yearly cost per kg of hydrogen delivered can be seen, accompanied by the supply and demand ratios of the demand scenarios in figure 29. As there are no processes that reduce the total amount of hydrogen in this system configuration, these ratios represent the total amount of hydrogen produced.

Cost €/kg	Low demand	Medium demand	High demand
2030	23.85	4.2	3.34
2040	9.15	1.7	1.48
2050	1.42	1.07	0.94

Table 7: Yearly total cost per kg of hydrogen delivered per year in the different demand scenarios.

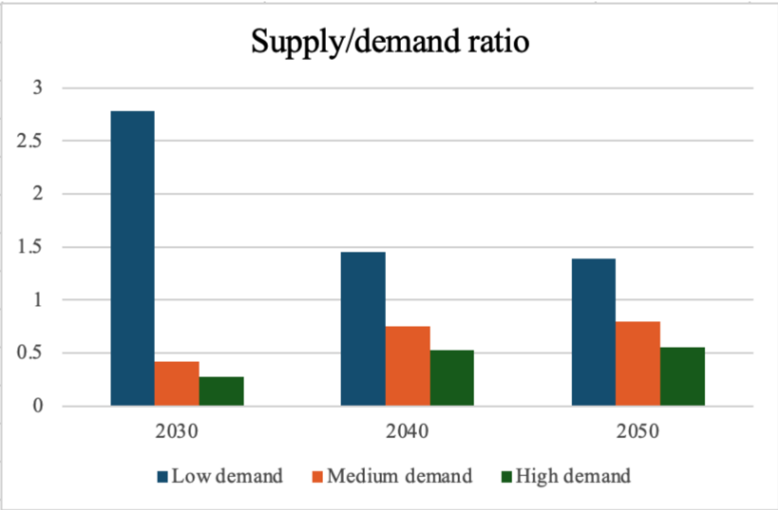

Figure 29: Supply and demand ratios low supply scenario.

6.2 Ship transportation

For both the shipping system configurations, the optimum routes for the ships to collect the hydrogen has been found using the Python model. The different demand scenarios have no influence on the cost of collecting the produced hydrogen, they do however influence the systems that are required onshore such as the dehydrogenation and PSA capacities required, and the amount of onshore storage needed.

6.2.1 Ammonia shipping

Low supply

In table 8 below are all costs for the different facilities and operations required under the different demand scenarios, followed by figure 30 containing a breakdown of the CAPEX costs.

	Low Demand	Medium Demand	High Demand
CAPEX	16.3	14.5	14.5
OPEX	36.4	32.4	32.4
Total cost	40.4	37.6	37.6

Table 8: Cost of low supply scenarios in Billion €.

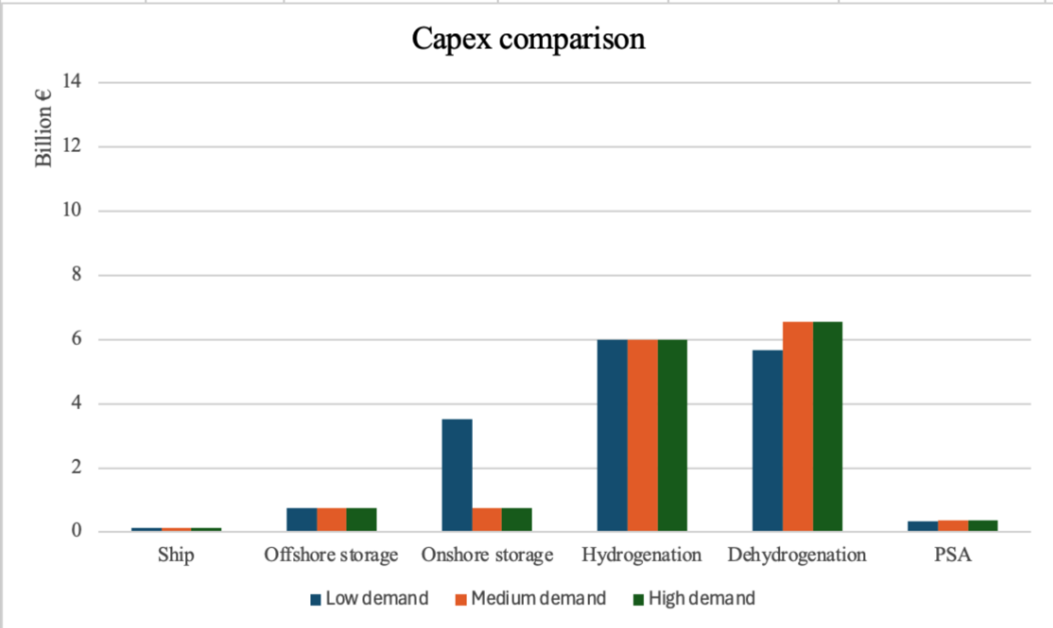

Figure 30: CAPEX comparison demand scenarios.

In all demand scenarios the driving costs are the required CAPEX for the hydrogenation and dehydrogenation facilities. With the storage, PSA and ships only being a small part of the total CAPEX.

What is immediately apparent is that the costs are for the most part equal. For the investments in ships and offshore storage facilities this is logical as these are not affected by the demand, and they are based on the same supply data. The hydrogenation also follows from the available supply, as the supply dictates how much hydrogen needs to be synthesised into ammonia per day.

The onshore storage, dehydrogenation and PSA capacities however are influenced by the demand scenarios. But due to the design decision outlined in the system configuration overview, their capacities will become exactly high enough to process the batched supply in time for a new ship to arrive. Due to this decision, the system configuration reaches an equilibrium over the demand scenarios if there is a shortage of supply.

A breakdown of the operational costs for each year can be seen in figure 31 below. Similarly to the CAPEX costs, the OPEX costs converge to handle to all available supply when the supply is lower than the demand. Explaining the similarities in the total yearly costs of the different demand scenarios.

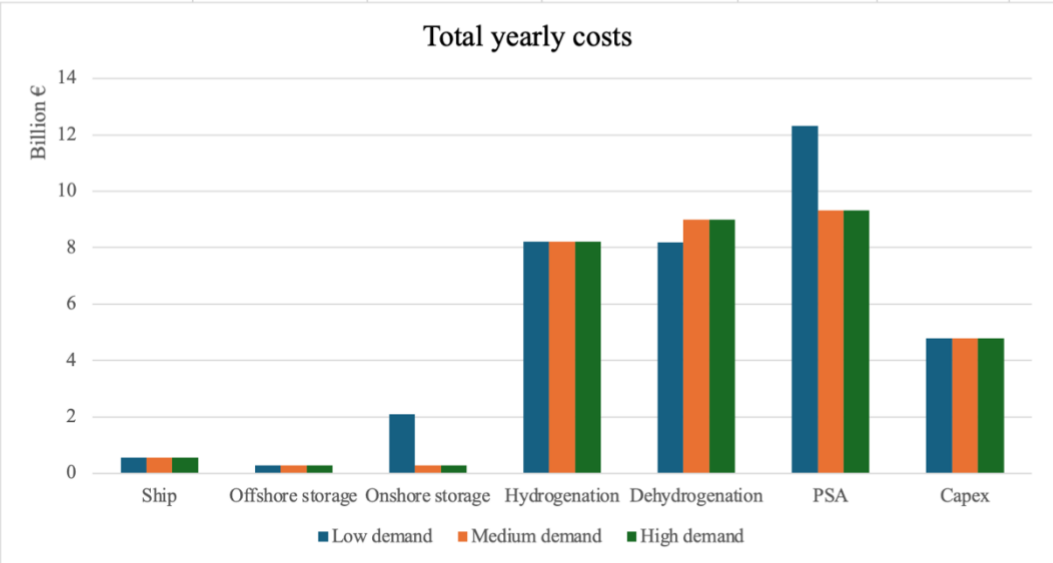

Figure 31: Total costs over all years comparison demand scenarios.

These total cost values for the demand scenarios lead to the final cost per kilogram of hydrogen. These can be seen in table 9 below.

Cost €/kg	Low demand	Medium demand	High demand
2030	5.77	5.7	5.7
2040	4.91	4.5	4.5
2050	4.28	3.95	3.95

Table 9: Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

Again the total cost per kilogram of hydrogen is similar for all demand scenarios due to the batched nature of the transportation. Again these values need to be put in the perspective of the supply and demand ratio. These can be seen in figure 32 below.

As can be seen, the supply and demand ratios are significantly lower than in the pipeline alternatives. This is due to the fact that all ammonia needs to undergo two processes subject to hydrogen losses to become usable as hydrogen. The PSA has a hydrogen recovery ratio of 80%, while the dehydrogenation of ammonia has a hydrogen recovery ratio of 77.6%. This means that of all available hydrogen only 62.08% can be used when using the ammonia shipping system configuration.

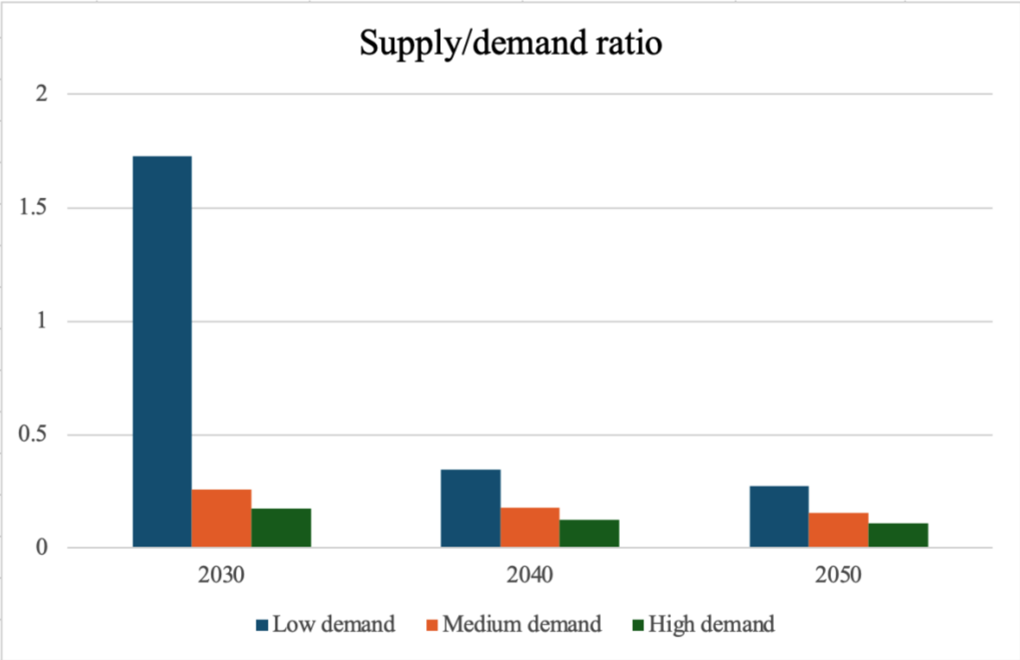

Figure 32: Supply and demand ratios low supply scenario

6.2.2 LOHC shipping

<u>Low supply</u>

In table 10 below are the costs for the different demand scenarios for the low supply scenario of the LOHC shipping system configuration, followed by the CAPEX breakdown and total yearly costs in figures 33 and 34 .

	Low Demand	Medium Demand	High Demand
CAPEX	10.3	7.8	7.8
OPEX	21.3	16.7	16.7
Total cost	23.1	18.8	18.8

Table 10: Cost of low supply scenarios in Billion €

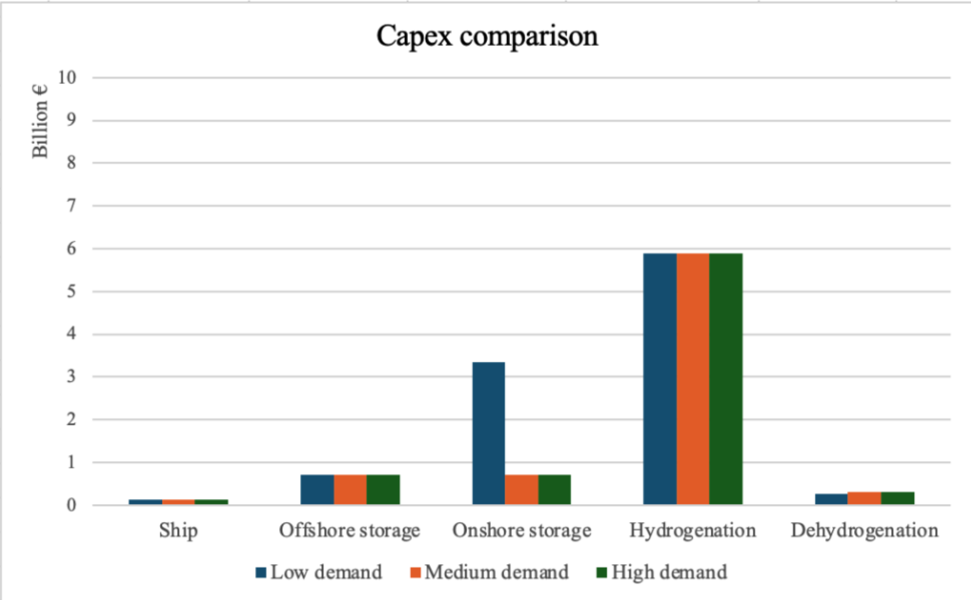

Figure 33: CAPEX comparison demand scenarios.

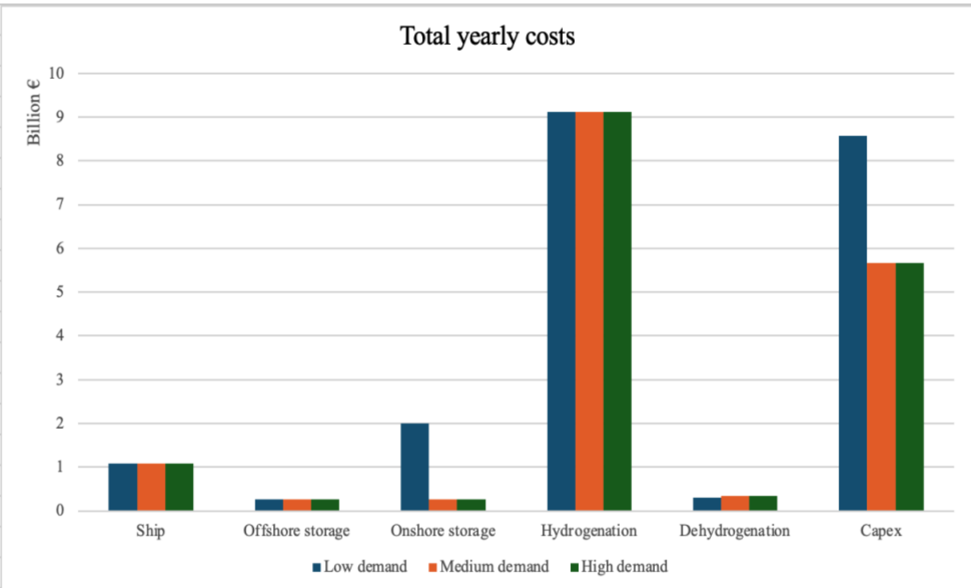

Figure 34: Total costs over all years comparison demand scenarios.

From looking at the costs for the different demand scenarios, two observations become apparent. The first being that the same trend emerges as in the ammonia system configuration, with the required capacities of the facilities converging to suit the available supply when the demand is higher. While an increase in storage becoming necessary when the demand is lower than the supply.

The second observation being that due to the lower CAPEX and OPEX of the dehydrogenation process, the total costs are significantly lower compared to the Ammonia option. This lower cost is also reflected in the total cost per kilogram of hydrogen delivered, as shown in table 11 below.

Cost €/kg	**Low demand**	**Medium demand**	**High demand**
2030	2.47	1.59	1.59
2040	1.58	1.29	1.29
2050	1.52	1.34	1.34

Table 11: Yearly total cost per kg of hydrogen delivered in the different demand scenario.

Again it is important to evaluate these costs in the context of the total demand that can be supplied, which can be seen in figure 35 below. Which in the case of LOHC is equal to the total amount of hydrogen produced, as the dehydrogenation cycle has a 100% recovery rate of hydrogen and requires no further purification steps meaning no hydrogen is lost in the process of transporting and storing the hydrogen prior to being consumed.

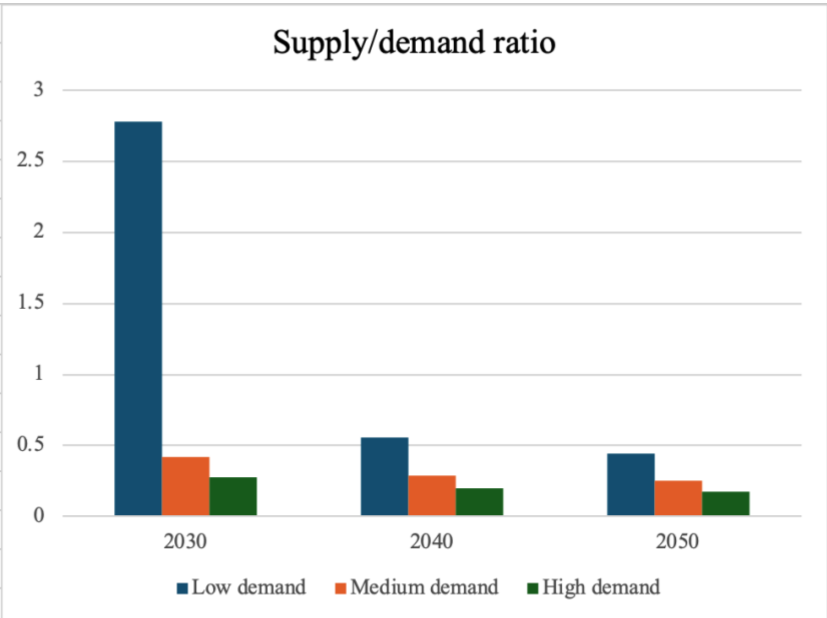

Figure 35: Supply and demand ratios low supply scenario.

6.3 Scenario performances

After this brief overview of the performance of the different system configurations, their combined performance will be measured along the scenarios. To facilitate this comparison, the total costs associated with each system configuration, and the resulting total cost per kilogram of hydrogen delivered are shown together in the following figures for each scenario.

Low supply

Low demand:

In the low supply and low demand scenario, the LOHC system configuration has the lowest total cost, and yields the lowest cost per kilogram of hydrogen delivered for the years 2030 and 2040. This is due to the fact that it requires relatively low CAPEX compared to the other system configurations. However due to the fact that the LOHC has relatively higher OPEX costs than the pipeline configurations, the pipelines with offshore storage configuration reaches a lower cost per kilogram of hydrogen delivered in 2050. By this time the high CAPEX of the seasonal storage has been paid off, as the lifetime of the offshore storage facilities is 20 years, and the costs per kilogram of hydrogen greatly reduces as its further yearly costs are lower. In figure 36, and tables 12 and 13 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

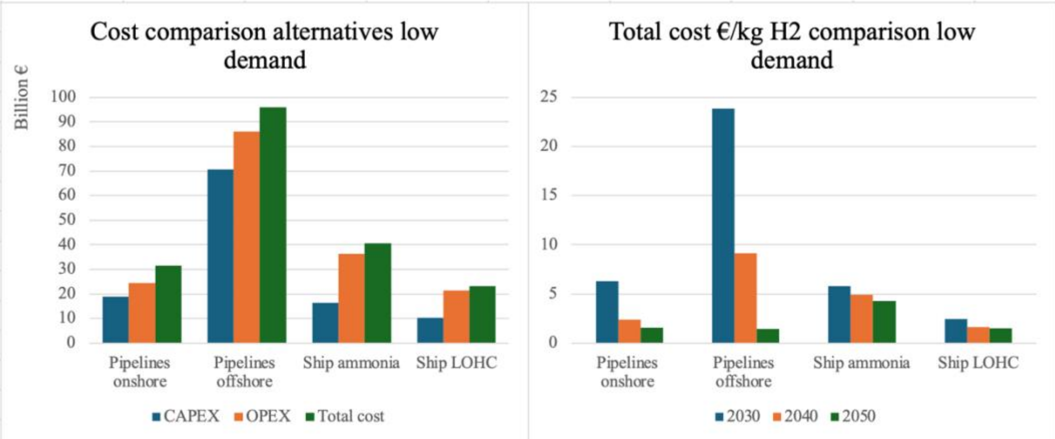

Figure 36: Cost comparison system configuration in the low supply, low demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	18.8	70.7	16.3	10.3
OPEX	24.4	86	36.4	21.3
Total cost	31.5	95.9	40.4	23.1

Table 12: Cost overview of system configurations in the low supply, low demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	6.33	23.85	5.77	2.47
2040	2.41	9.15	4.91	1.58
2050	1.57	1.42	4.28	1.52

Table 13: Yearly total cost per kg of hydrogen delivered for system configurations in the low supply, low demand scenario.

Medium demand:

In the low supply and medium demand scenario, the LOHC system configuration still has the lowest total cost, and yields the lowest cost per kilogram of hydrogen delivered for the years 2030 and 2040. Both of the pipeline configurations however come closer to the total cost of the LOHC system compared to the low demand scenario. In this scenario, the LOHC system reaches its lowest possible cost, as its processing capacities will match the supply due to the excess of demand and the batched nature of its supply. In the year 2050 however, both of the pipeline system configurations yield a lower cost per kilogram of hydrogen delivered. With the system configuration with the onshore storage in salt caverns yielding the lowest cost per kilogram of hydrogen. In figure 37, and tables 14 and 15 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

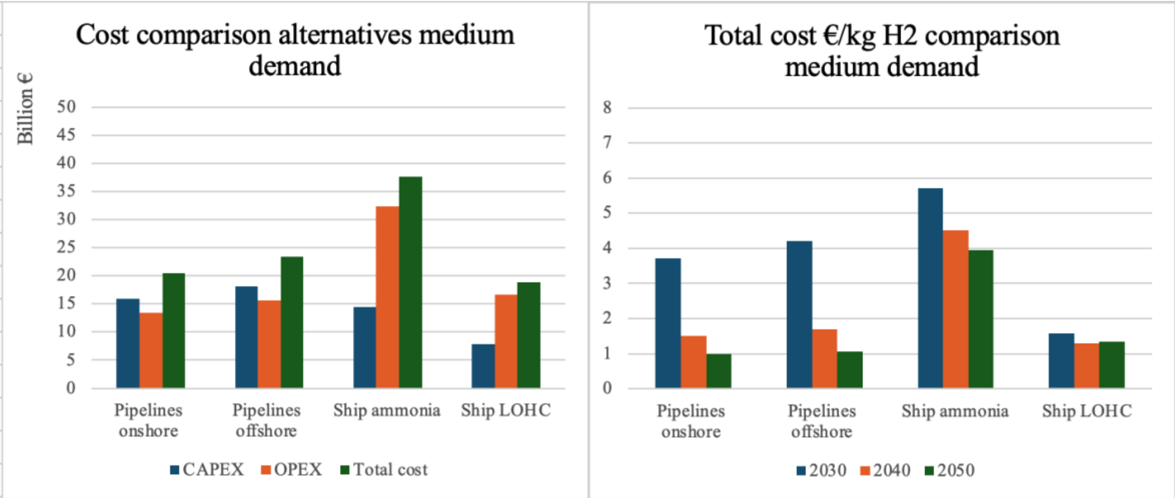

Figure 37: Cost comparison system configuration in the low supply, medium demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	15.9	18.2	14.5	7.8
OPEX	13.4	15.7	32.4	16.7
Total cost	20.5	23.4	37.6	18.8

Table 14: Cost overview of system configurations in the low supply, medium demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	3.72	4.2	5.7	1.59
2040	1.52	1.7	4.5	1.29
2050	0.99	1.07	3.95	1.34

Table 15: Yearly total cost per kg of hydrogen delivered for system configurations in the low supply, medium demand scenario.

