A Dutch hydrogen supply chain in 2050: a demand forecast and economic study of viable hydrogen production, storage and transport

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Abstract

In this thesis, a hydrogen supply chain for the Netherlands for the year 2050 is investigated. We gather national hydrogen estimates which we break down into regional NUTS3 demand using various data sources. Then, we gather costs and performance estimates of production, storage and transport of hydrogen, which we incorporate into a mixed integer linear programming (MILP) model. The results show that the largest part costs of the supply chain are in production of hydrogen. Moreover, we conclude that truck transport is a viable alternative to a pipeline network. This conclusion is robust against extreme demand scenarios. Lastly, we show that the capacity of the pipeline network will likely be exceeded, hinting at a need for future expansion of the network for a future hydrogen supply chain.

Keywords: Hydrogen supply chain, demand forecast distribution, mixed integer linear program

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Contents

1 Introduction

In 2015, the world signed and committed to limit the warming of the Earth below 1.5 degrees Celsius. While European governments are well underway in stimulating renewable energy production on sea and land, a large part of our energy needs still depends on energy carriers such as oil and natural gas (IEA, 2020). To limit this use, a big role is expected to be given to hydrogen. For example, the Dutch target is to replace 4% of its energy needs by hydrogen by 2030. (Ministerie van Economische Zaken en Klimaat, 2019b; CBS, 2018). Hydrogen is namely able to replace fossil fuels as it is able to act as feedstock for the chemical and manufacturing industry and for electricity power (Ministerie van Economische Zaken en Klimaat, 2019a). Moreover, hydrogen can be used as a fuel for road and shipping transport and as an energy source for household heating (Gallucci, 2021; BBC News, 2020, 2021; National Grid Group, 2020). In all these functions, hydrogen provides CO2-free power form which can be stored for longer periods (Ministerie van Economische Zaken en Klimaat, 2019a).

Nevertheless, some things still are unclear around the future of hydrogen. First, the Dutch government decided to completely leave the design of the production to the market in terms of hydrogen location and production size (Ministerie van Economische Zaken en Klimaat, 2019b). Yet, if we know what the hydrogen demand will be in each location, it would be better to know where and how much production is needed to facilitate this demand. Secondly, Netbeheer Nederland, a consortium of Dutch gas and electricity providing companies, assumes that all hydrogen transport will be performed by pipeline, while truck transport could also be a viable option (Netbeheer Nederland, 2021). In short, the ambivalence of the Dutch government together with the assumptions of Netbeheer Nederland leaves us to question whether the future supply chain in the Netherlands will be constructed efficiently, let alone feasibly. Inefficient production and storage locations might namely force the transport network of hydrogen to become expensive or infeasible. Consequently, the future hydrogen supply chain could become unnecessarily complicated and expensive, hindering a path to clean and renewable energy.

Finding out the feasible and most efficient configuration of production, storage and transport is exactly what we will be tackling in this thesis. Using the found optimal supply chain, we answer three hypotheses. Our first hypotheses answers which parts of the hydrogen supply chain are most costly. Then, our second and third hypotheses evaluate which transport modes are most efficient for the case of the Netherlands, and whether these modes are feasible. To do this, we first estimate the future hydrogen demand in the Netherlands for 2050. We discuss national hydrogen demand estimates, which we then distribute over each Dutch NUTS3 region using various data sources. Furthermore, we evaluate different cost and characteristics of different parts of the supply chain. Using this data, we formulate a new mixed-integer linear program (MILP) model to design the most cost-efficient supply chain in terms of production, storage and transportation. Our results show that the largest costs in the supply chain come from both the electricity use and the production of hydrogen. Furthermore, we conclude that pipeline and truck transportation are both economically competitive, depending on the transport volume. This result is robust against more extreme scenarios. More specifically, we find optimal supply chain networks which uses both pipeline and truck transport. Lastly, we conclude that in terms of the general network, the throughput of the pipeline network reaches throughput capacity in accommodating hydrogen in 2050. In more extreme scenarios this capacity is well exceeded. Therefore, pipeline capacity investments seem inevitable.

This paper aims to contribute to the literature of hydrogen supply chains through several ways. First, as the input of a given MILP model is crucial for its results we aim to estimate in detail both the hydrogen demand as well as the cost elements in the supply chain. While cost elements are well treated in the literature, the estimation of demand often relies on heavy assumptions.

For example, most literature compute the demand only for future hydrogen cars while it has become clear that most hydrogen demand will come from the industry and electricity power generation. Moreover, the spatial heterogeneity of estimated demand often relies on assumptions rather than specific data sources. In this thesis, we incorporate all sectors and also use detailed data sources to forecast the spatial heterogeneity of the demand. Secondly, most papers build upon older models, adding elements to it. This thesis creates a new formulation more geared towards our hypotheses, while still using the most important elements from the literature. We do this by making a formulation that can create a network of flows for pipelines as well as adding feasibility constraints specific for the Dutch context. These feasibility constraints contain rules for production locations and where it is possible to store hydrogen. These constraint help to increase the external validity of the results.

The answers to our hypotheses could be of relevance for governments and the industry for a few reasons. First, we know that feedstock and production costs are the main bottleneck in the supply chain. This information can be important for Dutch authorities by helping to alleviate any barriers from entering the hydrogen supply market. This could eventually lower the price of hydrogen and increase the chance of success for green renewable fuels. Furthermore, our results show that hydrogen transportation by truck and pipeline are both feasible. Consequently, Netbeheer Nederland has multiple options in facilitating hydrogen supply and demand. Moreover, for governments budgets and Netbeheer Nederland it is important to know that our results show that the existing network reaches capacity in a large part of the found pipeline network. Therefore, it is important for Netbeheer Nederland to already make plans to increase the maximum throughput.

The rest of this thesis proposal is organised as follows. First, a literature review on hydrogen supply chain is given and the hypotheses are presented in Section 2. Then, we treat the data for our model in Section 3. In Section 4 we present the methodology in the form of our model. Finally, in Section 5 and 6 we present our results and conclusions.

2 Literature

Since 2006 various papers have been written on the design and optimisation of future hydrogen supply chains within European countries. Most of them try to incorporate as many features as possible to arrive at such a complete supply chain configuration as possible. This thesis will try something different. Here, we focus on three different economic hypotheses which we adapt our mathematical model to. Therefore, we will not try to complete our supply chain model in detail, but rather implement more details which are important for each hypothesis.

In Section 2.1 we briefly discuss the main literature on hydrogen supply chain models. This is done to get an overview of the topic and to put the hypotheses into context. Using this overview, we address our contribution to shortcomings in the literature in Section 2.2. Finally, in Section 2.3 we will discuss our hypotheses through the use of more specific existing literature.

2.1 Hydrogen supply chain literature

A seminal paper in the field of hydrogen supply chain optimisation is the one from Almansoori and Shah (2006). Their model is one that many later works reference, replicate and extent. In their formulation for the UK, different blue hydrogen production (hydrogen production through fossil fuel) techniques are incorporated, as well as truck and train transportation and two types of hydrogen storage technologies. Their future hydrogen demand is estimated as the number of personal vehicles that adopt to hydrogen instead of diesel or gasoline.

Their work is extended in Almansoori and Shah (2009) where they extend their UK model to include multiple time periods, feedstock for hydrogen production and green hydrogen production (production only using renewable energy). Furthermore, due the way they optimise the model over different time periods, they also include a time varying demand for hydrogen. Their demand, however, is still based on road transport only.

Later Almansoori and Shah (2012) extend their work for the last time by also including the uncertainty of long-term variation in hydrogen demand. They do this by using scenario-based optimisation. Their demand