High demand:

In the low supply and high demand scenario, the LOHC system configuration still has the lowest total cost. However both pipeline configurations come very near now. This is due to the fact that the high demand virtually removes the need for storage in the pipeline configurations, while the LOHC system has the same costs as in the medium scenario due to reaching the equilibrium caused by the batched supply. In 2030 and 2040 the LOHC system still has the lowest costs per kilogram of hydrogen delivered, but it is again overtaken by both of the pipeline configurations in 2050. This time the pipelines with offshore storage configuration yields the lowest cost per kilogram delivered, but the margin is very slim. This is due to the fact that some PSA is still required in the pipelines with onshore storage. In figure 38, and tables 16 and 17 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

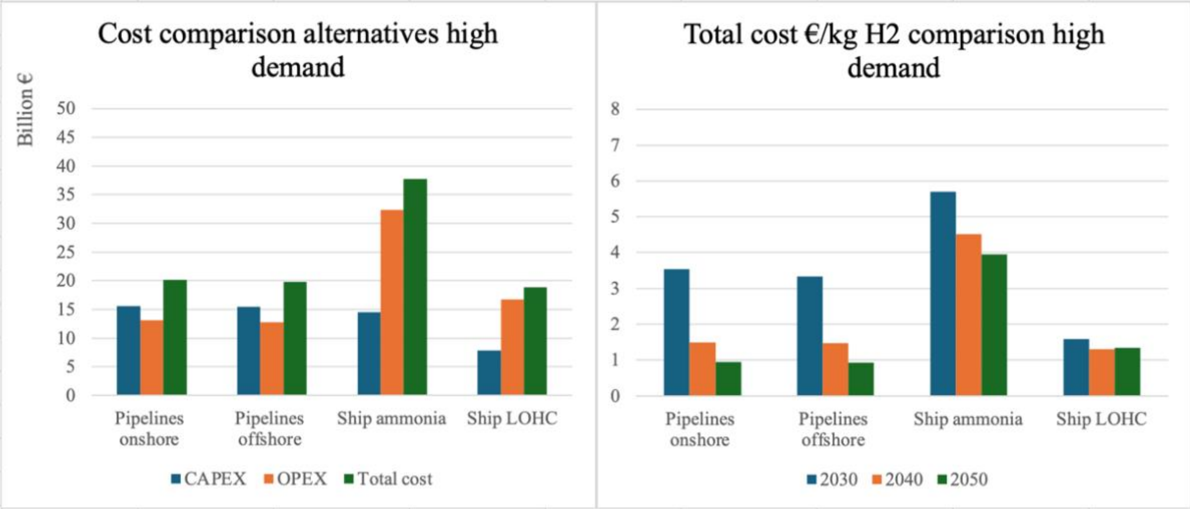

Figure 38: Cost comparison system configuration in the low supply, high demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	15.6	15.5	14.5	7.8
OPEX	13.1	12.8	32.4	16.7
Total cost	20.1	19.8	37.6	18.8

Table 16: Cost overview of system configurations in the low supply, high demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	3.54	3.34	5.7	1.59
2040	1.49	1.48	4.5	1.29
2050	0.96	0.94	3.95	1.34

Table 17: Yearly total cost per kg of hydrogen delivered for system configurations in the low supply, high demand scenario.

Medium supply

Low demand:

In the medium supply scenario the LOHC system configuration again has the lowest total cost in the low demand scenario, and start with the lowest cost per kilogram of hydrogen delivered. However, both pipeline configurations yield a lower cost per kilogram delivered in 2050. With the onshore storage configuration yielding the lowest. Especially the offshore storage pipeline configuration suffers from the need to store all excess supply, causing high initial investment needs. In figure 39, and tables 18 and 19 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

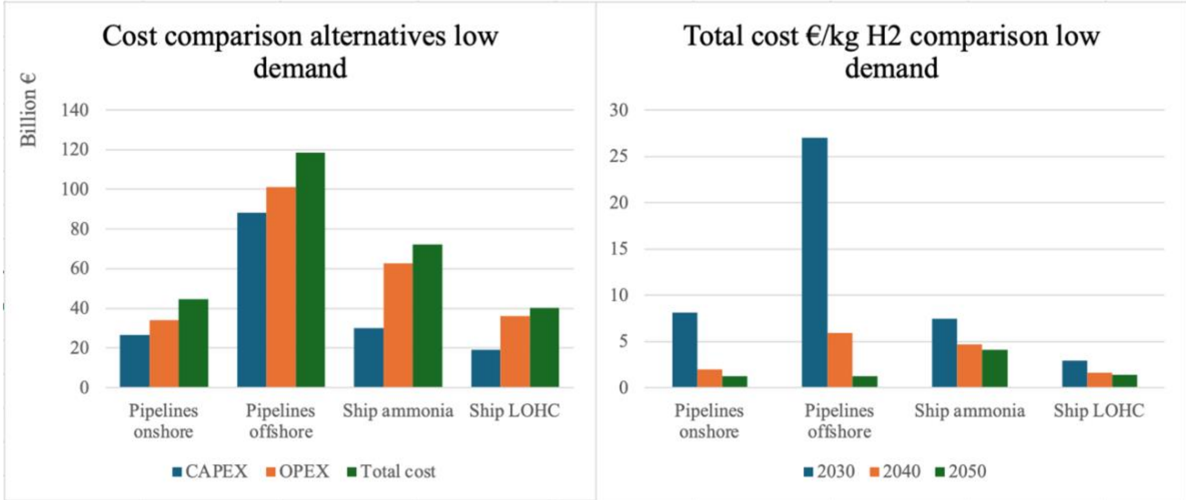

Figure 39: Cost comparison system configuration in the medium supply, low demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	26.5	88.4	29.8	19.2
OPEX	34.1	101.3	62.8	36.1
Total cost	44.7	118.5	72.2	40.5

Table 18: Cost overview of system configurations in the medium supply, low demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	8.12	27.01	7.44	2.95
2040	1.95	5.9	4.7	1.61
2050	1.21	1.26	4.09	1.39

Table 19: Yearly total cost per kg of hydrogen delivered for system configurations in the medium supply, low demand scenario.

Medium demand:

In the medium supply and medium demand scenario the LOHC system no longer has the lowest total cost. Instead it is overtaken by the pipelines with onshore storage configuration. The LOHC configuration does still have the lowest initial cost per kilogram of hydrogen delivered in 2030, but it is overtaken by the pipelines with onshore storage in 2040, and the pipelines with offshore storage configuration in 2050. In figure 40, and tables 20 and 21 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

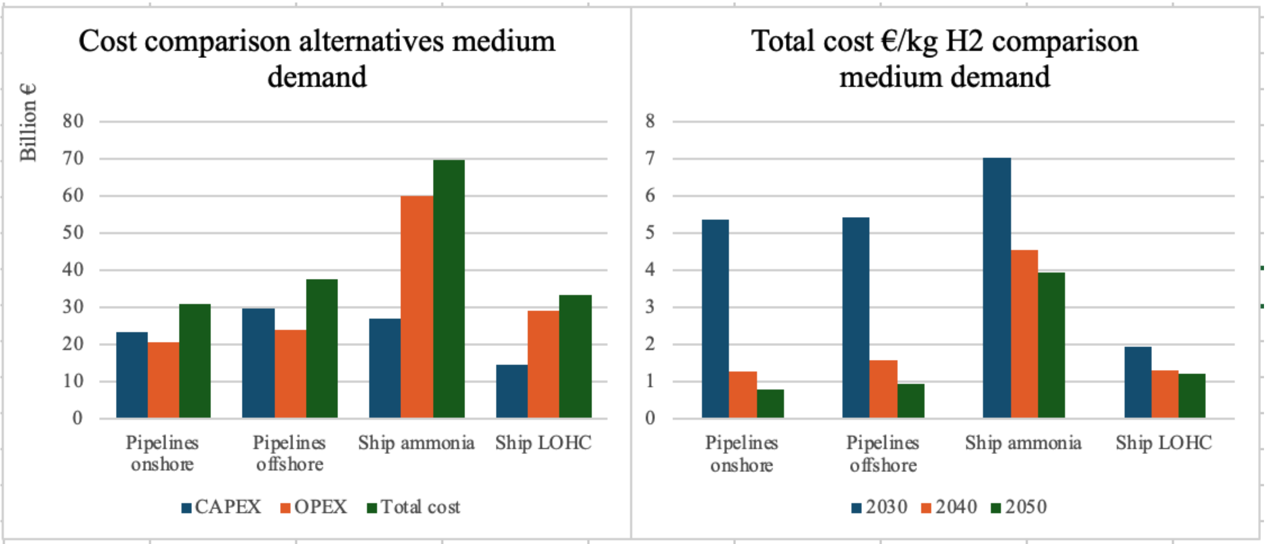

Figure 40: Cost comparison system configuration in the medium supply, medium demand scenario.

	Pipelines onshore	**Pipelines offshore**	**Ship ammonia**	**Ship LOHC**
CAPEX	23.4	29.7	26.9	14.5
OPEX	20.5	23.9	60.1	29.3
Total cost	30.9	37.6	69.6	33.3

Table 20: Cost overview of system configurations in the medium supply, medium demand scenario in Billion €.

	Pipelines onshore	**Pipelines offshore**	**Ship ammonia**	**Ship LOHC**
2030	5.36	5.41	7.03	1.96
2040	1.27	1.56	4.56	1.29
2050	0.78	0.95	3.95	1.23

Table 21: Yearly total cost per kg of hydrogen delivered for system configurations in the medium supply, medium demand scenario.

High demand:

In the high demand scenario both pipeline configurations yield a lower total cost. The costs of the LOHC system are equal to the medium demand scenario, as the configuration reaches the equilibrium again. In terms of yearly cost per kilogram of hydrogen delivered the LOHC configuration starts with a lower cost due to the lower CAPEX requirements, but is overtaken by both pipeline configurations by 2050. With the onshore storage configuration having a consistently slightly lower yearly cost per kilogram of hydrogen delivered compared to the offshore storage configuration. In figure 41, and tables 22 and 23 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

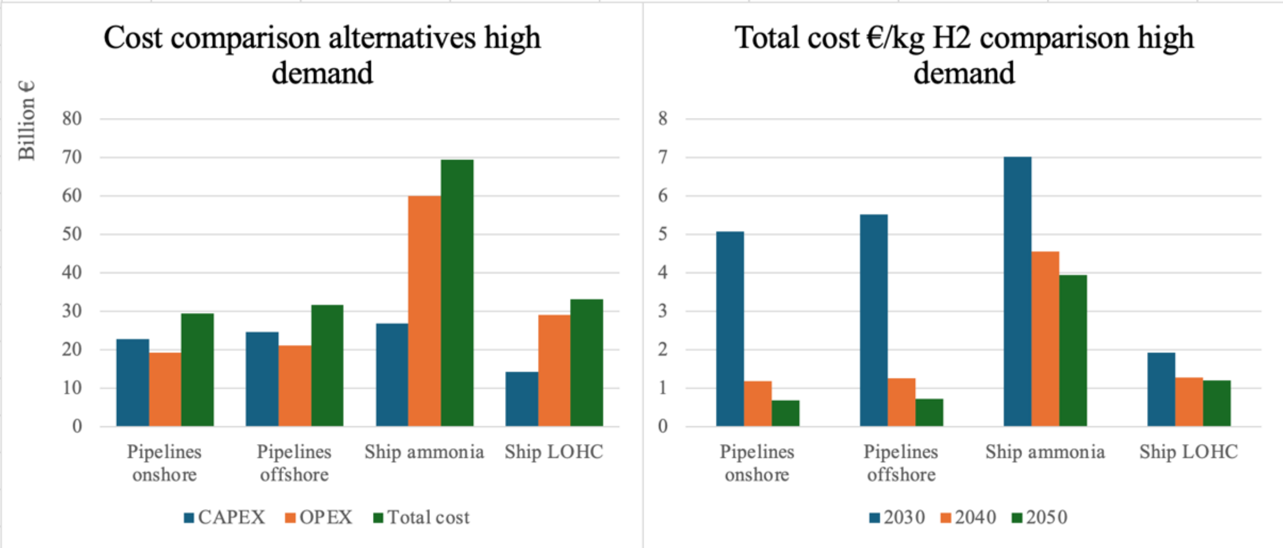

Figure 41: Cost comparison system configuration in the medium supply, high demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	22.9	24.7	26.9	14.5
OPEX	19.4	21.2	60.1	29.3
Total cost	29.5	31.7	69.6	33.3

Table 22: Cost overview of system configurations in the medium supply, high demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	5.09	5.52	7.03	1.96
2040	1.2	1.26	4.56	1.29
2050	0.69	0.73	3.95	1.23

Table 23: Yearly total cost per kg of hydrogen delivered for system configurations in the medium supply, high demand scenario.

High supply
Low demand:

In the high supply scenarios the LOHC system again has the lowest total cost in the low demand scenario, this time however it is also tied with the onshore storage pipeline configuration for lowest cost per kilogram of hydrogen delivered in 2050. With the costs per kilogram being lower for the LOHC in prior years. In figure 42, and tables 24 and 25 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

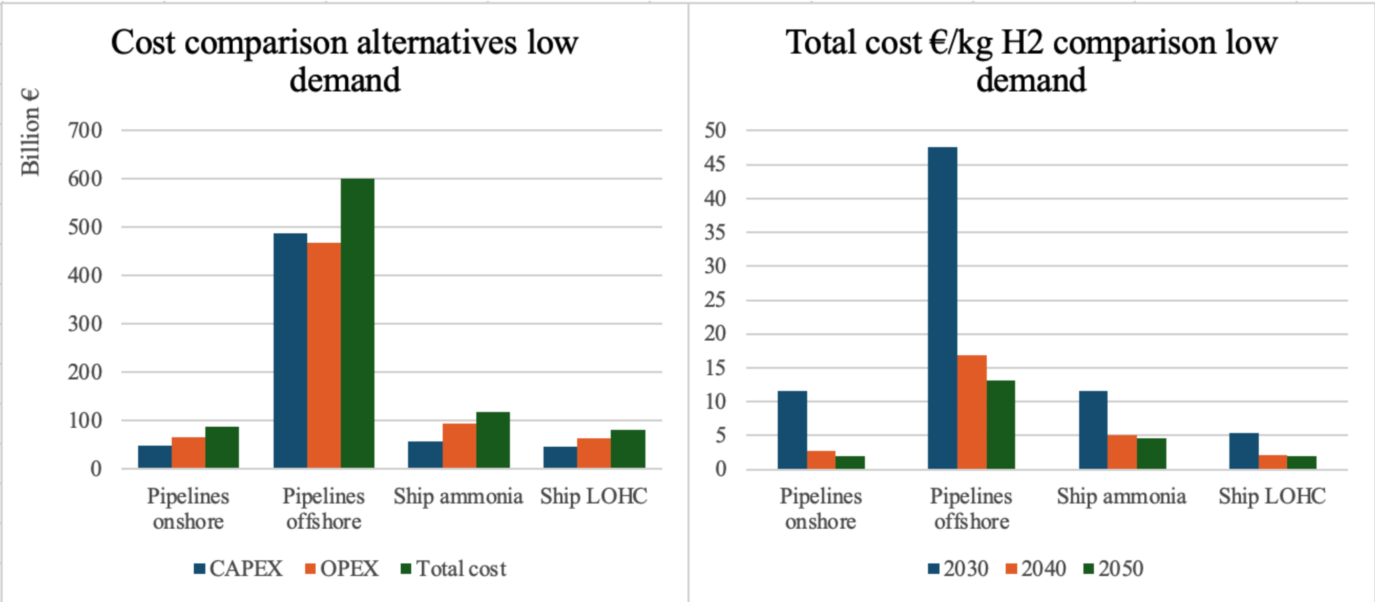

Figure 42: Cost comparison system configuration in the high supply, low demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	48.5	488.6	58.1	46.2
OPEX	66.5	467.9	95	64
Total cost	87.8	600.2	118	81.3

Table 24: Cost overview of system configurations in the high supply, low demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	11.56	47.62	11.63	5.43
2040	2.7	16.89	5.13	2.15
2050	1.93	13.13	4.54	1.93

Table 25: Yearly total cost per kg of hydrogen delivered for system configurations in the high supply, low demand scenario.

Medium demand:

In the high supply medium demand scenarios the LOHC again reaches its lowest possible cost. Both the onshore and offshore storage pipeline configurations have a lower total cost and lower final cost per kilogram of hydrogen delivered in 2050 at €0.79 and €0.85 in the medium demand scenario. In figure 43, and tables 26 and 27 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

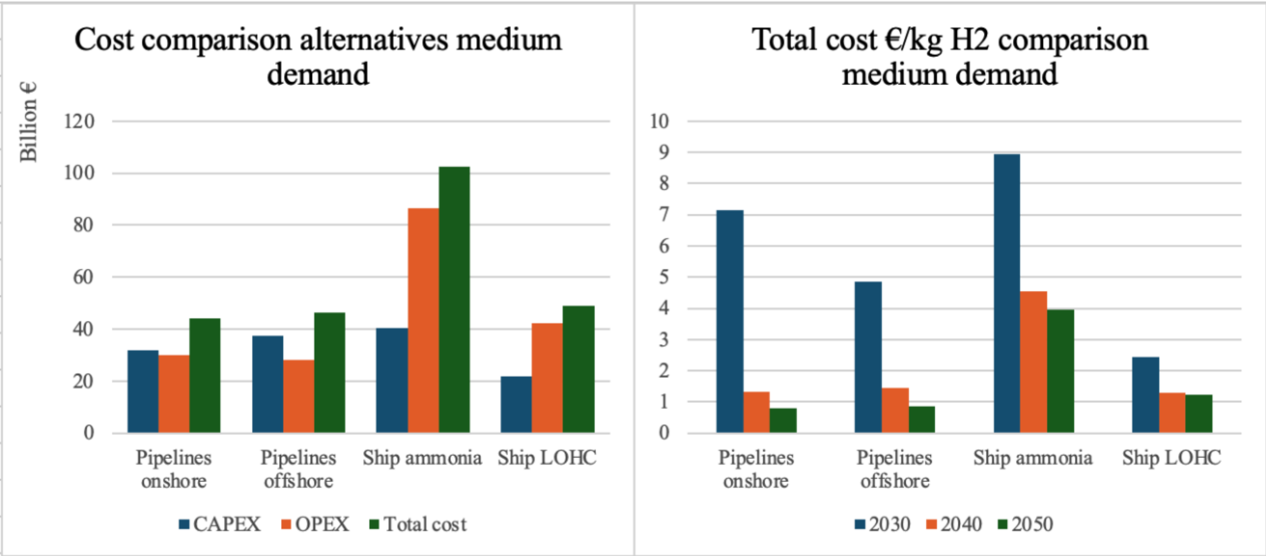

Figure 43: Cost comparison system configuration in the high supply, medium demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	31.7	37.3	40.4	21.8
OPEX	29.9	28.1	86.6	42.2
Total cost	44.2	46.3	102.3	48.8

Table 26: Cost overview of system configurations in the high supply, medium demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	7.14	4.86	8.94	2.45
2040	1.33	1.44	4.55	1.3
2050	0.79	0.85	3.97	1.22

Table 27: Yearly total cost per kg of hydrogen delivered for system configurations in the high supply, medium demand scenario.

High demand:

In the high supply and high demand scenario the pipelines with onshore storage facilities configuration is again the cheapest, followed by the pipeline with offshore storage configuration. The costs of the LOHC system are equal to medium demand scenario as it remains in the equilibrium. Whereas the costs per kilogram of hydrogen delivered fall further for the pipeline configurations, which now both yield a lower starting from 2040. In figure 44, and tables 28 and 29 the total cost and cost per kilogram of hydrogen delivered can be seen for al system configurations.

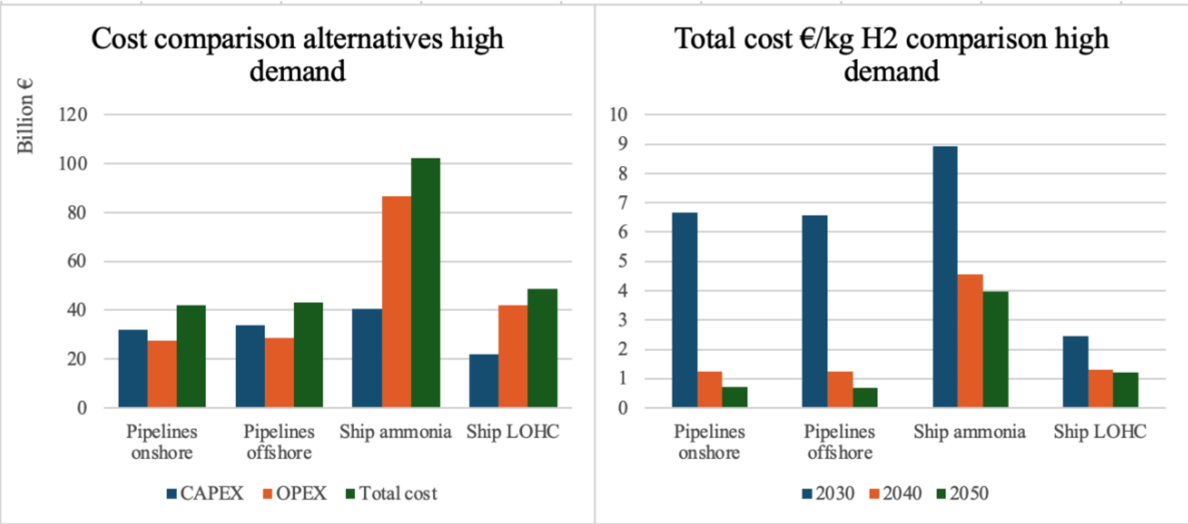

Figure 44: Cost comparison system configuration in the high supply, high demand scenario.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
CAPEX	31.9	33.7	40.4	21.8
OPEX	27.5	28.5	86.6	42.2
Total cost	42.1	43	102.3	48.8

Table 28: Cost overview of system configurations in the high supply, high demand scenario in Billion €.

	Pipelines onshore	Pipelines offshore	Ship ammonia	Ship LOHC
2030	6.65	6.57	8.94	2.45
2040	1.24	1.23	4.55	1.3
2050	0.7	0.69	3.97	1.22

Table 29: Yearly total cost per kg of hydrogen delivered for system configurations in the high supply, high demand scenario.

7. Discussion

In this chapter, the executed research is reflected upon and its implications are discussed. First the validity of the results is analysed, followed by a reflection on the societal and scientific contribution this thesis offers. Finally the limitation of this research are laid out, and recommendations for further work are given.

7.1 Validity

As some of the system configuration analysed in this thesis were designed for the purpose of this research, validating them is unfortunately hard. Furthermore, one of the main knowledge gap this thesis focuses on is that purification cost are often ignored in hydrogen transportation system analyses, whereas this thesis has included them. This makes it hard to find research with which a comparison can be drawn. Finally considering the fact that currently very little offshore electrolysis capacity is actually build, little data is available on the costs incurred to transport the produced hydrogen.

Information can be found however on the total current cost per kilogram of green hydrogen, and how these costs are set to develop. Even though the costs per kilogram of hydrogen calculated in this research do not include the costs associated with the production and the final distribution, comparing them can provide some insight in the reliability of the results and the feasibility of the alternatives.

Forecasts for the cost of green hydrogen in 2030 vary. The lowest cost found was 2.00 €/kg (Oliveira, 2021), with the highest forecast being 4 €/kg (Gerlog, 2023). Most estimates however are that the costs will be between 2.3 - 3.8 €/kg (IEA, 2024), which is expected to fall further to between 2 - 3 €/kg (Gerlog, 2023) in 2050. In 2030 the cost per kilogram is above these estimates for most scenarios, with the exception of the LOHC system. This is caused by the high investment cost needed in that year, leading to a high cost per kilogram as relatively small amounts of hydrogen are produced. In 2050 however, the cost per kilogram for the LOHC and both pipelines alternatives is slightly under or over 1 €/kg in most scenarios. This is well below the forecasts of 2 - 3 €/kg, which makes sense considering the cost of production and final distribution is not included. For the ammonia system configuration however, the cost per kilogram remains high at around 4 €/kg.

Overall, for the pipeline alternatives and the LOHC system the resulting costs per kilogram of hydrogen seem realistic and in line with forecasts for the future. The costs of the ammonia system however remain high, indicating that the current system configuration using ammonia may not be feasible.

In discussing the validity and feasibility of the alternative system configurations, it is important to realise how the values used for certain parameters may have influenced the final results. For certain system components it was difficult to find exact cost figures as certain system configurations were designed for this thesis. For instance the hydrogenation and dehydrogenation of the ammonia were found to be very expensive. However economies of scale might allow the construction and use of such facilities to be significantly less expensive. Another facet contributing to the high cost of the ammonia system however is that all hydrogen needs to be purified after dehydrogenation. Whereas other configurations only required purification for a part of the processed hydrogen. Lower cost values for large scale hydrogenation and dehydrogenation facilities would therefore have decreased the total cost of the ammonia system, but it would likely remain the most expensive alternative.

Another parameter that will have influenced the results, is the frequency with which the ships collected the hydrogen at the wind farms. Had this been more often, both the required offshore and onshore storage need would have decreased leading to lower investment and operational costs. However the costs for shipping, dehydrogenation and purification would have increased. As the dehydrogenation and purification capacities were tailored to exactly handle all hydrogen in the time it takes for the next ship to arrive. As the shipping, dehydrogenation and purification combined have had a larger influence on the total cost, increasing the frequency of collecting the hydrogen would likely have had a negative impact on the costs for both the ammonia and the LOHC system configurations.

7.2 Societal contribution

The societal contribution this research adds, is that it may help in deciding how the hydrogen from the North-Sea is to be transported. The societal importance of transitioning away from fossil fuels and towards renewable energy cannot be overstated. The development of the hydrogen economy is therefore vital, and to that effect the decision on how the transportation configuration will be shaped should be made as soon possible.

7.3 Scientific contribution

The first scientific contribution this thesis offers, is that it considers the collection of the hydrogen from the North-Sea using ships. In scientific literature on hydrogen transport, it is often mentioned that ships are only economically viable over longer distances for the import and export of hydrogen. To the best of the authors knowledge, no research has been published before that considers the case of ships collecting offshore hydrogen to transport it to shore on a regular basis.

Further scientific contribution this research adds is that it identifies the knowledge gap of ignoring the purification requirements when designing hydrogen pathways. By analysing multiple hydrogen system configurations including the purification processes the importance of including this step is stipulated, and the knowledge gap is partially filled.

7.4 Limitations

In order to set up the models and experiments, choices had to be made on the design of the experiments which will inherently have affected the resulting outcomes and performances of the alternative system configurations.

The design choice that has had the most obvious influence on the results, is the choice to exclude the possibility of exporting energy. This choice however had to be made for several reasons. Firstly, in finding the potential hydrogen production excluding this possibility was necessary as the ETM would otherwise balance the system by exporting electricity whenever there was a surplus. This would have led to no electricity being available the production of hydrogen. In the real world however where import and export of electricity is possible, this would result in different potentials for hydrogen production. The second reason this decision had to be made for the scope of this thesis, is that it was necessary in order to be able to compare the different system configurations fairly. Due to the inherent difference of pipelines continuously supplying hydrogen and ships supplying hydrogen in batches, allowing the excess supply to be exported at a certain time step would give the pipeline configurations a lower need for hydrogen storage resulting in lower costs. Yet in the current set up of the experiments, the performance of all system configurations are punished in the case of excess supply as this leads to high extra costs. Especially the performance of the pipelines with offshore storage performed poorly under excess supply, as could be seen in the low demand scenarios. This resulted in the low demand scenarios being more expensive than they may be in reality.

Aside from the high storage costs in circumstances of excess supply, another facet of the results of the pipelines with offshore storage system configuration was unexpected. The experiments where set up so that the maximum amount of storage required in the analysed week was available, and this was scaled to the output of each windfarm so that enough storage capacity would be available at all wind farms. Yet the resulting costs seem counterintuitive, as the high demand scenarios often had lower pipeline CAPEX requirements compared to the low and medium scenarios. While one would expect the CAPEX to be higher, as higher demand means more hydrogen needs to be transported per time step leading to higher capacities. A logical explanation for this could be that for some of the wind farms the storage capacities, were too low resulting in a need for the model to transfer part of the hydrogen to storages at other wind farms. However upon inspection of the storage data it became apparent that this is not the case. In fact, some of the storage facilities remained empty throughout the experiments while others storage facilities were filled.

7.5 Recommendations for further research

Based on the results and discussion, the following recommendations are given for future research:

1. As mentioned in the discussion, the scope of this thesis does not incorporate the possibility of export of import of hydrogen. Incorporating this could give a more realistic overview of the costs associated with different system configurations under different demand scenarios.
2. More research should be done on the system configuration with offshore storage. As this configuration did return low costs per kilogram of hydrogen delivered in many scenarios, but its performance was reduced due to the lack of export in the model, and the unexpected pipeline costs. Furthermore research should be done on potential future storage of hydrogen in offshore gas fields. As this could combine the advantage of both pipeline configurations assessed in this thesis.
3. More research should be done on the possibility of incorporating repurposed gas pipelines. This was originally one of the system configurations to be analysed in this thesis, but no clear data was found on pipelines that can be repurposed in the future. Only on gas pipelines that are available for

repurposing now, but these were found to have too low capacities to be of added value to the networks.

4. Finally, more research could be done on scaling advantages for certain installations like the hydrogenation and dehydrogenation facilities. Perhaps they can be realized for lower costs on large scales. Furthermore the future development of costs such as these could be incorporated, as the technologies will likely mature further and become more affordable leading to different system configuration performances.

8. Conclusion

The research question this thesis aimed to answer is:

What is the cost optimal system configuration to transport hydrogen from the North-Sea to shore under uncertain levels of future supply and demand, and considering the resulting purity?

To answer this question one has to consider the uncertainty that it is surrounded in. Due to the uncertainty present in both the future supply and demand for hydrogen, there is no system configuration that uniformly performs best over the scenarios. What is apparent however is that the ammonia system configuration is not feasible, as it has the highest total cost in most scenarios, and consistently yields the highest cost per kilogram of hydrogen delivered in 2050. This is due to the high losses in hydrogen caused by the dehydrogenation and PSA process, combined with high OPEX costs related to the hydrogenation and dehydrogenation.

Certain system configurations however, are more robust in their performance under the uncertain circumstances simulated in the scenarios. Therefore a hybrid system configuration is proposed below, combining the LOHC system configuration with the pipelines with onshore storage configuration.

The LOHC system configuration has the lowest CAPEX requirements in nearly all supply and demand scenarios considered. Due to this it also has the lowest starting cost per kilogram of hydrogen delivered in the year 2030 for all scenarios. Considering this, the LOHC system configuration seems like the safest system configuration for the short term. As the market for hydrogen will begin to form in the years up to and following 2030, more precise demand scenarios can be created reducing the uncertainty. Furthermore the plans by the Dutch government regarding the wind capacity past 2030 will likely begin to crystalize, giving more clarity on the potential future hydrogen supply.

When the absolute amount of hydrogen that needs to be transported grows, the cost per kilogram of hydrogen delivered of the LOHC system will no longer be optimal. Therefore when there is more clarity on the future supply and demand, a pipeline network should be developed for the long term. Both of the pipeline configurations considered in this thesis offer similar costs per kilogram of hydrogen delivered. Yet the offshore storage configuration brings with it the risk of extremely high investment costs in storage in the event of excess supply, and the onshore storage option offers more flexibility in the case of high excess of supply. Therefore the proposed system configuration for the long term, is a pipeline network with onshore storage in salt caverns. The investments in the LOHC system are not totally wasted then however, as the facilities can still be used for the importation of hydrogen.

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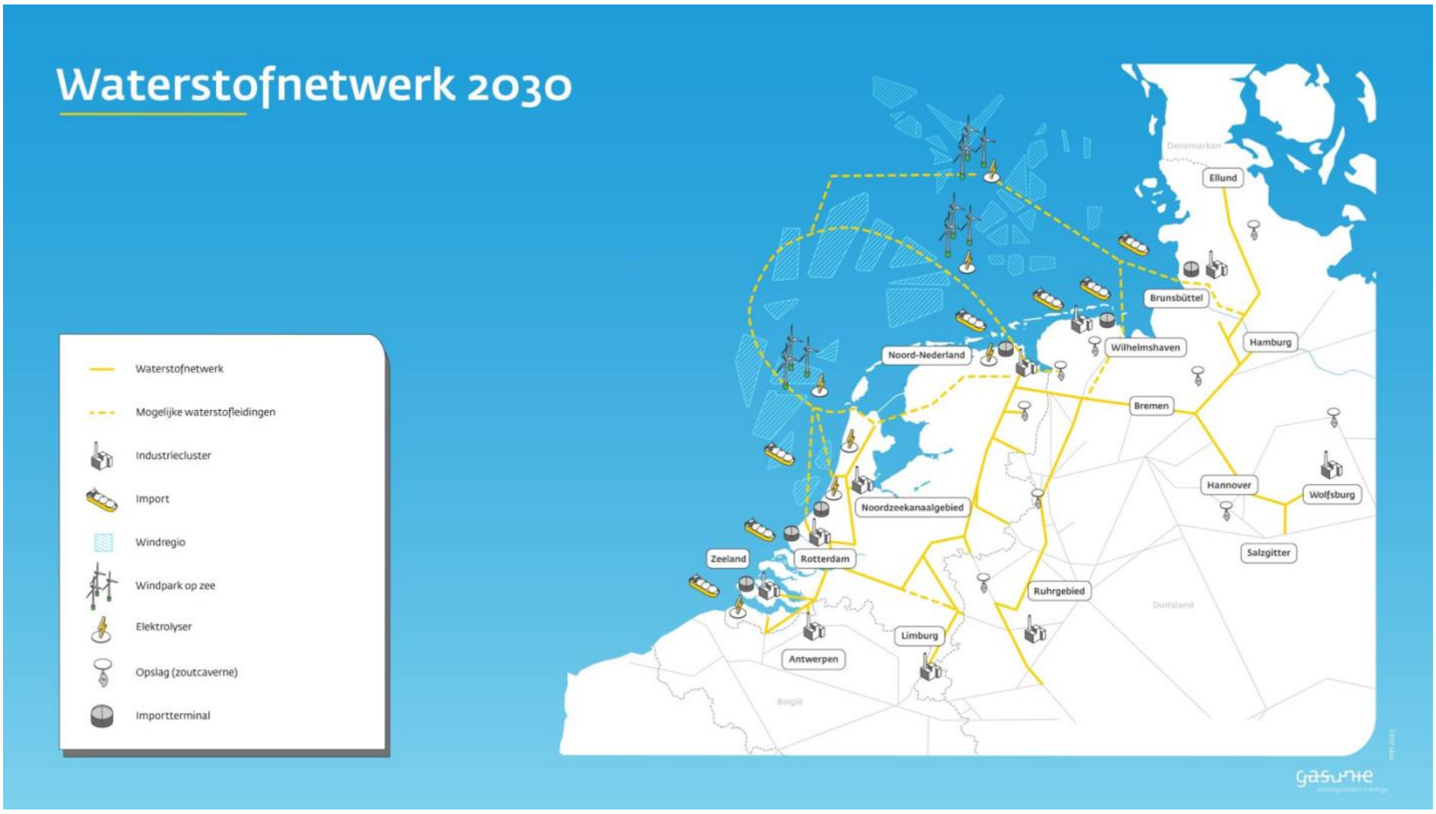
Appendix

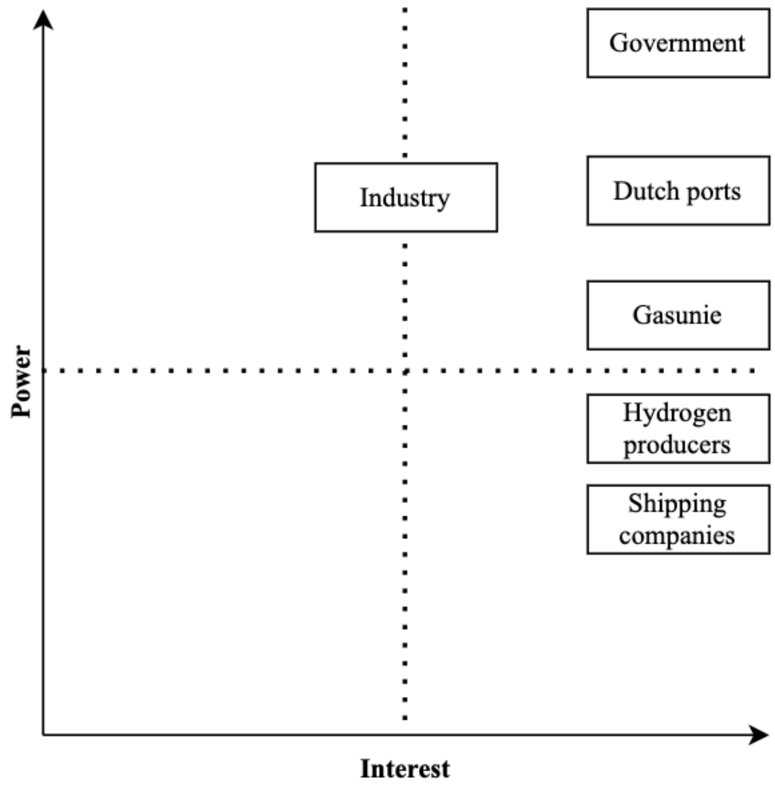
A1. Overview of transport network Gasunie

In the figure below is an overview of the proposed network of Gasunie (Gasunie, 2022). As can be seen, the plans for the offshore network are marked as potential. This is due to postponement of the decision on the gas specification of the onshore network, as explained in the introduction of this thesis.

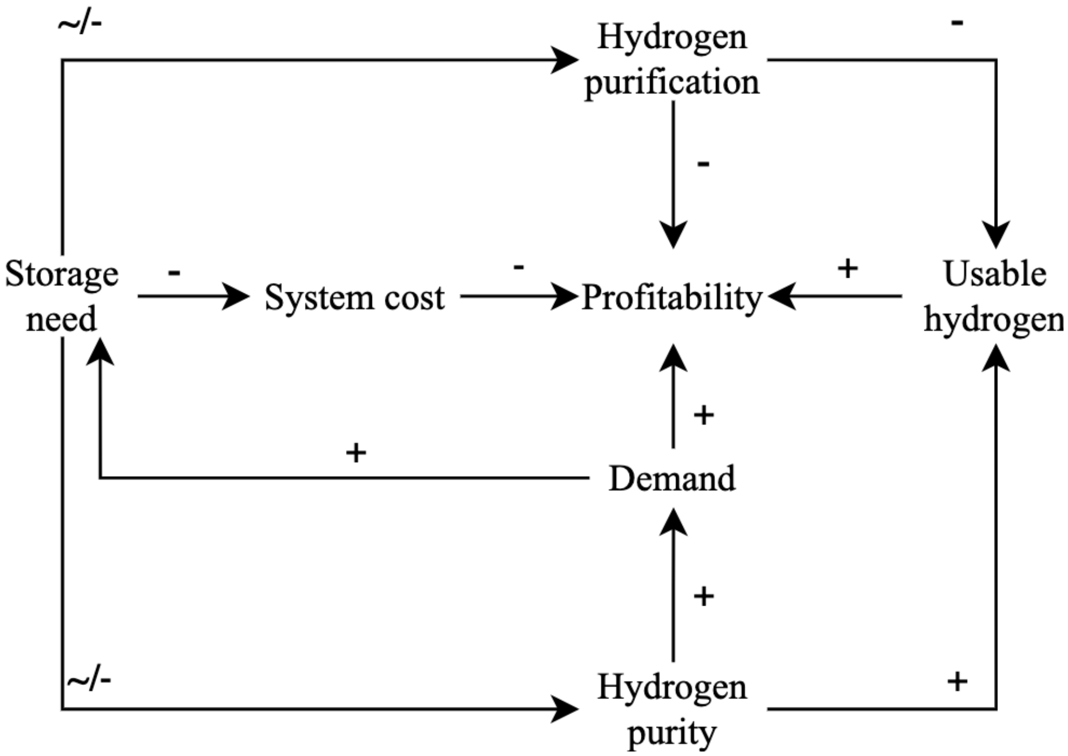


A2. Stakeholder analysis

Power interest grid of stakeholders:

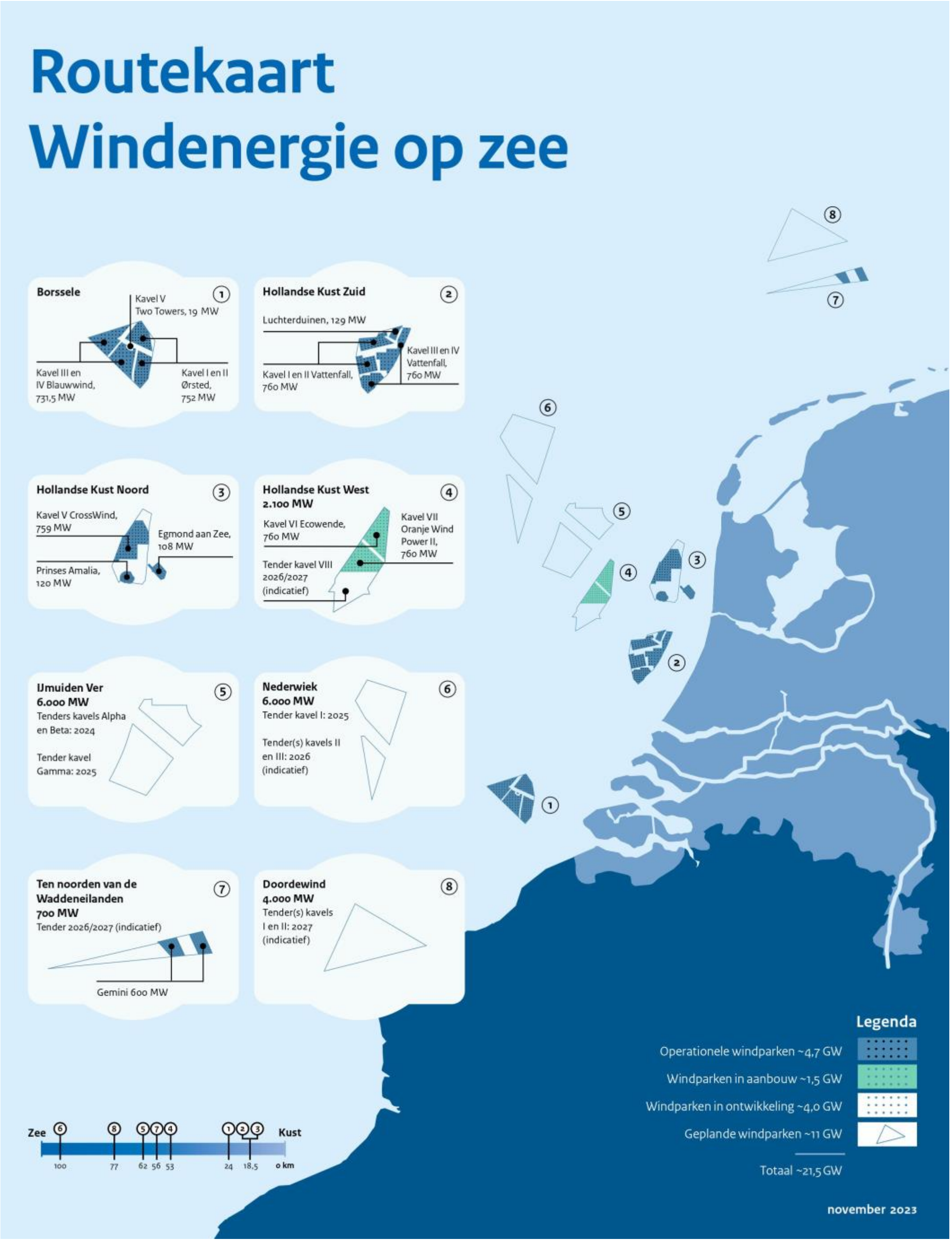


Causal loop diagram of hydrogen system:



B1. Routekaart wind op zee

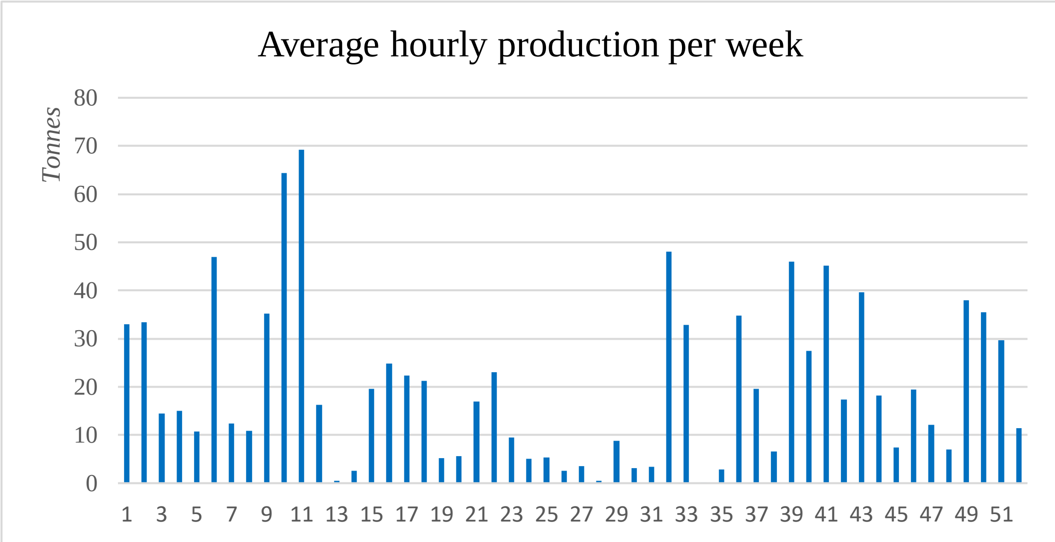
On this map the capacities of the wind parks for 2030 is based.



B2. Winter and summer week analyses

In this appendix an analysis is shown of how an average seasonal week is selected. Furthermore the analysis shows that a week representing a season does not necessarily need to fall within that season.

2030



Average hourly total production per week 2030.

In the figure above, the hourly average potential production for all weeks in 2030 is illustrated. The weeks that are closest to the seasonal averages are week 4 for the summer and week 16 for the winter. These weeks fall out of the season they represent. To analyse if this means that they cannot be representative for the seasons they were compared the to the closes alternative week that did fall within the season, which were weeks 21 and 40 for the summer and winter respectively. In order to make a decision, two indicators were used. These are the hours per week there is 0 potential, and the average hourly production, not taking into account hours with zero potential. The ratios of these values were then compared for both the real summer and winter weeks, and the weeks closest to the real averages. The results of the comparison can be seen in the table below.

	Week 4	**Week 16**	**Week 21**	**Week 40**
Zero potential hours	108	95	113	100
Average without zeros (kg/MW/h)	1.83	2.49	2.25	2.96
Ratio summer/winter 0 potential hours	1.14		1.13	
Ratio of average potential without 0 hours	0.73		0.76	

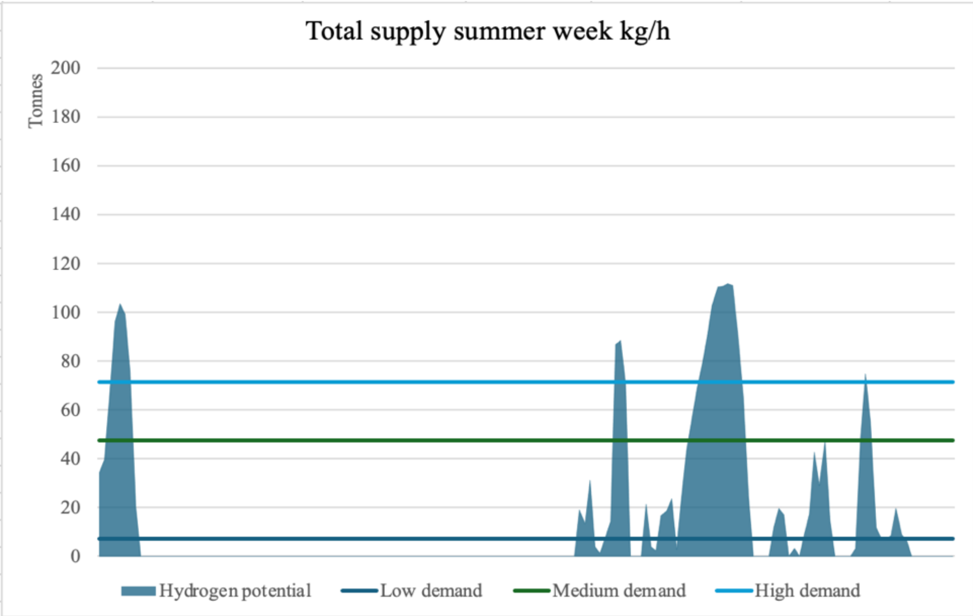
Summer and winter week comparison.

Considering both of the indicators used have roughly the same ratio between the pair of real weeks for summer and winter and for the selected weeks, it was decided that week's representing the summer or winter, do not necessarily need to fall within that season.

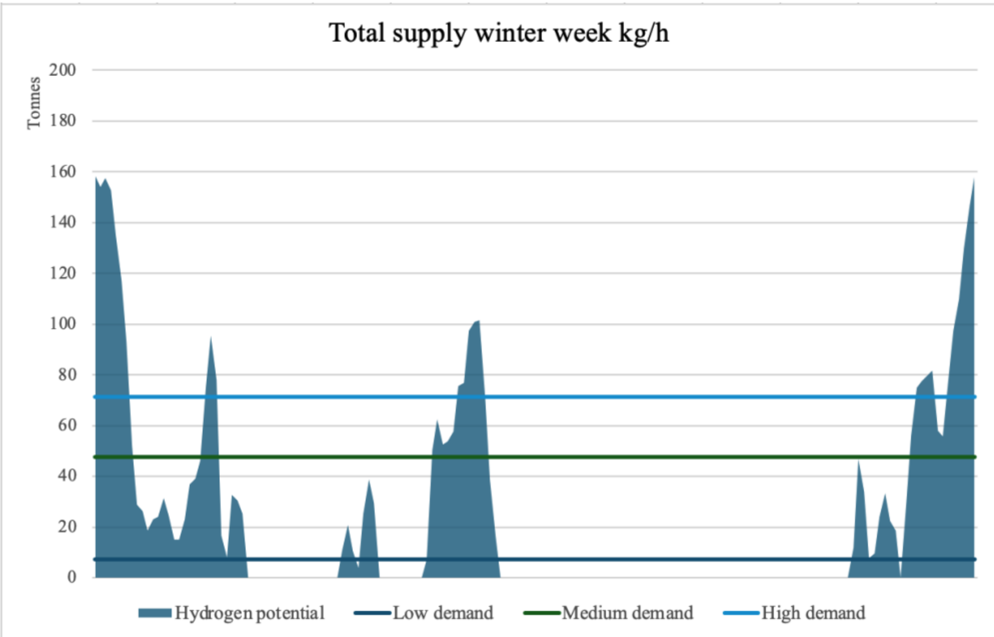
B3. Hydrogen production supply scenarios

In this appendix an overview is given of the total hydrogen production of all supply scenarios.

2030



Weekly hydrogen production summer week.



Weekly hydrogen production winter week.

The total hydrogen production for the full year of 2030 can be seen below in the table.

Supply	**Tonnes H2**
Summer week	2514
Winter week	4175
Total yearly	173914

Total hydrogen production potential 2030

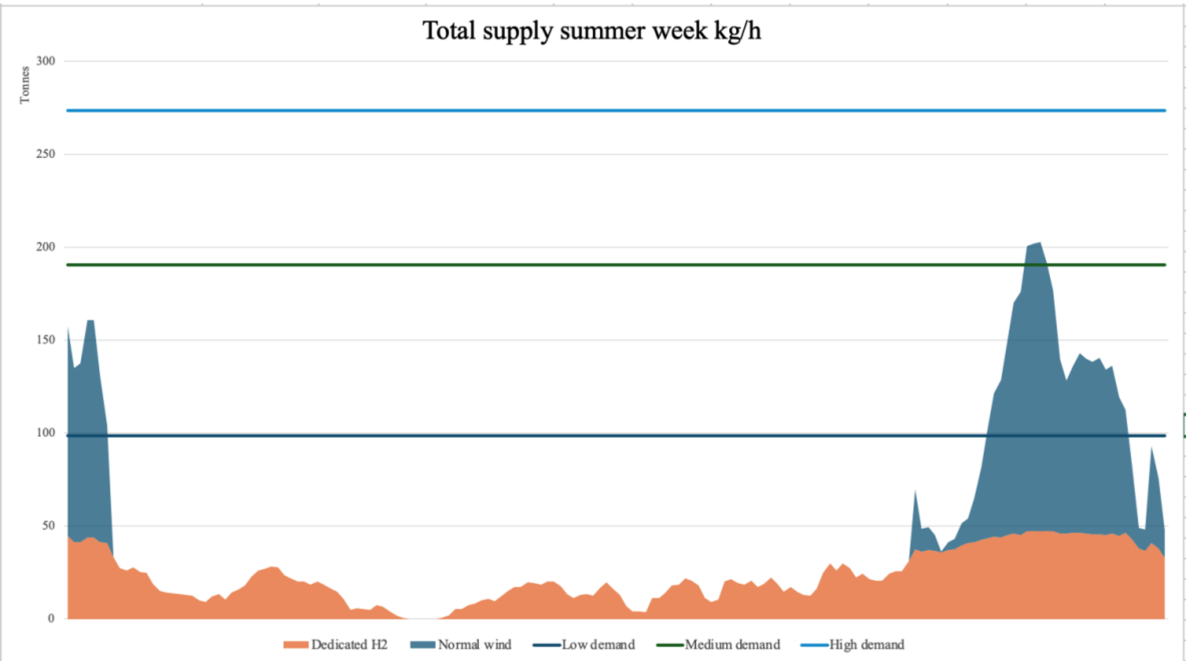
Comparing this potential supply with the different demand scenario in the table below, makes it apparent that only in the low demand scenario the installed wind capacity is sufficient to supply all demand.

	Tonnes/year	**Supply/demand ratio**
Low demand	62500	2.78
Medium demand	416667	0.42
High demand	625000	0.28

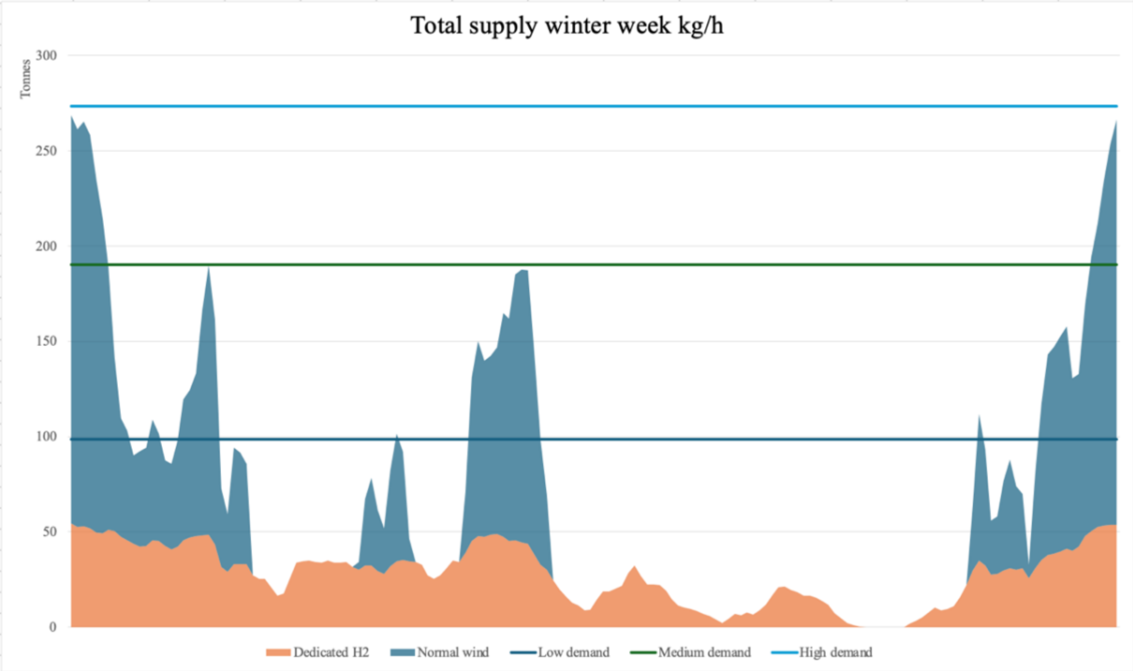
Potential supply and demand ratios 2030

<u>2040 Low wind</u>

In 2040 the first dedicated hydrogen windfarms are installed. What is immediately noticeable is that there is now more often a baseline of hydrogen potential. This is due to the fact that even when there is no surplus, there will still be hydrogen production if there is wind. Below are the total supply curves for the summer and winter week the figures below respectively.



Summer hydrogen potential 2040 low wind scenario.



Winter hydrogen potential 2040 low wind scenario

In the low wind scenario it is clear from the figures that the demand cannot be met. In the tables below are the total hydrogen supply in the scenario, and a comparison to the demand scenarios respectively.

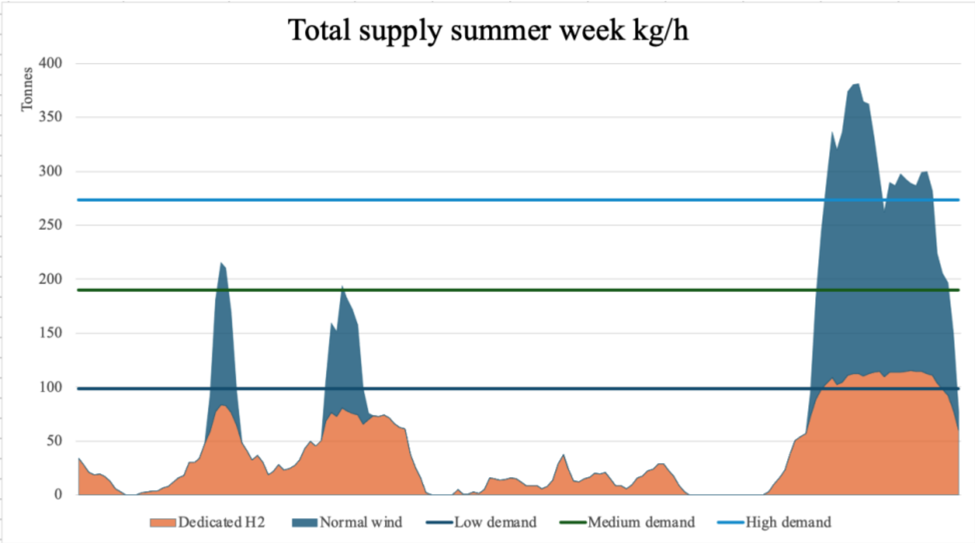
Supply	Tonnes H2
Summer week	7136
Winter week	11322
Total yearly	479908

Hydrogen supply 2040 low wind scenario

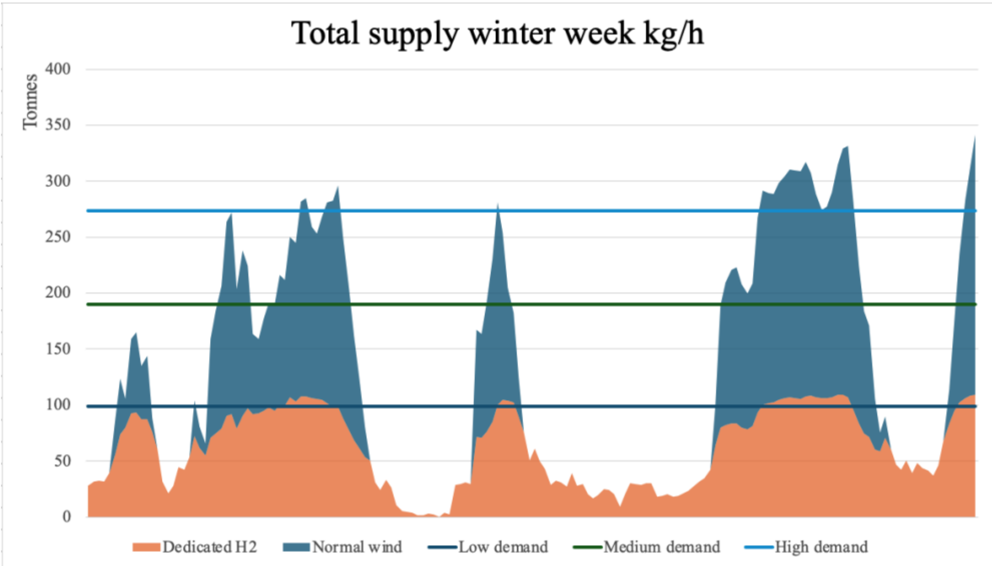
	Tonnes/year	Supply/Demand ratio
Low scenario	864583	0.56
Medium scenario	1666667	0.29
High scenario	2395833	0.2

Potential supply and demand ratios 2040 low wind scenario

2040 Medium wind scenario



Summer hydrogen potential 2040 medium wind scenario.



Winter hydrogen potential 2040 medium wind scenario.

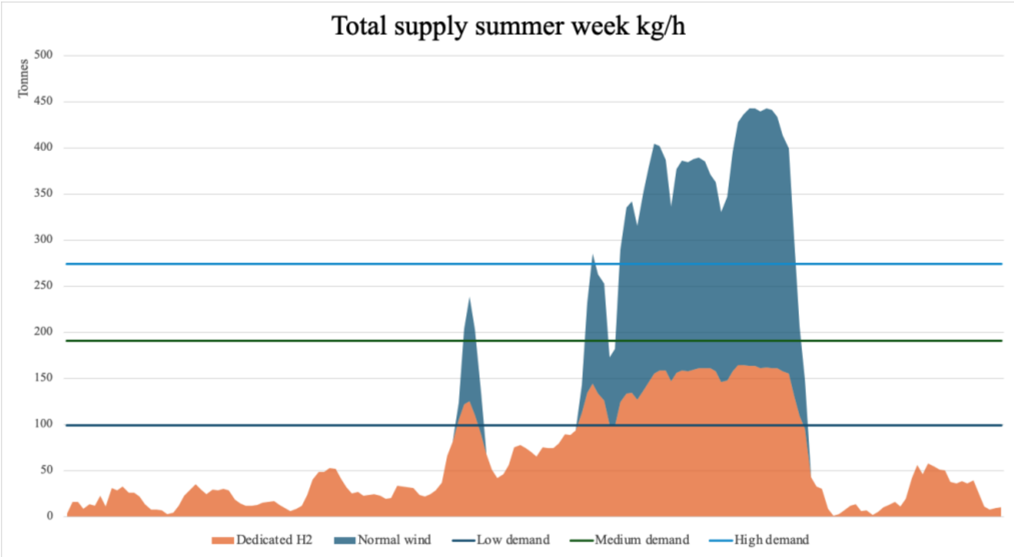
Supply	Tonnes H2
Summer week	12647
Winter week	21562
Total yearly	889434

Hydrogen supply 2040 medium wind scenario.

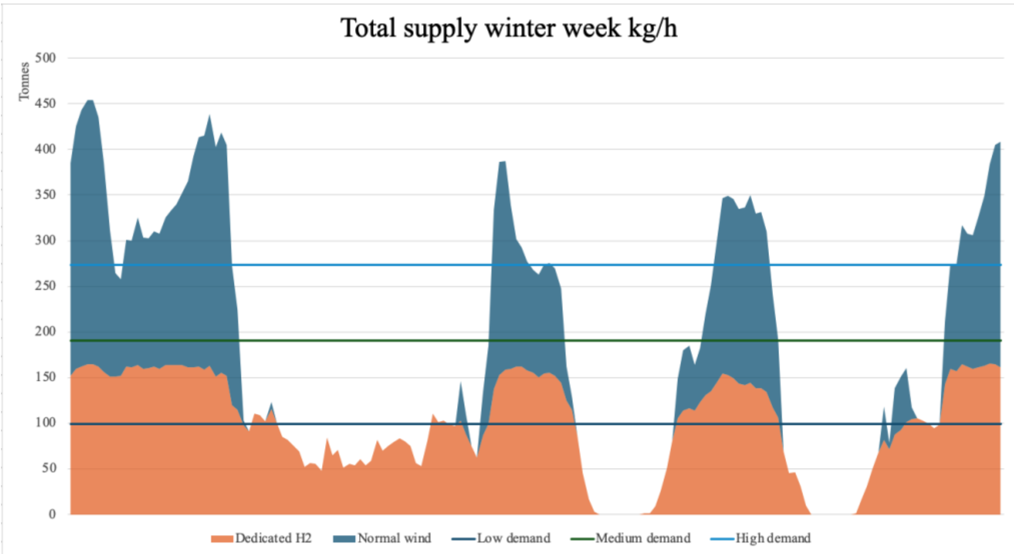
	Tonnes/year	Supply/Demand ratio
Low scenario	864583	1.029
Medium scenario	1666667	0.54
High scenario	2395833	0.37

Potential supply and demand ratios 2040 medium wind scenario.

2040 High wind scenario



Summer hydrogen potential 2040 high wind scenario.



Winter hydrogen potential 2040 high wind scenario.

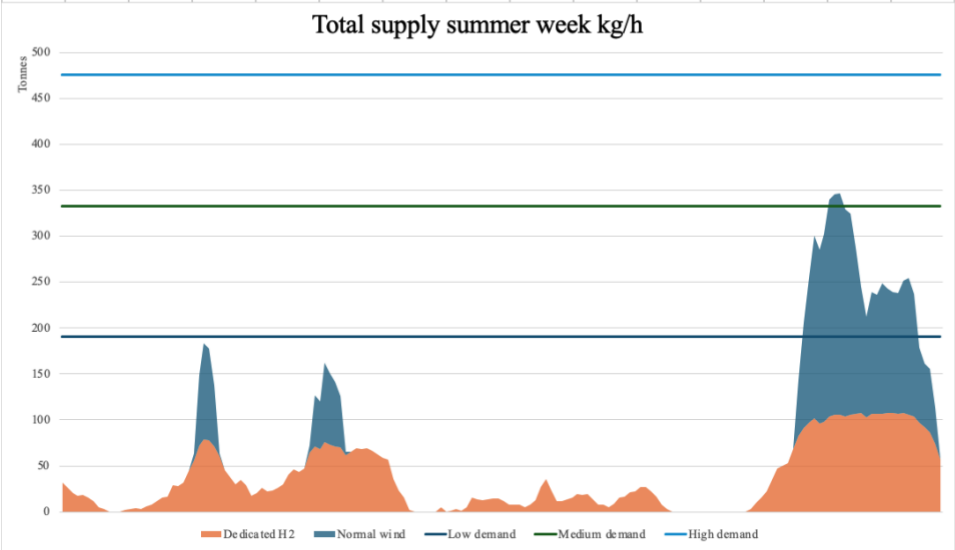
Supply	**Tonnes H2**
Summer week	18760
Winter week	29638
Total yearly	1258348

Hydrogen supply 2040 high wind scenario.

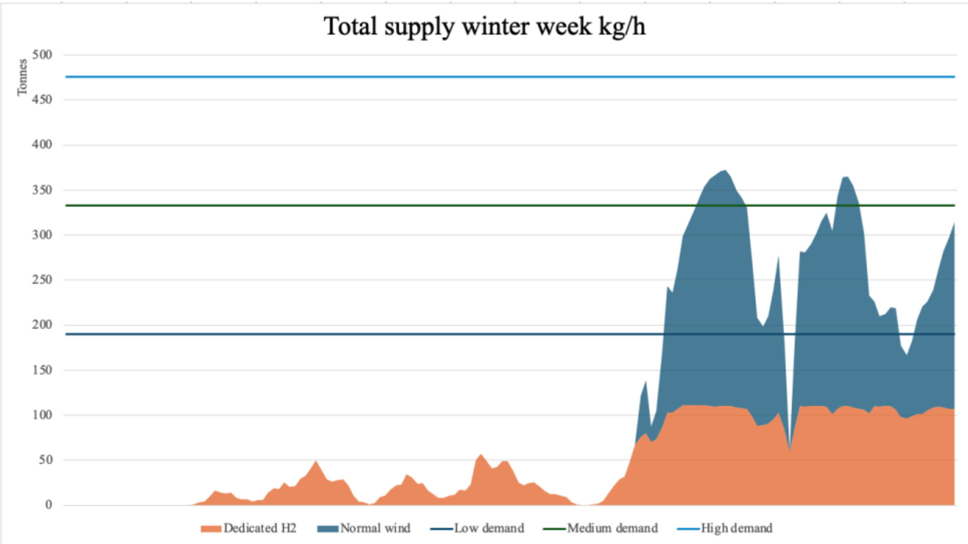
	Tonnes/year	**Supply/Demand**
Low scenario	864583	1.46
Medium scenario	1666667	0.76
High scenario	2395833	0.53

Potential supply and demand ratios 2040 high wind scenario.

2050 Low wind



Summer hydrogen potential 2050 low wind scenario.



Winter hydrogen potential 2050 low wind scenario.

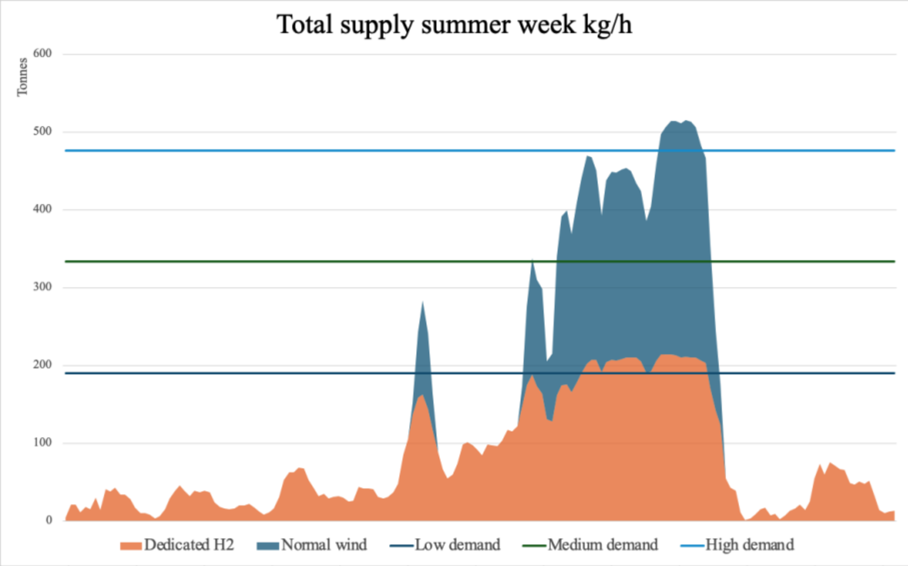
Supply	**Tonnes H2**
Summer week	10854
Winter week	17427
Total yearly	735306

Hydrogen supply 2050 low wind scenario.

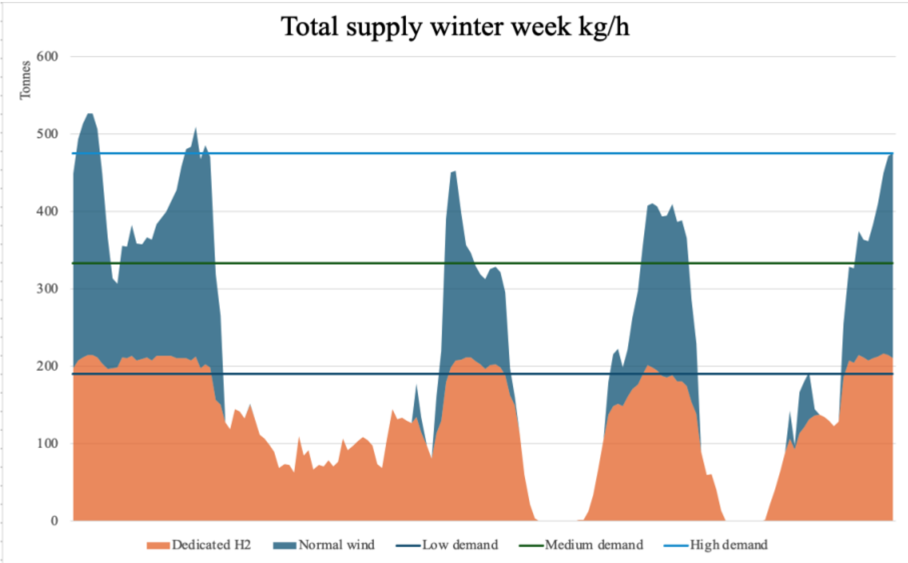
	Tonnes/year	**Supply/Demand ratio**
Low scenario	1666667	0.44
Medium scenario	2916667	0.25
High scenario	4166667	0.18

Supply and demand ratios 2050 low wind scenario.

2050 Medium wind



Summer hydrogen potential 2050 medium wind scenario.



Winter hydrogen potential 2050 medium wind scenario.

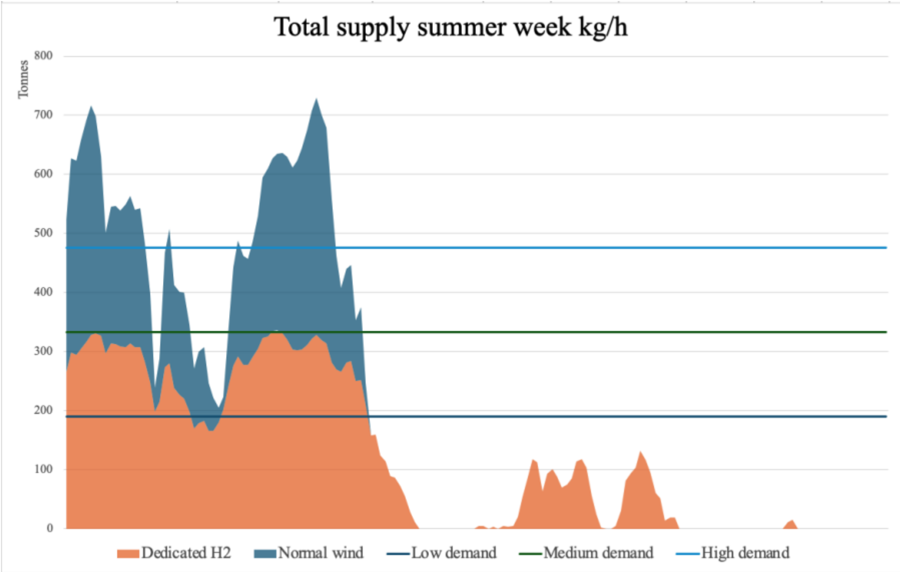
Supply	Tonnes H2
Summer week	22451
Winter week	35475
Total yearly	1506076

Hydrogen supply 2050 medium wind scenario.

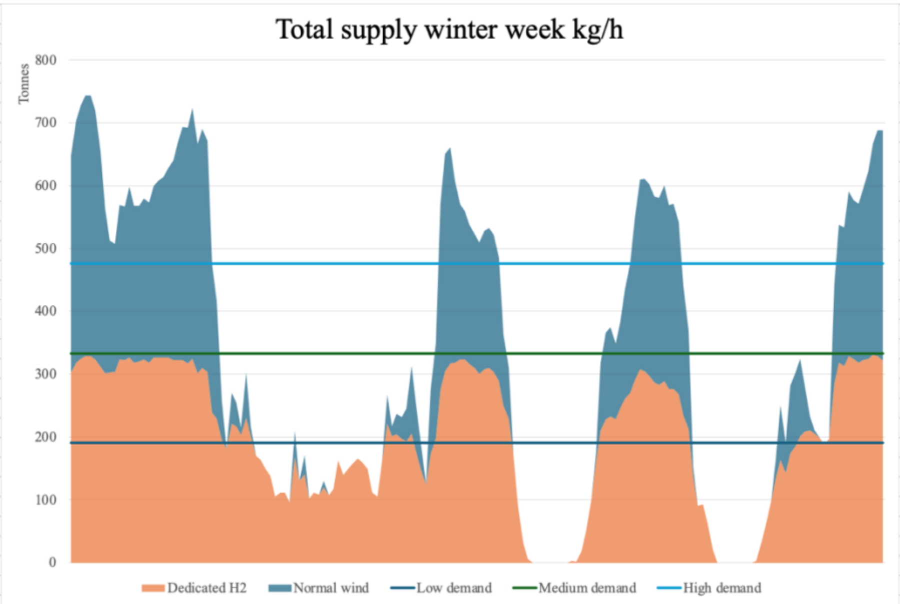
	Tonnes/year	Supply/Demand ratio
Low scenario	1666667	0.90
Medium scenario	2916667	0.52
High scenario	4166667	0.36

Potential supply and demand ratios 2050 medium wind scenario.

2050 High wind



Summer hydrogen potential 2050 high wind scenario.



Winter hydrogen potential 2050 high wind scenario.

Supply	Tonnes H2
Summer week	33973
Winter week	55278
Total yearly	2320526

Hydrogen supply 2050 high wind scenario.

	Tonnes/year	Supply/Demand ratio
Low scenario	1666667	1.39
Medium scenario	2916667	0.8
High scenario	4166667	0.56

Potential supply and demand ratios 2050 medium wind scenario.

C. Performance of all system configurations on all scenarios

In this appendix a complete overview is given of the performance of all system configurations, under the circumstances of all different scenarios.

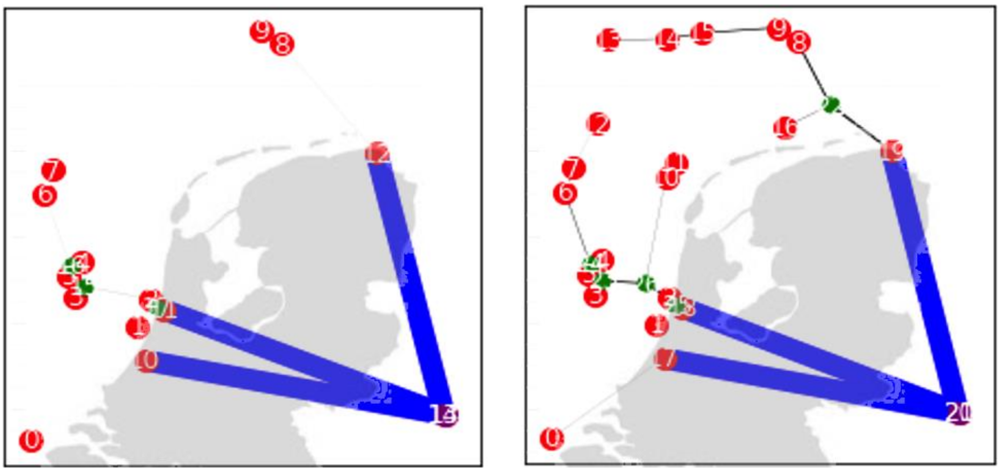
Pipelines

Pipelines onshore central storage

In the pipelines with central onshore hydrogen storage in salt caverns, the CAPEX for the required pipelines are equal amongst the demand scenarios for the same supply scenarios. This is due to the fact that the model will transport all produced hydrogen either to the super-sink where both the demand and storage facilities are located. The difference between the demand scenarios stems from the amount of hydrogen that needs to be stored at each time step. Furthermore the amount of hydrogen that is extracted from the storage needs to be purified using PSA resulting in extra costs, and a loss in hydrogen.

<u>*Low supply*</u>

Depicted in the figure below are the optimal networks to transport all supply for the year 2030 and 2050 respectively. As can be seen nodes 8 and 9 at the top of the figures need to be connected using a Steiner node. Even though this node is not yet used in 2030, the edges to it should be built already to facilitate the optimal network in 2050.



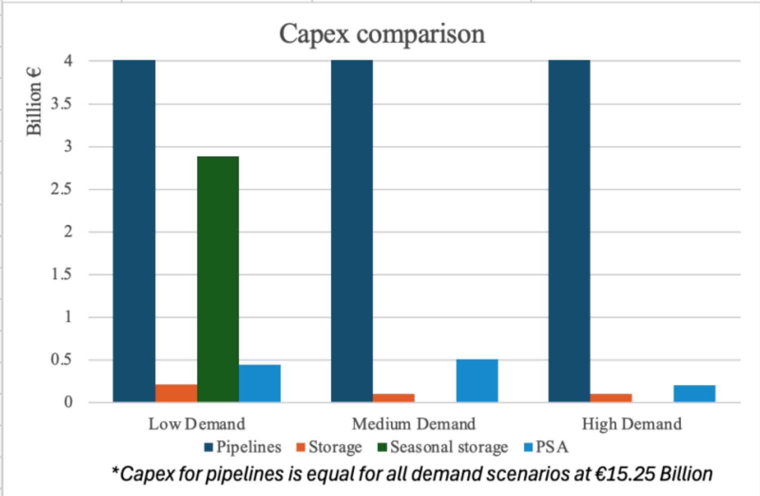
Optimal networks for low supply scenario in 2030 and 2050 respectively.

The total costs for the construction and operation of all required facilities in the period from 2030 to 2060 can be seen in the table below for all demand scenarios.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	18.8	15.9	15.6
OPEX	24.4	13.5	13.1
Total cost	31.5	20.5	20.1

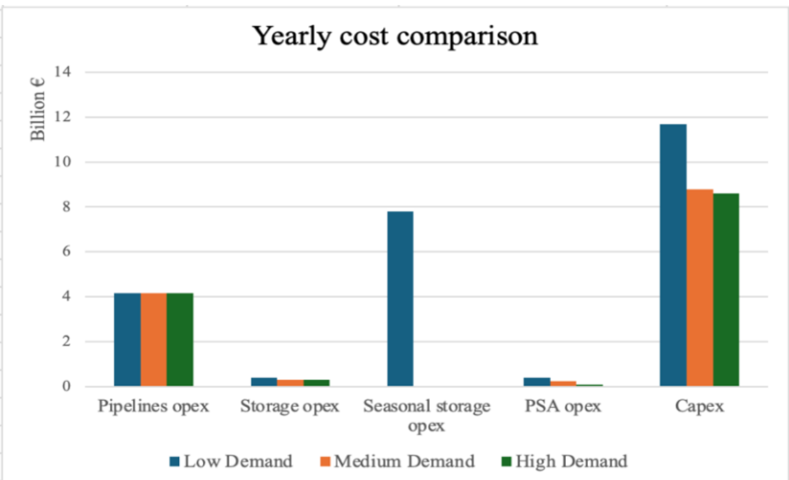
Cost of low supply demand scenarios in Billion €.

The low demand scenario is clearly the most expensive amongst the demand scenarios. This is due to the fact that in 2030 the supply is higher than the demand, requiring a higher storage capacity. This mismatch between supply and demand is so large that for both the summer and winter week additional storage is required. This extra storage is labelled seasonal storage as the hydrogen is stored in it for a longer period of time. Whereas the regular storage is used to balance the mismatch of supply and demand over a shorter period of hours to days. This additional storage requirement is also the reason the OPEX of the low demand scenario is considerably higher. In the figure below is a complete overview of the CAPEX requirements for all demand scenarios.



CAPEX comparison demand scenarios.

Another noteworthy observation is that the medium demand scenario requires the most PSA investment. This is due to the fact that when the short term storage is filled regularly when the supply is higher than the demand, but when there is a shortage the total flow out of the storage is higher per time step than in the low demand scenario. This flow out of the storage dictates the PSA capacity as its associated CAPEX cost is decided by its feed rate. Whereas in the high demand scenario almost all supplied hydrogen is consumed directly by the demand, only allowing small quantities to be stored. This in term means that only small quantities can be extracted from the storage, leading to a lower PSA feed rate and CAPEX. The OPEX of the PSA installations is decided by the total amount of hydrogen purified. In the figure below is a cost breakdown of the total yearly cost per demand scenario.

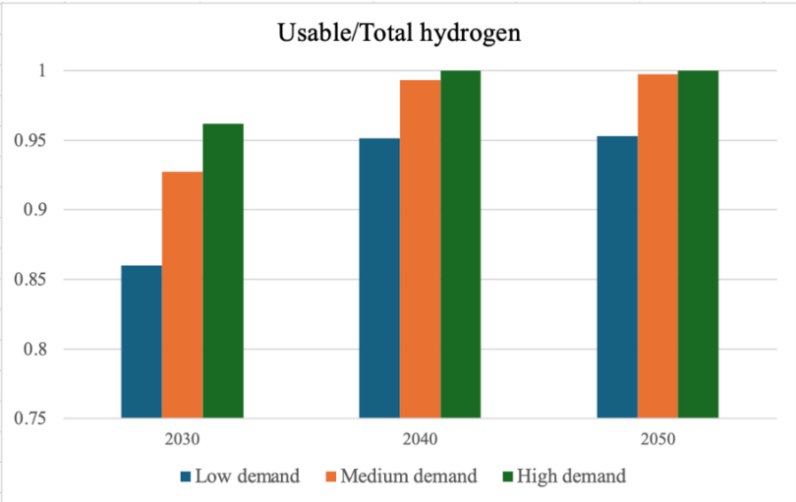


Total yearly cost comparison demand scenarios

As can be seen the high OPEX of the low demand scenario is mostly associated with the seasonal storage. As it is the only scenario in which this is required, this makes the gap to the others demand scenarios substantial.

Even though the medium demand scenario has the highest PSA capex, in total more hydrogen is purified in the low demand scenario. This is because similarly to the high demand scenario, the total supply is used directly more often than in the low demand scenario. This reduces the total amount of hydrogen that needs to be extracted from the storage and purified.

The usage of PSA has a double effect on the final cost per kg of hydrogen, as there are not only added costs associated with it, but also a loss of usable hydrogen. In the figure below the ratio of usable hydrogen versus the totally available hydrogen is shown for the different demand scenarios. As can be seen nearly all supply is delivered directly in the medium and high scenario, whereas there are considerable losses in the low demand scenario.



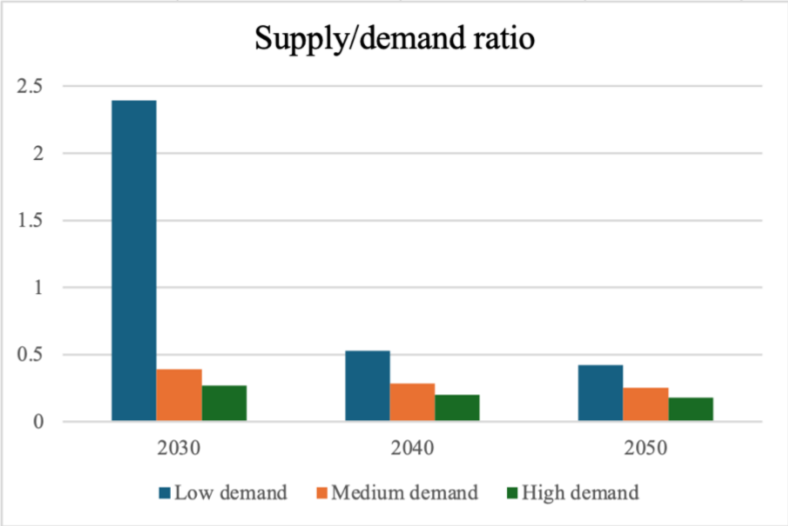
Ratio of usable and total hydrogen in demand scenarios.

This all leads to the final cost per kilogram of hydrogen delivered, these can be seen for the respective scenarios for the years 2030, 2040 and 2050 in the table below.

Cost in €/kg	Low demand	Medium demand	High demand
2030	6.33	3.72	3.54
2040	2.41	1.52	1.49
2050	1.57	0.99	0.96

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

There is one final context in which the costs of the demand scenarios should be evaluated, and that is the amount of the demand that can actually be supplied. As seen in the hydrogen potential section, the level of demand is in most cases significantly higher than the level of supply. In the low supply scenario this is especially true. In the figure below the ratios of the supply and demand can be seen for the demand scenarios in the different time years.

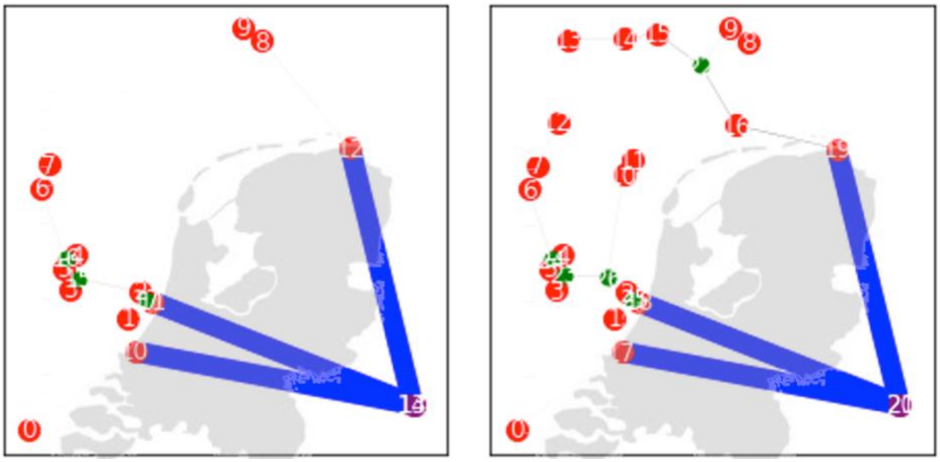


Supply and demand ratios low supply scenario

As illustrated above, only in 2030 can the entire low demand be delivered. This is also the explanation for the high cost additional storage requirements for the low demand scenario, as it is the only occasion in the low supply scenarios where there is enough supply to surpass the demand.

Medium supply

In the figure below are the optimal networks to transport all supply in the medium supply scenario for all demand scenarios.

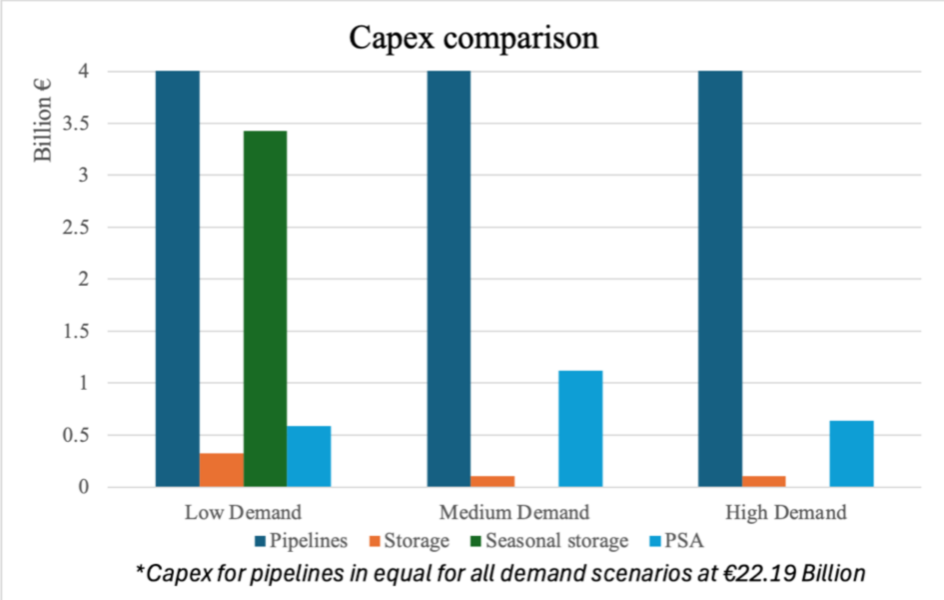


Optimal networks for medium supply scenario in 2030 and 2050 respectively.

The total costs for all equipment and operations are listed in the table below. In the figure below a is breakdown of the required CAPEX for all demand scenarios.

	Low Demand	Medium Demand	High Demand
CAPEX	26.5	23.4	22.9
OPEX	34.1	20.5	19.4
Total cost	44.7	30.9	29.5

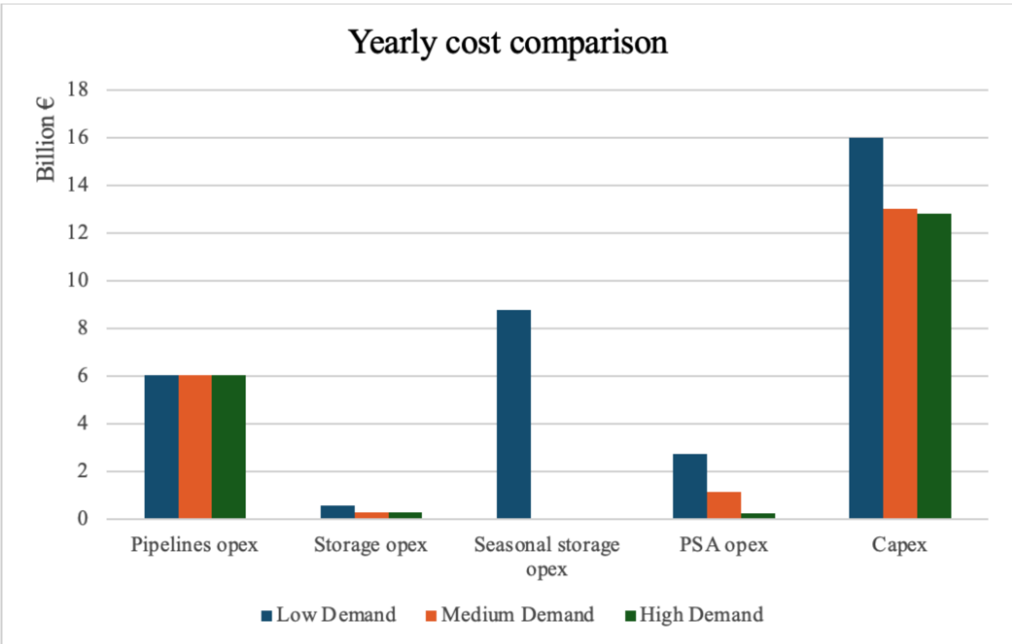
Cost of medium supply scenarios in Billion €.



CAPEX comparison demand scenarios.

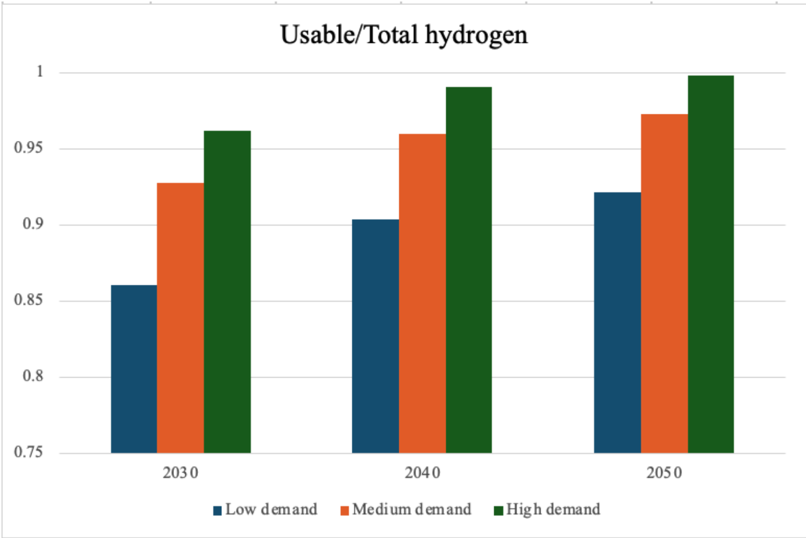
The same trends can be observed as in the low supply scenarios, with the low demand scenario clearly being more expensive due to the need for long term storage. The required investments for PSA facilities is again clearly the highest in the medium demand scenario, but now the high demand scenario also requires more PSA as the peaks in the hydrogen production are now more often higher than the level of demand.

Below in the figure is the breakdown of the total yearly costs for all three demand scenarios. Again the same trend can be observed as in the low supply scenario, with the low demand scenario requiring seasonal storage, and its PSA OPEX being the highest due to the absolute amount of hydrogen being purified



Total yearly cost comparison demand scenarios

This higher PSA requirement is also visible in the percentage of usable hydrogen, depicted in the figure below.



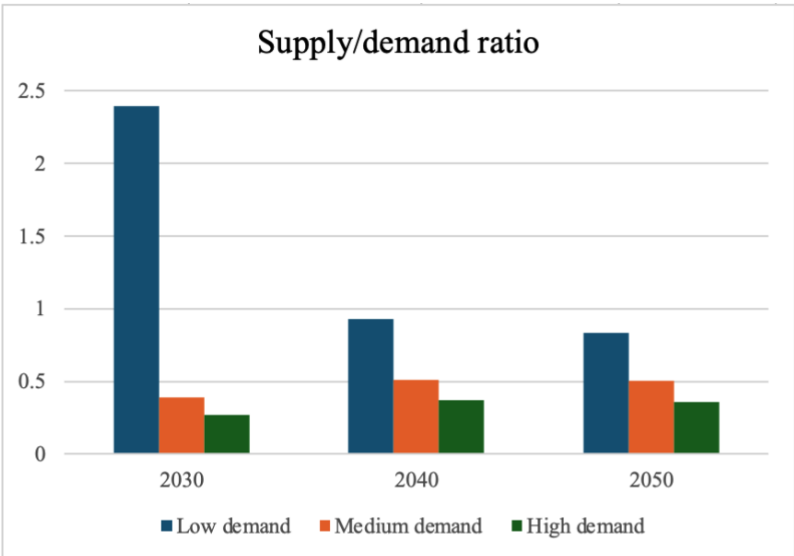
Ratio of usable and total hydrogen in demand scenarios.

In the table below the final total cost per kg of hydrogen delivered can be seen for all demand scenarios. Even though the total costs are higher for all demand scenarios, the cost per kilogram of hydrogen is substantially lower than in the low demand scenarios.

Cost in €/kg	**Low demand**	**Medium demand**	**High demand**
2030	8.12	5.36	5.09
2040	1.95	1.27	1.2
2050	1.21	0.78	0.69

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

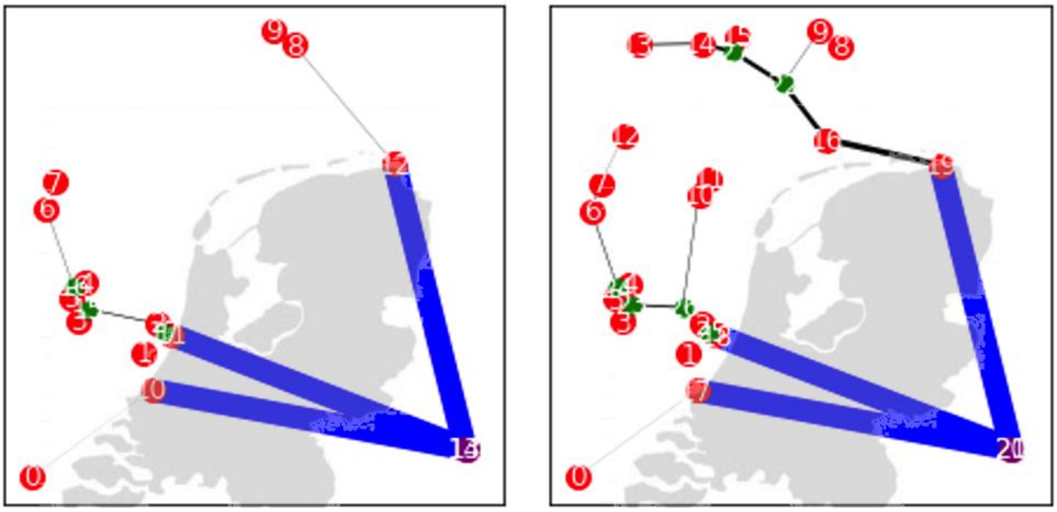
Again the total costs should be evaluated in the light of the supply and demand ratios for the different demand scenarios, these are illustrated in the figure below. The low demand can be supplied for 83% in 2050, while the medium demand can just be supplied for 50%. The high demand can be supplied for 36%.



Supply and demand ratios low supply scenario

High supply

The optimal network found for the high supply scenario is illustrated below in the figure. The main difference with the previous networks is the capacity of the edges. The topology is equal for the most part.

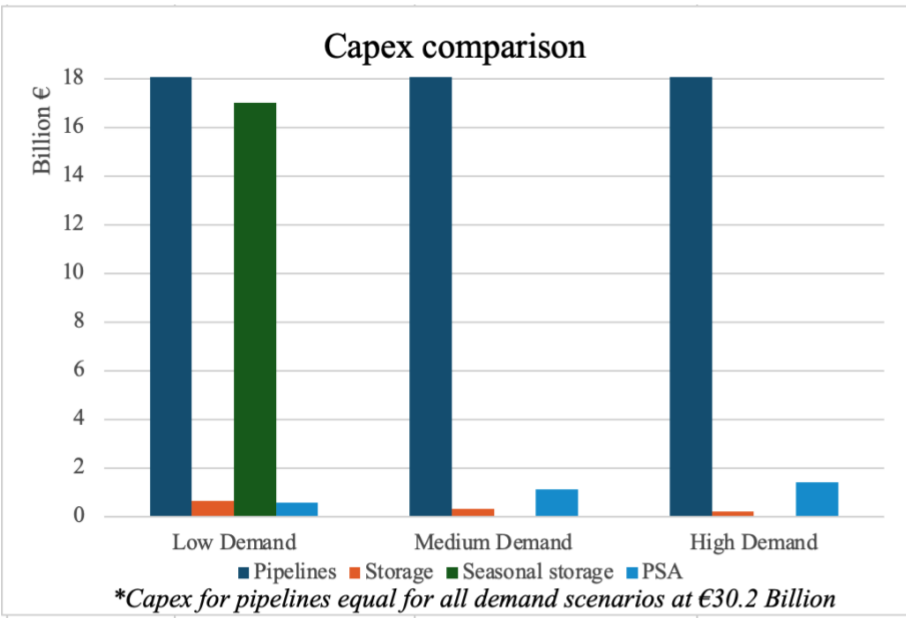


Optimal networks for high supply scenario in 2030 and 2050 respectively.

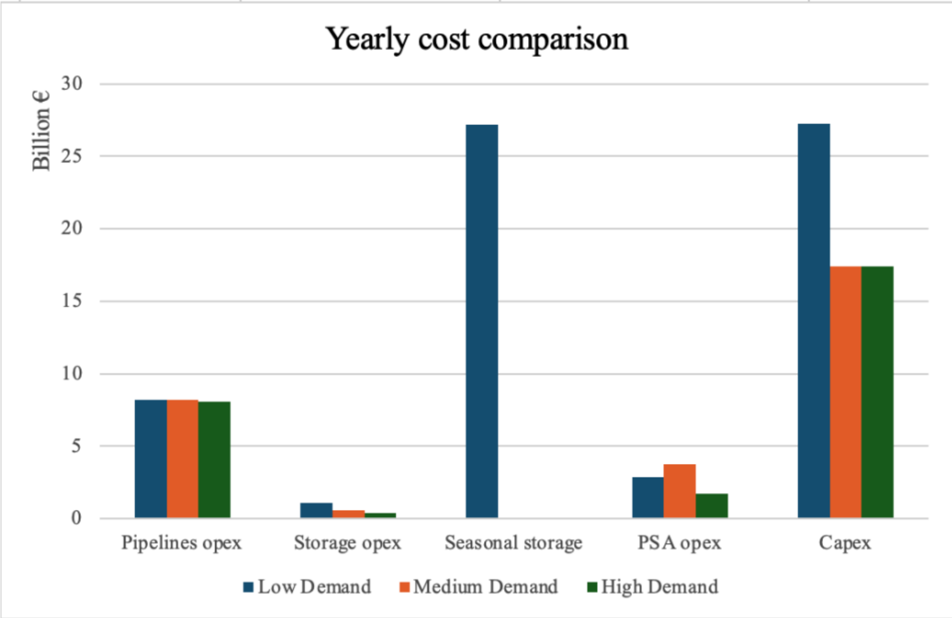
Below in the table the total costs for the different demand scenarios in the high supply scenario can be seen. These are followed by the breakdown of the CAPEX costs and the OPEX costs.

	Low Demand	Medium Demand	High Demand
CAPEX	48.5	31.7	31.9
OPEX	66.5	29.9	27.5
Total cost	87.8	44.2	42.1

Cost of high supply scenarios in Billion €.



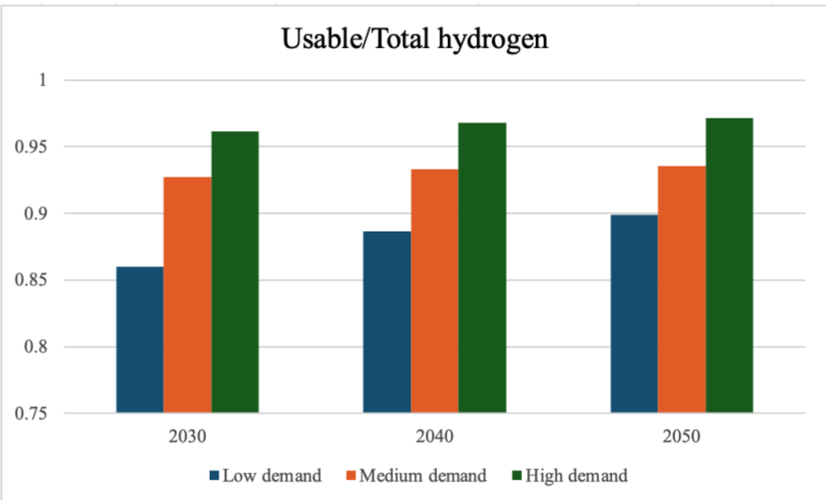
CAPEX comparison demand scenarios.



Total costs over all years comparison demand scenarios.

The same trends that were visible in the low and medium supply scenario again become apparent in the high supply scenario with some small differences. The low demand scenario again sees large extra costs related to the long term storage of the excess supply, which are even higher as the total supply levels now surpass the low demand in al all years. Meanwhile the medium and high demand scenario require little storage as most of the supply is consumed immediately.

The high demand scenario now does have the highest PSA CAPEX spending, indicating that at times enough hydrogen is stored that the entire hourly demand can be extracted when there is no wind. This would require higher PSA spending as the CAPEX of the PSA installations depend on the maximum feed rate of the installation. Additionally, the medium demand scenario now has PSA OPEX indicating that the highest absolute amount of hydrogen is extracted from the salt caverns. These increased usages of PSA are again visible in the ratios of usable and available hydrogen, illustrated in the figure below. With the low demand scenario coming closer to the ratio of the medium scenario, and the high scenario having a lower ratio as well.



Ratio of usable and total hydrogen in demand scenarios.

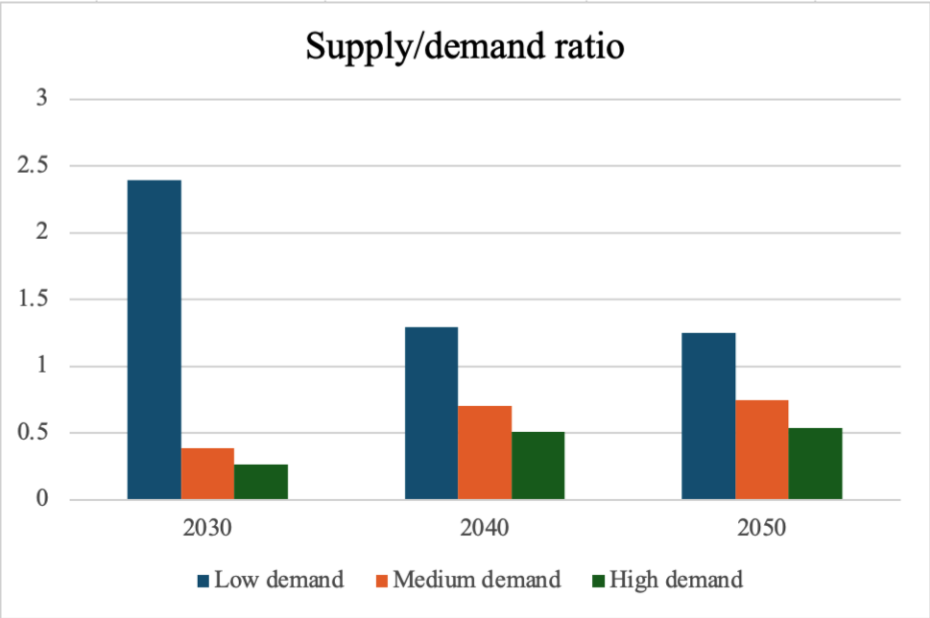
In the table below are the costs per kilogram of hydrogen for the different demand scenarios can be found. Interestingly, they are all higher than the cost per kilogram in the medium supply scenario. The increased supply levels now lead to a significantly higher cost for the low demand scenario as additional long term storage is now required in other years as well.

Although the costs for the medium and high scenario only increase with 1 cent, this might indicate that this price approaches the lowest value obtainable.

Cost €/kg	Low demand	Medium demand	High demand
2030	11.56	7.14	6.65
2040	2.7	1.33	1.24
2050	1.93	0.79	0.7

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

Again these cost values need to be placed in the perspective of the ratio of the supplied demand, which are illustrated in the figure below. The low demand can now be fully supplied in all years, while the medium demand reaches 74% in the year 2050. The high demand can be supplied for 54% in 2050.



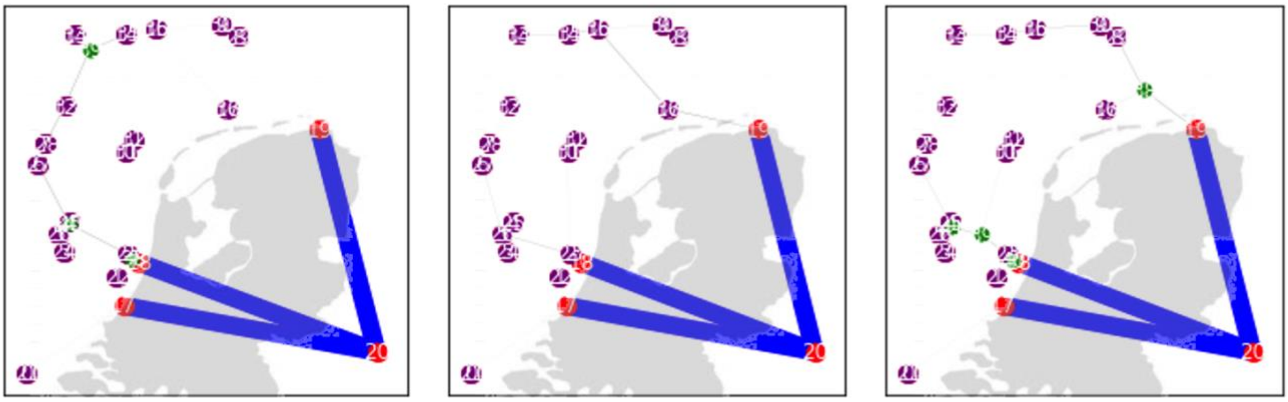
Supply and demand ratios high supply scenario.

Pipelines offshore storage

Unlike in the pipelines with central storage system configuration, in the offshore storage configuration the networks found do differ for the different demand scenarios. This is due to the fact the model will try to minimize the costs required to deliver all supply to either the source of the demand or a storage facility if there is an excess of supply. As the storage facilities are now located at the wind farms instead of at the super-sink together with the demand, the model now finds different routes when different demand are set.

Low supply

In the figure below are the resulting networks for the different demand scenarios in the low supply scenario. As can be seen three very different topologies emerge

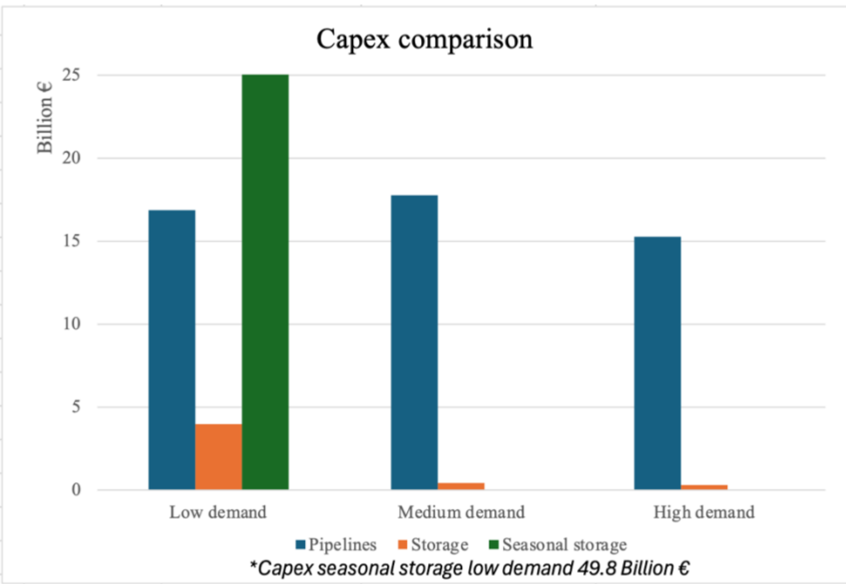


Network topologies demand scenarios low supply.

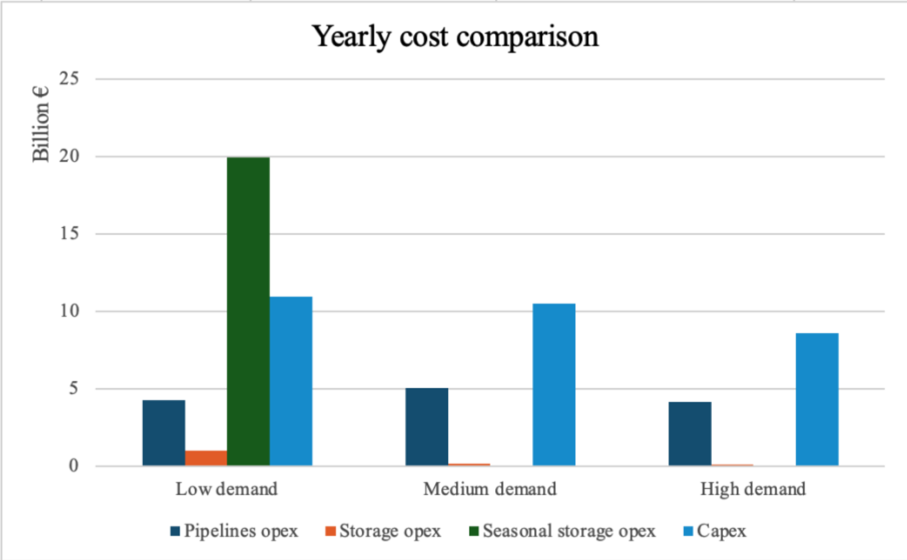
In the table below are the total costs for the different demand scenarios, followed by a breakdown of the CAPEX costs and yearly operation costs in the figures below respectively.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	70.7	18.2	15.5
OPEX	86	15.7	12.8
Total cost	95.9	23.4	19.8

Cost of low supply scenarios in Billion €.



CAPEX comparison demand scenarios.



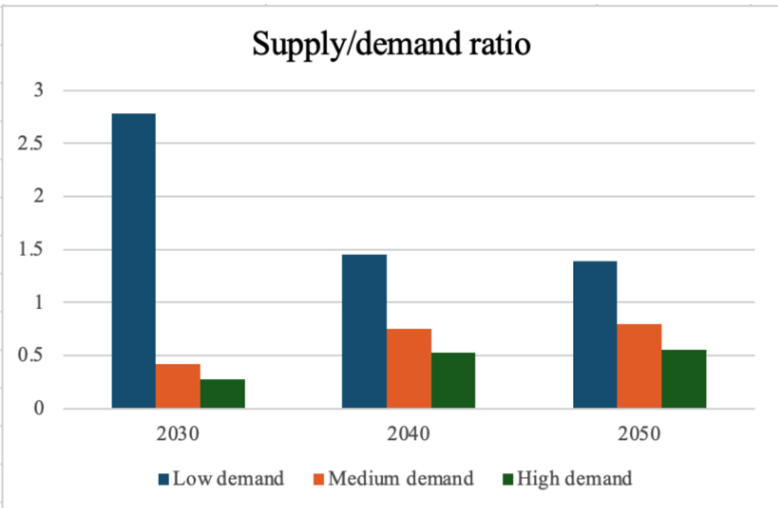
Total costs over all years comparison demand scenarios.

As can be seen from the table and the cost breakdown figures, the total cost is the highest for the low demand scenario. This is due to the extra CAPEX required for seasonal storage caused by the excess of supply. Interestingly, the CAPEX required for the pipelines is lowest in the high scenario, where it converges to the same cost of the network with the onshore storage. While the CAPEX required pipelines for the medium demand is the highest, followed by the low demand scenario.

In the table below the total yearly cost per kg of hydrogen delivered can be seen, accompanied by the supply and demand ratios of the demand scenarios. As there are no processes that reduce the total amount of hydrogen in this system configuration, these ratios represent the total amount of hydrogen produced.

Cost €/kg	Low demand	Medium demand	High demand
2030	23.85	4.2	3.34
2040	9.15	1.7	1.48
2050	1.42	1.07	0.94

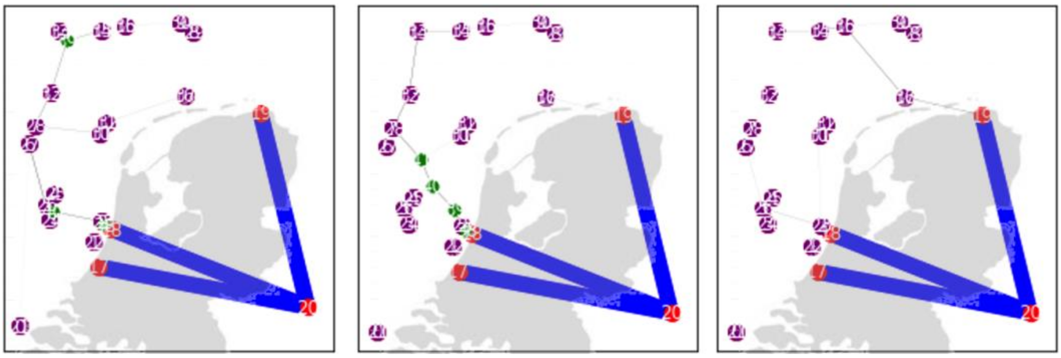
Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.



Supply and demand ratios low supply scenario

Medium supply

In the figure below are the optimal networks for the different demand scenarios in the medium supply scenario. Again three distinctly different topologies emerge.

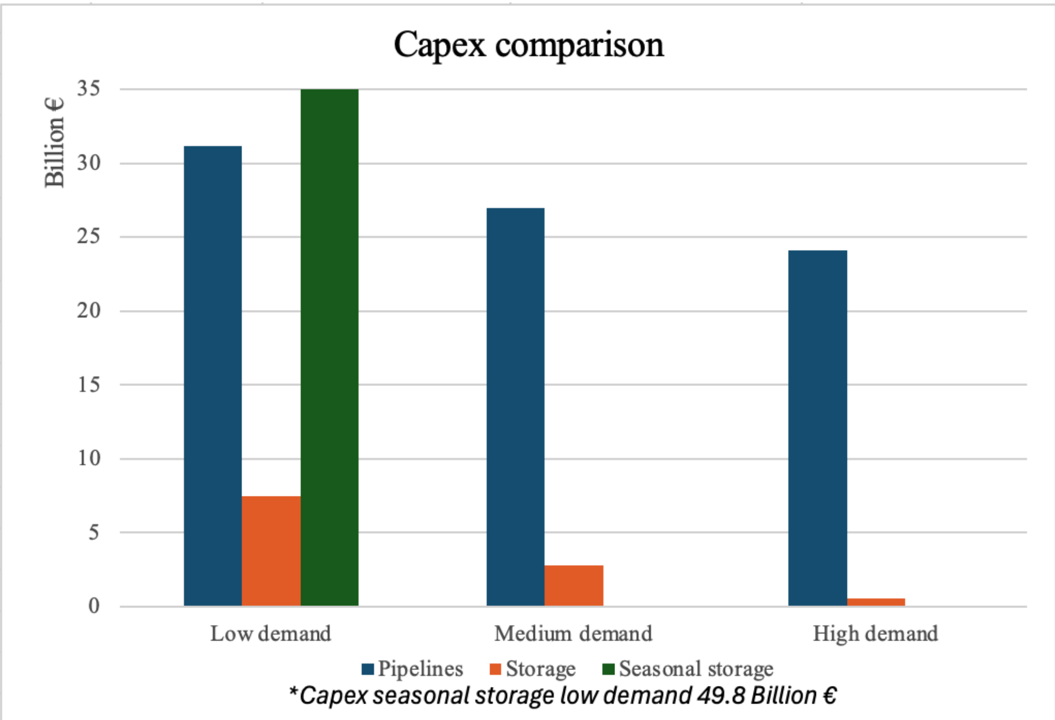


Network topologies demand scenarios in medium supply scenario.

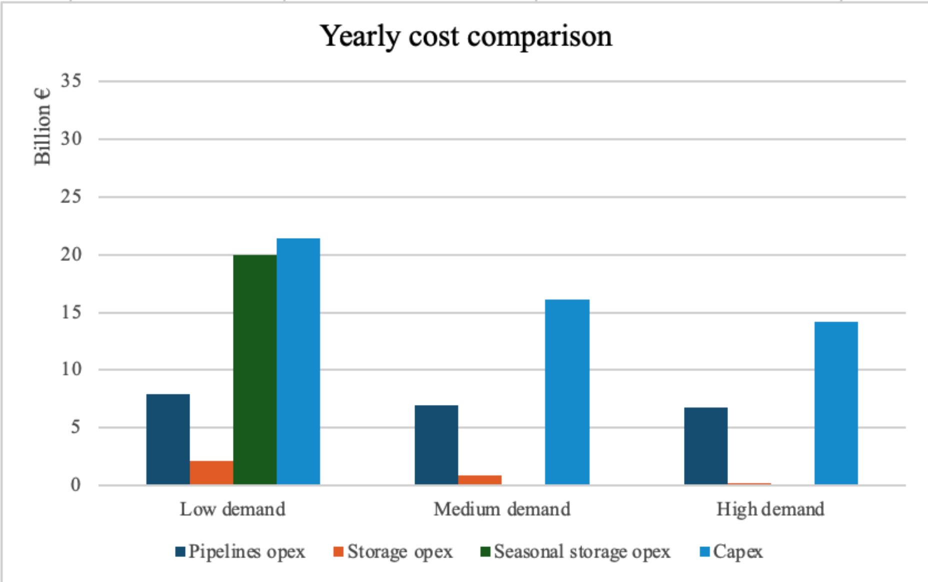
In the table below are the total costs for the system configuration for the different demand scenarios, followed by a breakdown of the total CAPEX and OPEX cost in the figures below respectively.

	Low Demand	Medium Demand	High Demand
CAPEX	88.4	29.7	24.7
OPEX	101.3	23.9	21.2
Total cost	118.5	37.6	31.7

Cost of medium supply scenarios in Billion €.



CAPEX comparison demand scenarios.



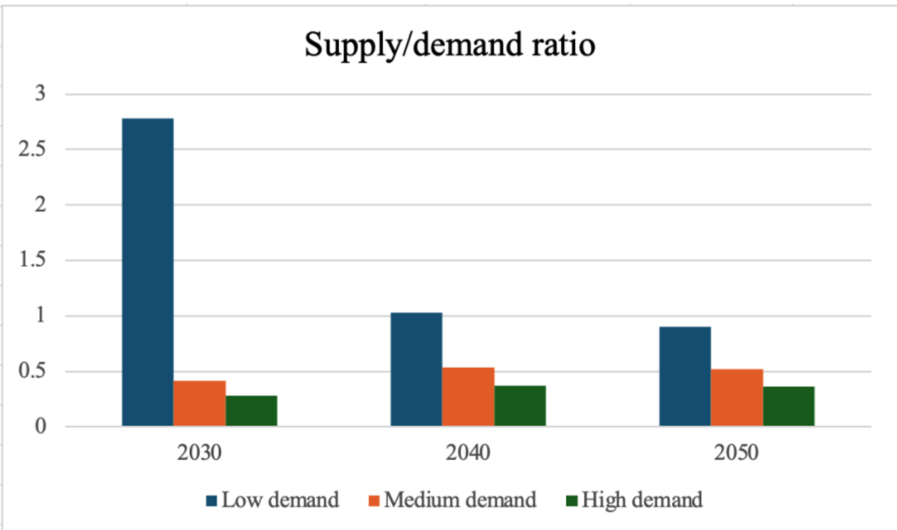
Figure…: Total costs over all years comparison demand scenarios

As can be seen in the figures above, the low demand scenario is still the most expensive due to the additional storage requirements. The CAPEX required for the pipelines is now the highest in the low demand scenario and again the lowest in the high demand scenario.

Cost €/kg	Low demand	Medium demand	High demand
2030	27.01	5.41	5.52
2040	5.9	1.56	1.26
2050	1.26	0.95	0.73

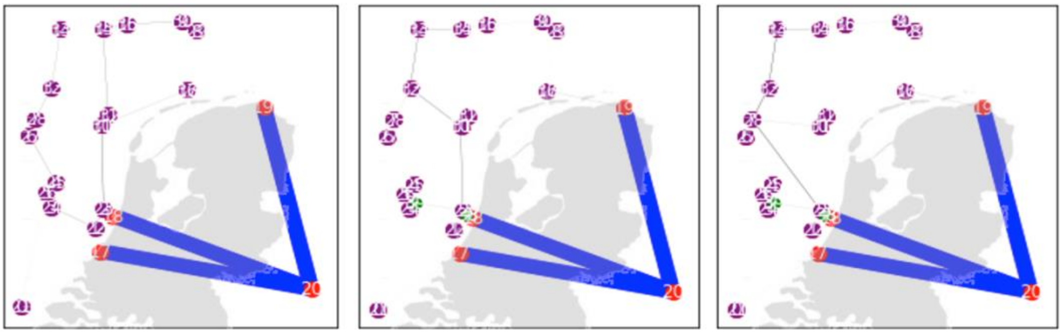
Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

The total yearly costs per kilogram of hydrogen of the demand scenarios, are similar to the low supply scenario in terms of how they relate to each other. Again these costs need to evaluated in the context of the ratio of the supply demand, illustrated in the figure below.



Supply and demand ratios low supply scenario

<u>High supply</u>
The following network topologies were found for the various demand scenarios within the high supply scenario.

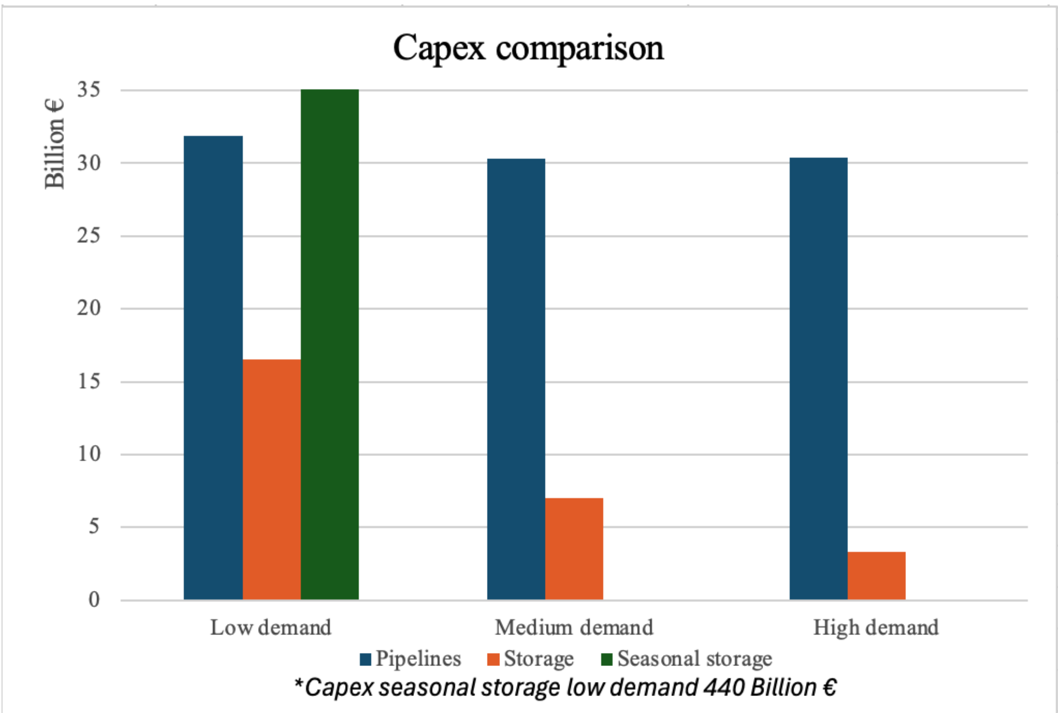


Network topologies demand scenarios in high supply scenario.

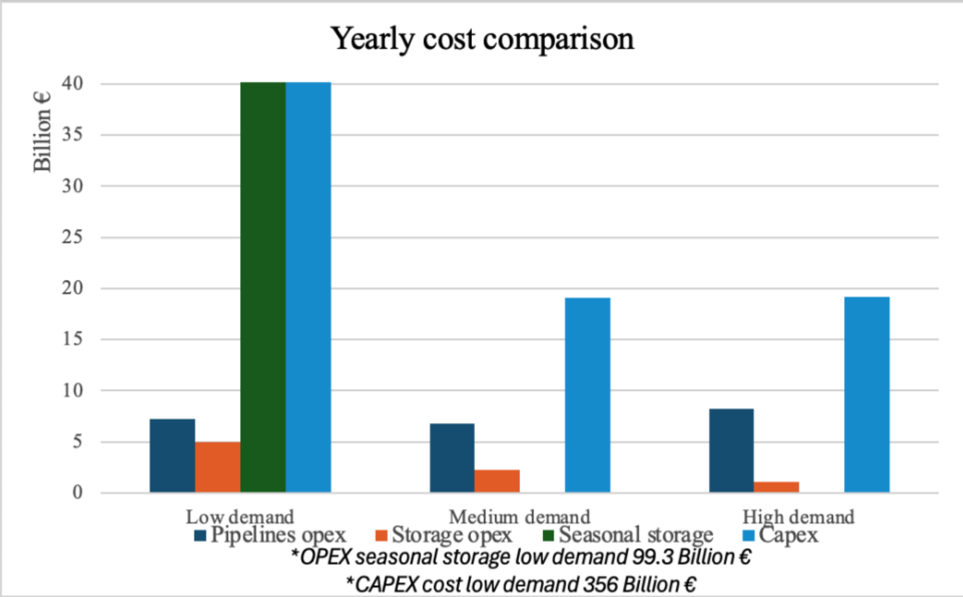
In the table below the total costs for the demand scenarios is listed, followed by a breakdown of the CAPEX and OPEX costs associated with the system components.

	Low Demand	Medium Demand	High Demand
CAPEX	488.6	37.3	33.7
OPEX	467.9	28.1	28.5
Total cost	600.2	46.3	43

Cost of high supply scenarios in Billion €.



CAPEX comparison demand scenarios.



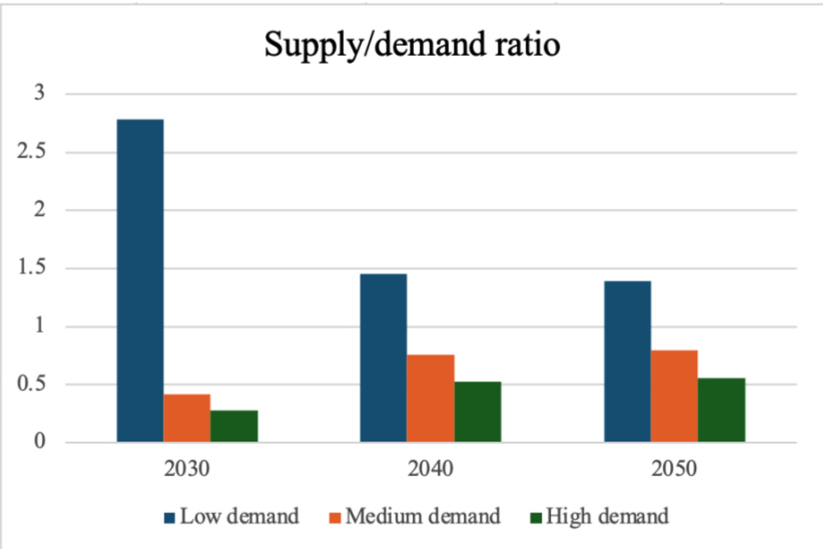
Total costs over all years comparison demand scenarios

Again the high demand scenario has the lowest overall cost, and the lowest pipelines CAPEX. With the low demand scenario being the most expensive due to its high storage requirements.

In the table below are the total yearly costs per kilogram of hydrogen delivered for the demand scenarios, followed by their respective supply and demand ratios.

Cost €/kg	Low demand	Medium demand	High demand
2030	47.62	4.86	6.57
2040	16.89	1.44	1.23
2050	13.13	0.85	0.69

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.



Supply and demand ratios high supply scenario

Ship transportation

For both the shipping system configurations, the optimum routes for the ships to collect the hydrogen has been found using the clustering algorithm. The different demand scenarios have no influence on the cost of collecting the produced hydrogen, they do however influence the systems that are required onshore such as the dehydrogenation and PSA capacities required, and the amount of onshore storage needed. Another important distinction between the pipeline alternatives and the shipping alternatives, is that the clustering was performed on the hydrogen production for one week. Meaning that the hydrogen is supplied to land in batches instead of continuously.

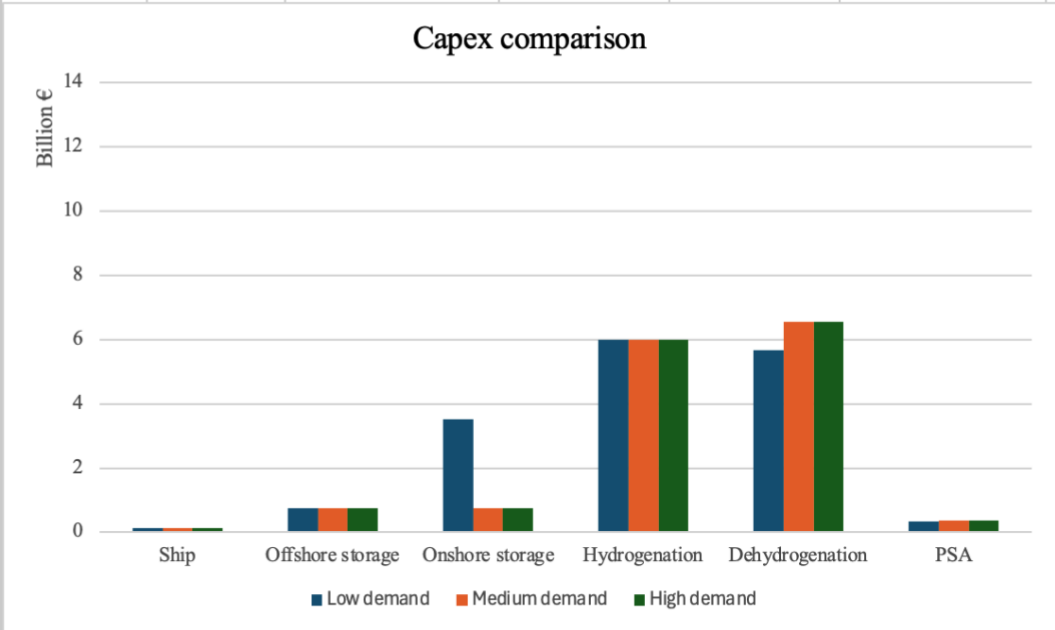
Ammonia shipping

<u>*Low supply*</u>

In the table below are all costs for the different facilities and operations required under the different demand scenarios, followed by a figure containing a breakdown of the CAPEX costs.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	16.3	14.5	14.5
OPEX	36.4	32.4	32.4
Total cost	40.4	37.6	37.6

Cost of low supply scenarios in Billion €.



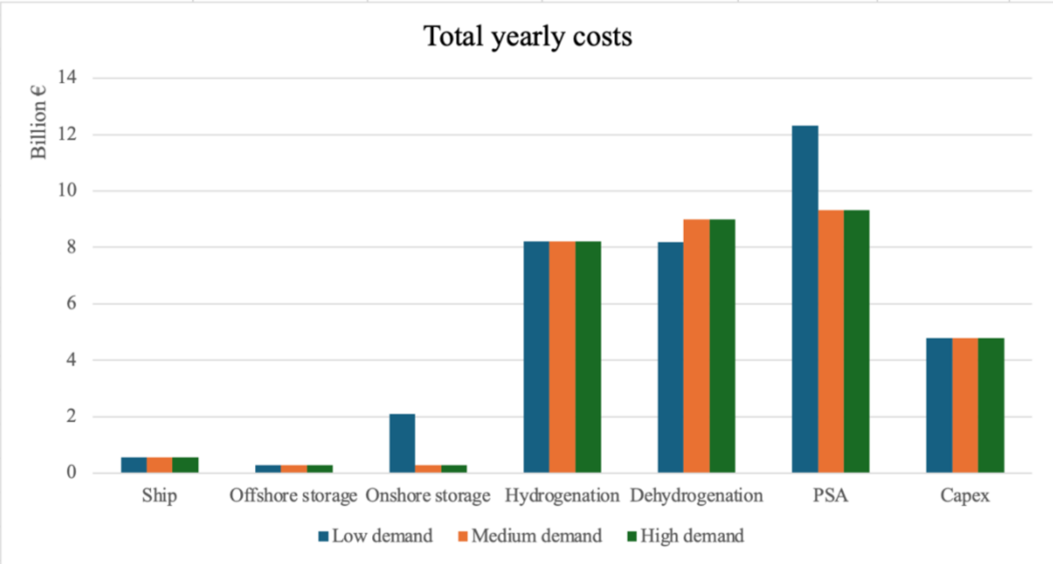
CAPEX comparison demand scenarios.

In all demand scenarios the driving costs are the required CAPEX for the hydrogenation and dehydrogenation facilities. With the storage, PSA and ships only being a small part of the total CAPEX.

What is immediately apparent is that the costs are for the most part equal. For the investments in ships and offshore storage facilities this is logical as these are not affected by the demand, and they are based on the same supply data. The hydrogenation also follows from the available supply, as the supply dictates how much hydrogen needs to be synthesised into ammonia per day.

The onshore storage, dehydrogenation and PSA capacities however are influenced by the demand scenarios. However due to the batched nature of transporting the hydrogen with ships, if the supply is lower than the demand the costs for these facilities converge to an equilibrium. The onshore storage that is required in the event the supply is higher than the demand, is the sum of the supply for 1 week plus the excess supply of all other weeks in the year.

A breakdown of the operational costs for each year can be seen in the figure below. Similarly to the CAPEX costs, the OPEX costs converge to handle to all available supply when the supply is lower than the demand.



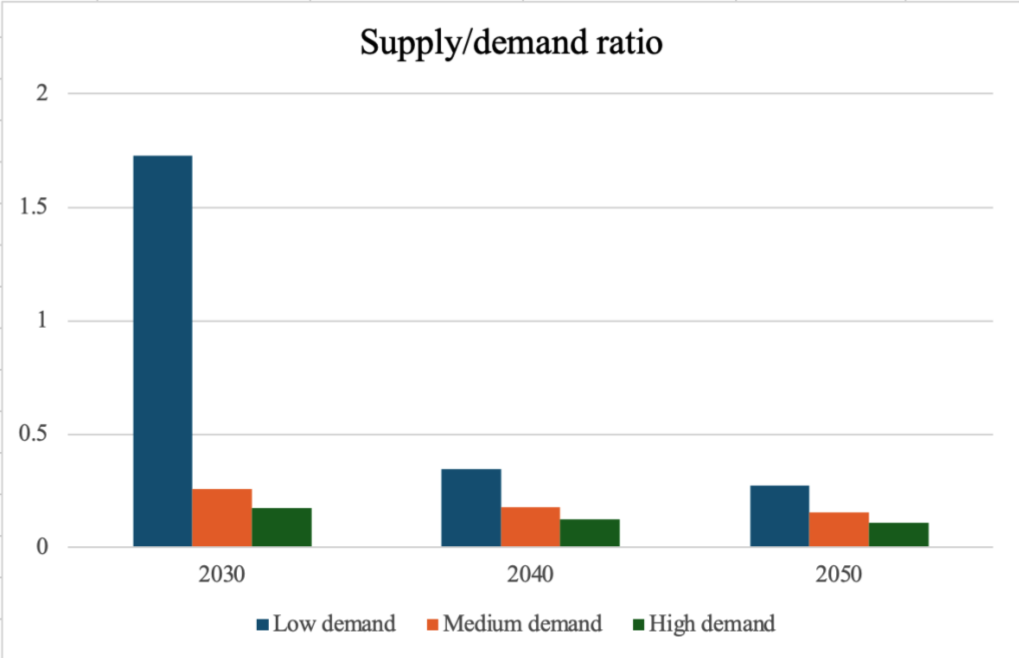
Total costs over all years comparison demand scenarios.

These total cost values for the demand scenarios lead to the final cost per kilogram of hydrogen. These can be seen in the table below.

Cost €/kg	Low demand	Medium demand	High demand
2030	5.77	5.7	5.7
2040	4.91	4.5	4.5
2050	4.28	3.95	3.95

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

Again the total cost per kilogram of hydrogen is similar for all demand scenarios due to the batched nature of the transportation. Again these values need to be put in the perspective of the supply and demand ratio. These can be seen in the figure below.



Figure…: Supply and demand ratios low supply scenario

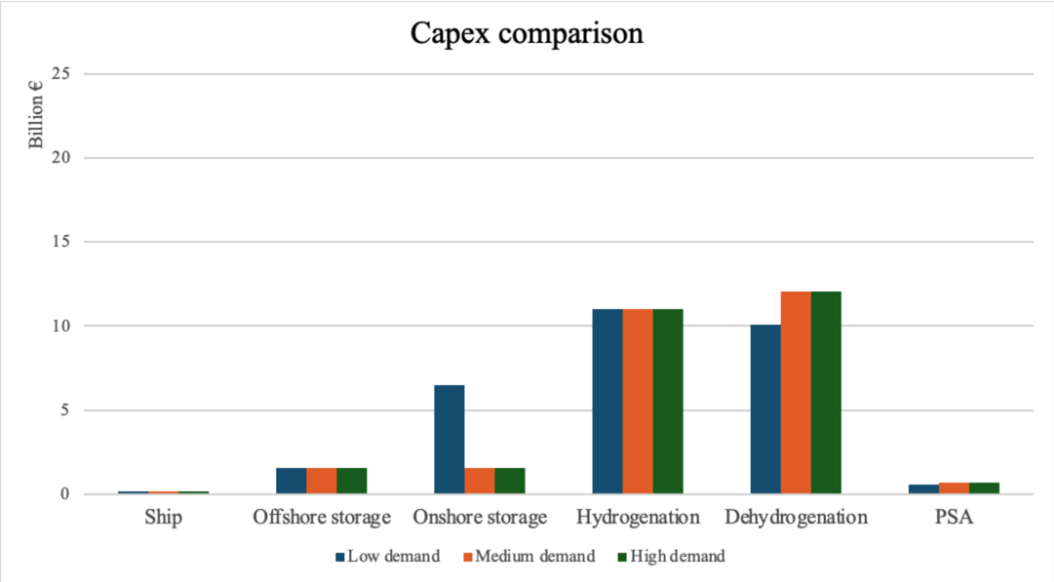
As can be seen, the supply and demand ratios are significantly lower than in the pipeline alternatives. This is due to the fact that all ammonia needs to undergo two processes subject to hydrogen losses to become usable as hydrogen. The PSA has a hydrogen recovery ratio of 80%, while the dehydrogenation of ammonia has a hydrogen recovery ratio of 77.6%. This means that of all available hydrogen only 62.08% can be used when using the ammonia shipping system configuration.

Medium supply

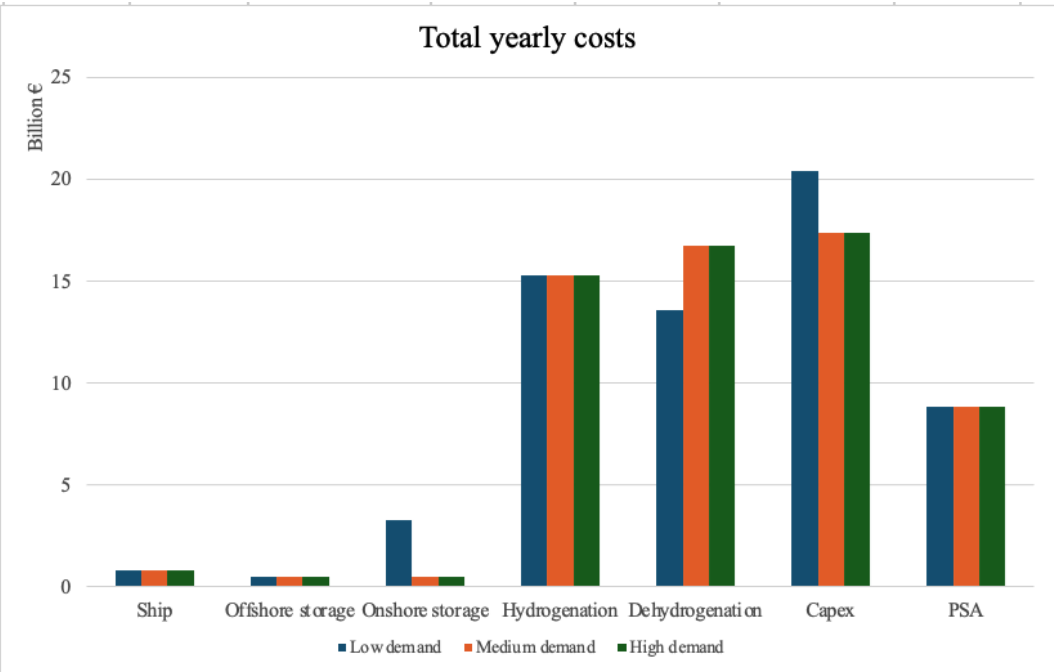
In the table below are the total cost figures for the different demand scenarios for the medium supply scenario accompanied by the breakdown of the CAPEX required and operational expenses in the figures below respectively.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	29.8	26.9	26.9
OPEX	62.8	60.1	60.1
Total cost	72.2	69.6	69.6

Cost of medium supply scenarios in Billion €



CAPEX comparison demand scenarios.



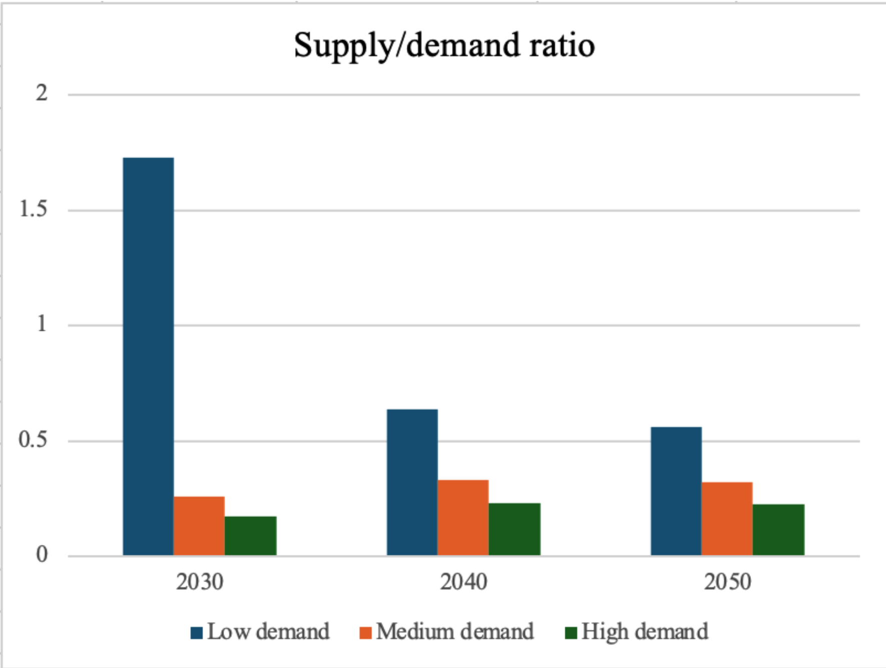
Total costs over all years comparison demand scenarios.

In the table below are the total costs per kg of hydrogen for the different demand scenarios. From the CAPEX and yearly costs breakdown it became apparent that the trend of the low supply scenarios is still present, with the low demand scenario being more expensive due to the need for extra storage. The cost per kilogram of hydrogen supplied however drops the most for the low demand scenario, coming down €0.20 per kg delivered, compared to a €0.01 drop in cost per kg for the medium and high demand scenarios.

Cost €/kg	**Low demand**	**Medium demand**	**High demand**
2030	7.44	7.03	7.03
2040	4.7	4.56	4.56
2050	4.09	3.95	3.95

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

At these cost the supply and demand ratios illustrated in the figure below can be supplied.



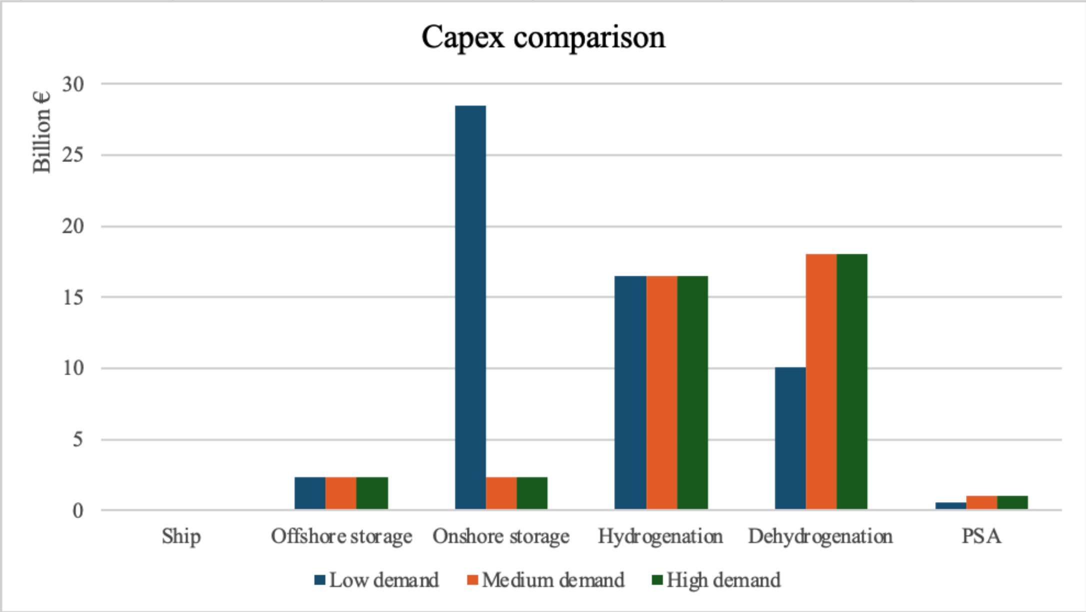
Supply and demand ratios medium supply scenario.

<u>High supply</u>

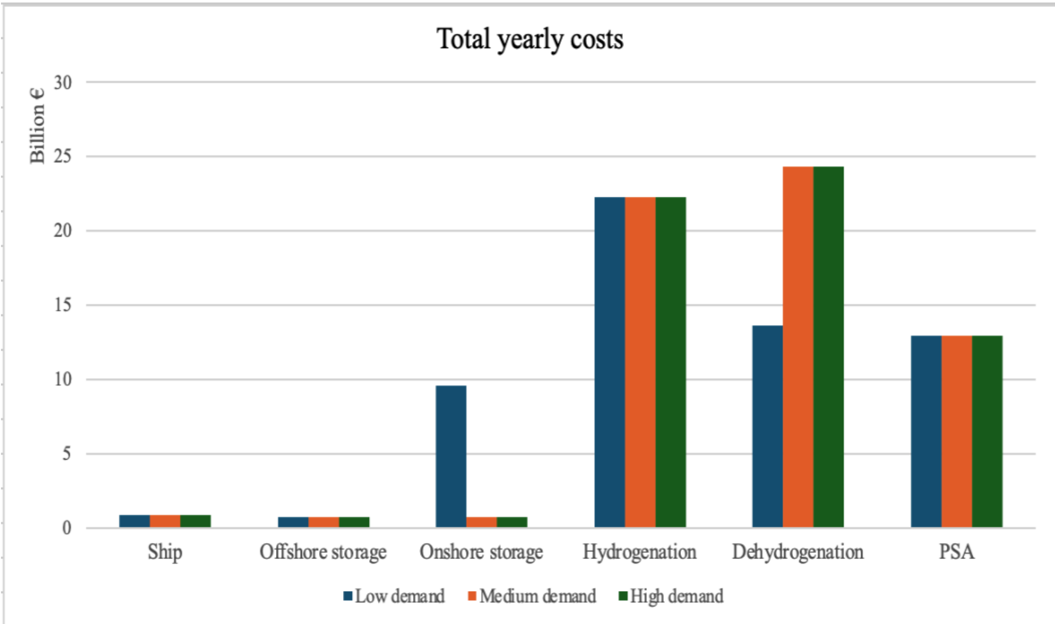
In the table below are the total cost figures for the different demand scenarios for the high supply scenario followed by the breakdown of the CAPEX required and operational expenses in the figures below respectively.

	Low Demand	**Medium Demand**	**High Demand**
CAPEX	58.1	40.4	40.4
OPEX	95	86.6	86.6
Total cost	118	102.3	102.3

Cost of medium supply scenarios in Billion €



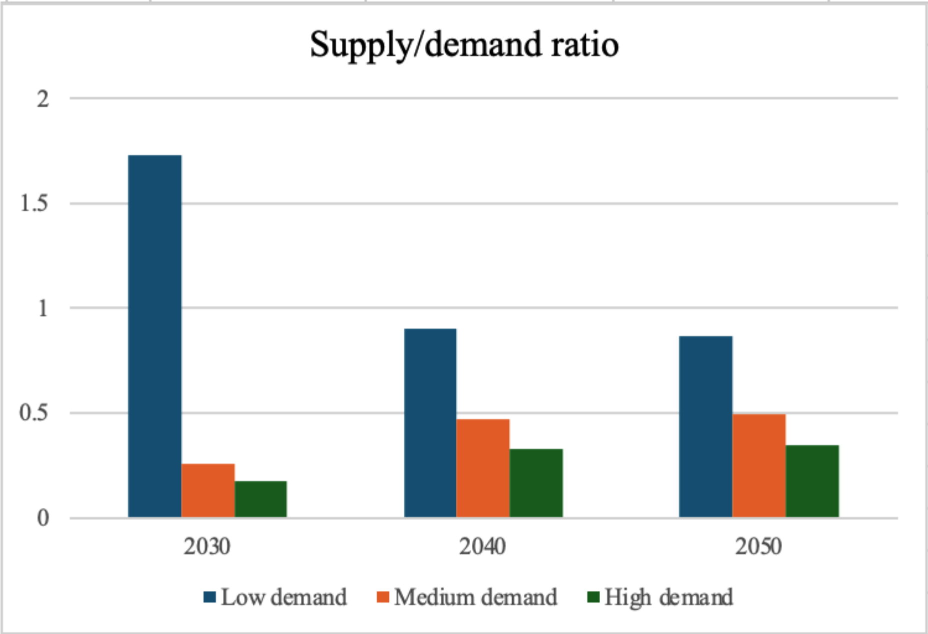
CAPEX comparison demand scenarios.
Total costs over all years comparison demand scenarios.



Cost €/kg	Low demand	Medium demand	High demand
2030	11.63	8.94	8.94
2040	5.13	4.55	4.55
2050	4.54	3.97	3.97

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

Again the same pattern can be seen in the costs of the demand scenarios, with the low demand being more expensive due to the excess supply, and the medium and high demand scenario reaching an equilibrium of spending exactly enough to process all supply. In the figure below the corresponding supply and demand ratios for the demand scenarios are illustrated.



Supply and demand ratios high supply scenario.

Due to the combined losses of the dehydrogenation cycle and the PSA purification, the gap between the potential supply and the demand scenario is larger than in the other system configurations. For the low demand scenario only 86% can be supplied in high supply scenario, compared to 50% and 36% for the medium and high demand scenarios respectively.

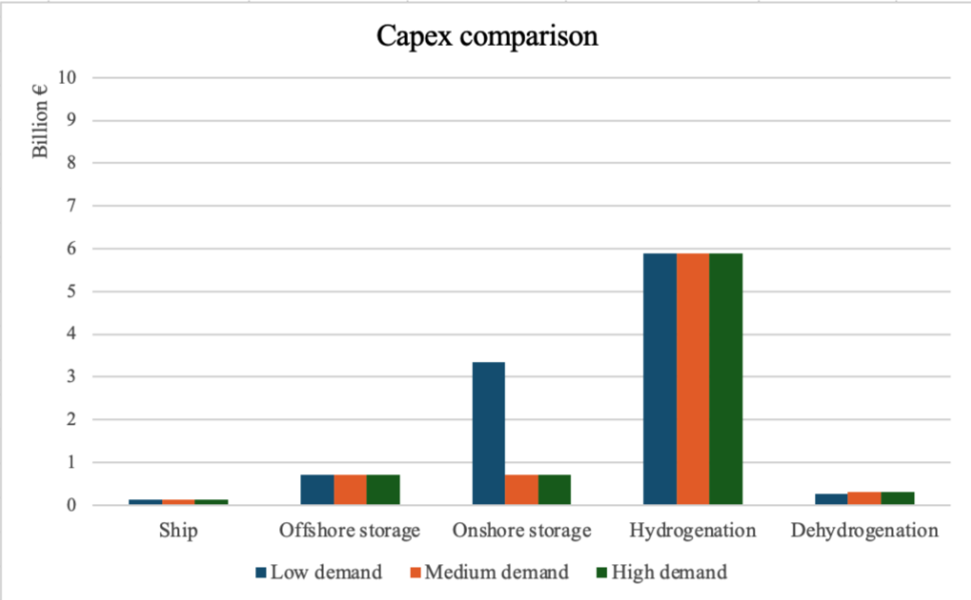
LOHC shipping

<u>*Low supply*</u>

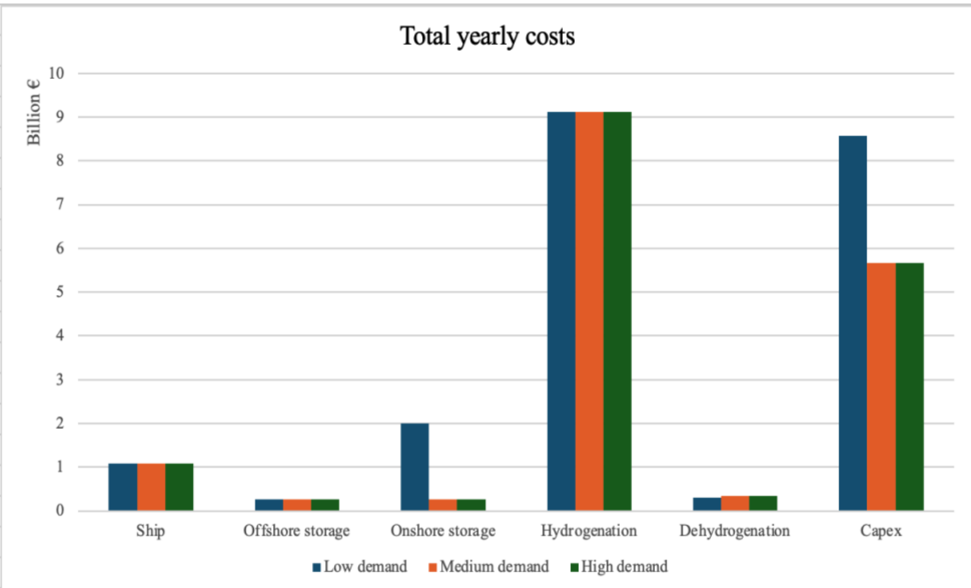
In the table below are the costs for the different demand scenarios for the low supply scenario of the LOHC shipping system configuration, followed by the CAPEX breakdown and total yearly costs in the figures below.

	Low Demand	Medium Demand	High Demand
CAPEX	10.3	7.8	7.8
OPEX	21.3	16.7	16.7
Total cost	23.1	18.8	18.8

Cost of low supply scenarios in Billion €



CAPEX comparison demand scenarios.



Total costs over all years comparison demand scenarios.

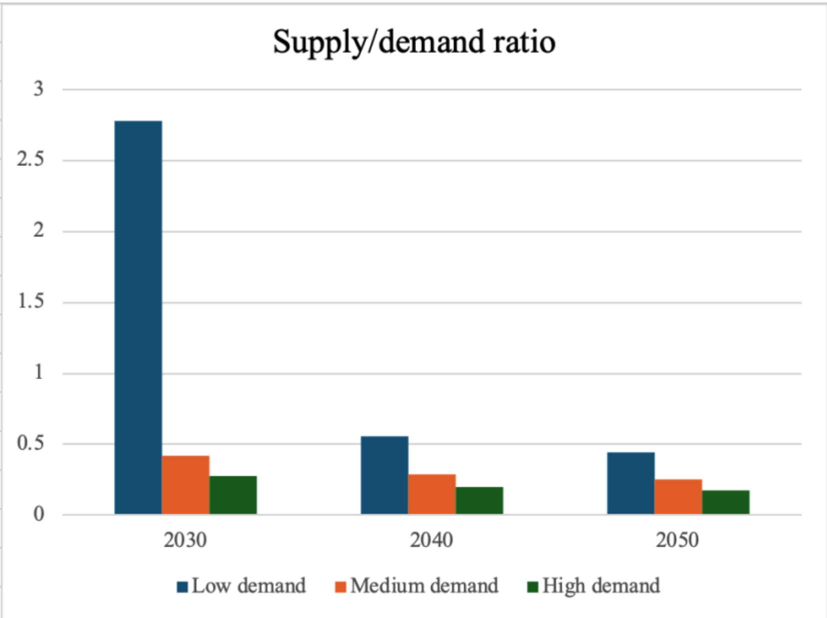
From looking at the costs for the different demand scenarios, two observations become apparent. The first being that the same trend emerges as in the ammonia system configuration, with the required capacities of the facilities converging to suit the available supply when the demand is higher. While an increase in storage becoming necessary when the demand is lower than the supply.

The second observation being that due to the lower CAPEX and OPEX of the dehydrogenation process, the total costs are significantly lower compared to the Ammonia option. This lower cost is also reflected in the total cost per kilogram of hydrogen delivered, as shown in the table below.

Cost €/kg	**Low demand**	**Medium demand**	**High demand**
2030	2.47	1.59	1.59
2040	1.58	1.29	1.29
2050	1.52	1.34	1.34

Yearly total cost per kg of hydrogen delivered in the different demand scenario.

Again it is important to evaluate these costs in the context of the total demand that can be supplied. Which in the case of LOHC is equal to the total amount of hydrogen produced, as the dehydrogenation cycle has a 100% recovery rate of hydrogen and requires no further purification steps meaning no hydrogen is lost in the process of transporting and storing the hydrogen prior to being consumed.

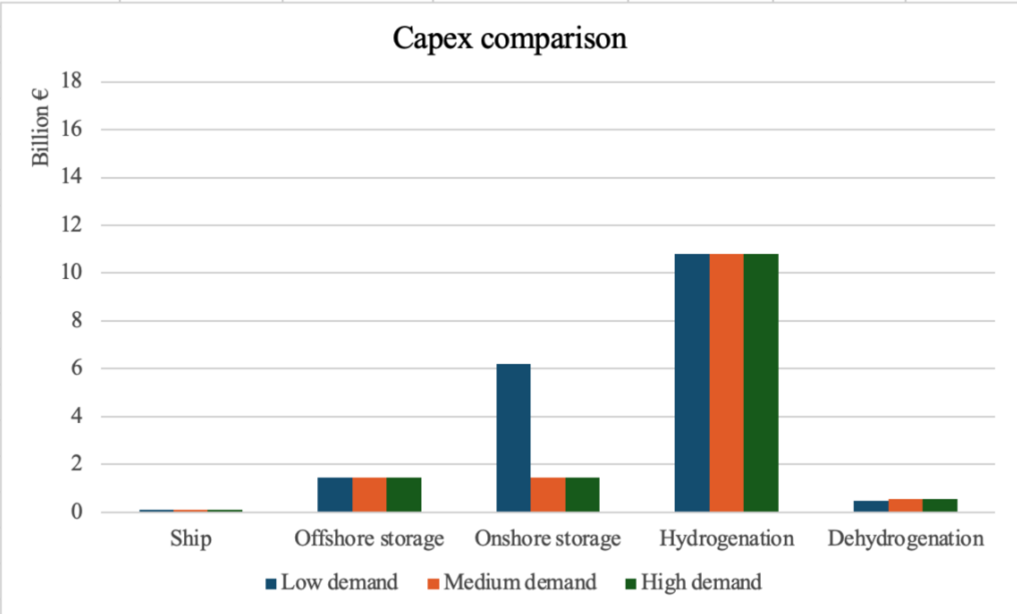


Supply and demand ratios high supply scenario.

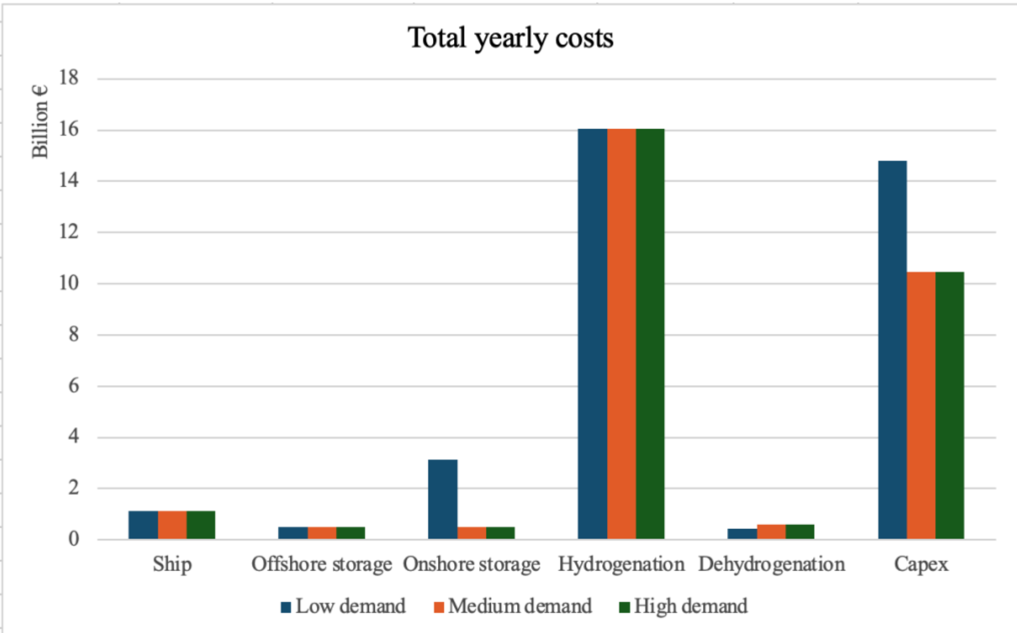
Medium supply
In the table below are the costs for the different demand scenarios for the medium supply scenario of the LOHC shipping system configuration, followed by the CAPEX breakdown and total yearly costs in the figures below respectively.

	Low Demand	Medium Demand	High Demand
CAPEX	19.2	14.5	14.5
OPEX	36.1	29.3	29.3
Total cost	40.5	33.3	33.3

Cost of medium supply scenarios in Billion €.



CAPEX comparison demand scenarios.



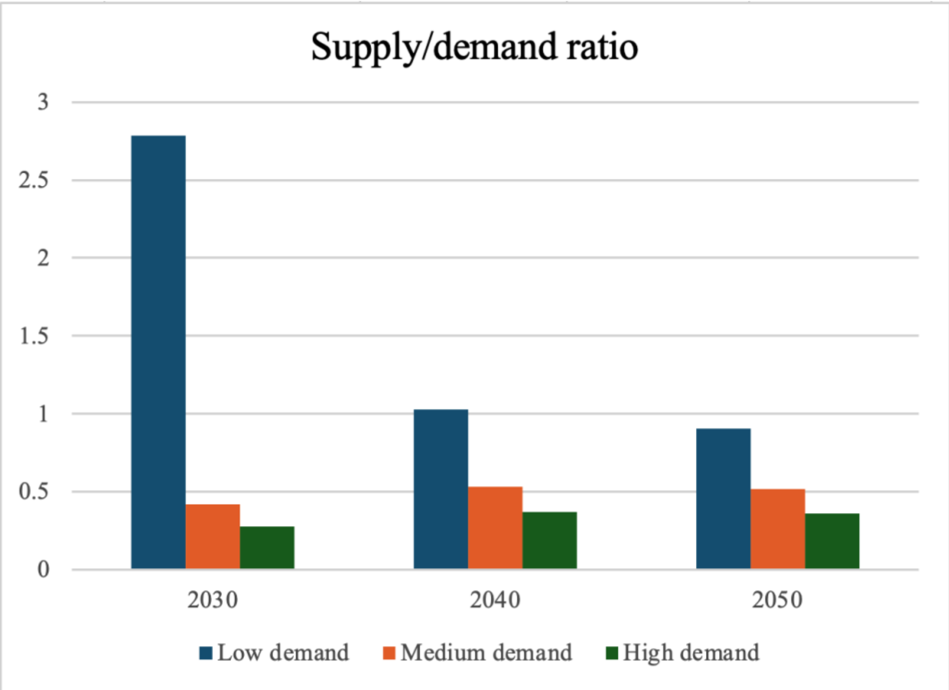
Total costs over all years comparison demand scenarios.

The low demand scenario is again more expensive due to the need for extra storage onshore. The gap between its cost per kilogram hydrogen and the costs for the medium and high demand scenarios, which are listed in the table below, remains comparable to the low supply scenario. This can be explained by the supply and demand ratios in the figure. As the excess of supply for the low demand scenario only just surpasses the demand in 2040, and in 2050 the low demand can no longer be met leading the system configuration to converge to the same costs as the other demand scenarios.

Cost €/kg	Low demand	Medium demand	High demand
2030	2.95	1.96	1.96
2040	1.61	1.29	1.29
2050	1.39	1.23	1.23

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.

Supply and demand ratios medium supply scenario.

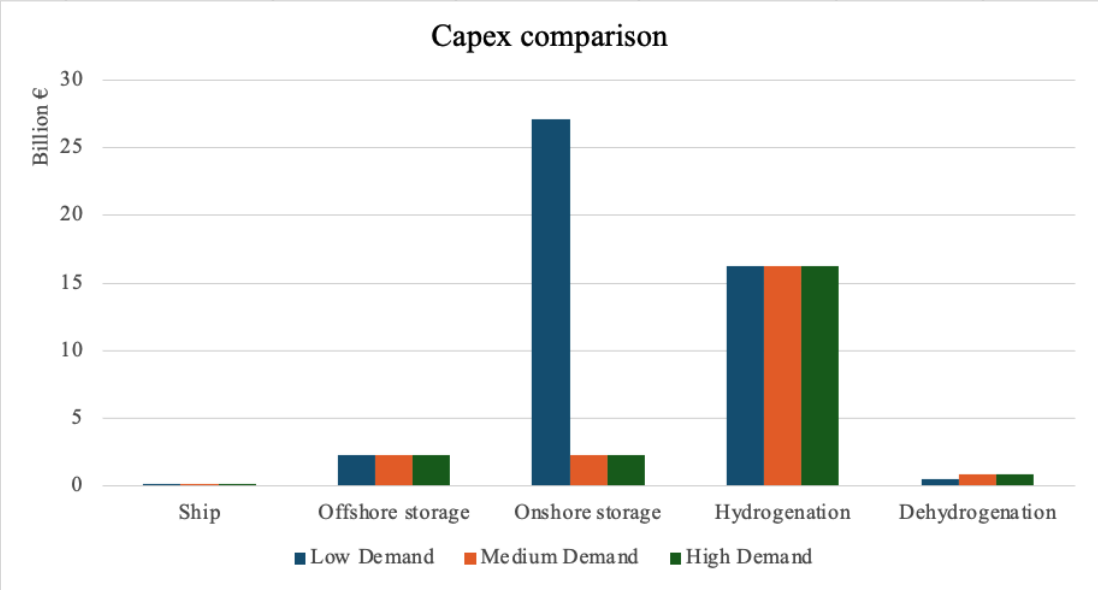


High supply

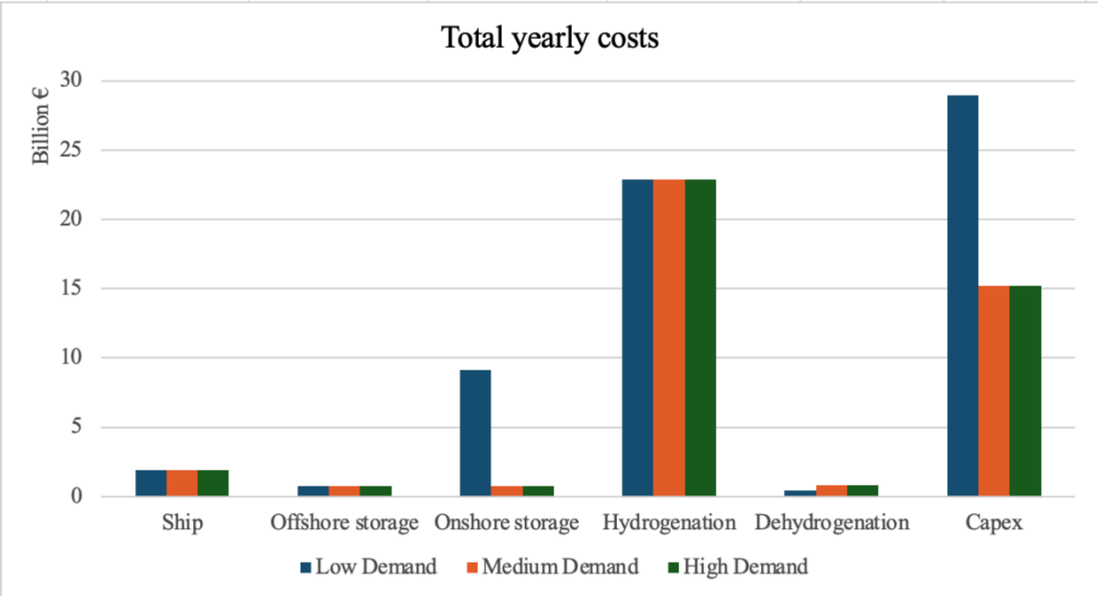
In the table below are the costs for the different demand scenarios for the high supply scenario of the LOHC shipping system configuration, followed by the CAPEX breakdown and total yearly costs in the figures below.

	Low Demand	Medium Demand	High Demand
CAPEX	46.2	21.8	21.8
OPEX	64	42.2	42.2
Total cost	81.3	48.8	48.8

Cost of high supply scenarios in Billion €.



CAPEX comparison demand scenarios

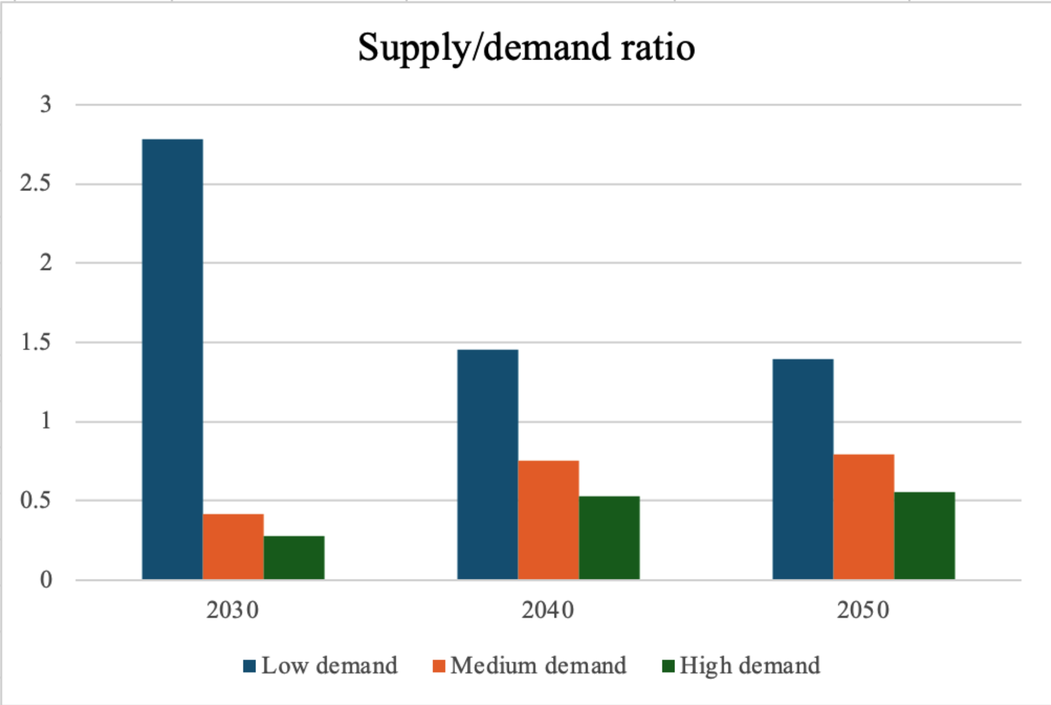


Total costs over all years comparison demand scenarios.

Again the low demand scenario is more expensive as there is an even higher need for onshore storage, while the medium and high demand scenarios reach the equilibrium. The gap between the costs does increase however, this is due to the fact the low demand can now also be fully satisfied in 2050. This is also reflected in the yearly cost per kilogram of hydrogen delivered, as listed in the table below. In the figure on the next the supply and demand ratios are illustrated for the respective demand scenarios.

Cost €/kg	**Low demand**	**Medium demand**	**High demand**
2030	5.43	2.45	2.45
2040	2.15	1.3	1.3
2050	1.93	1.22	1.22

Yearly total cost per kg of hydrogen delivered per year in the different demand scenario.



Supply and demand ratios high supply scenario.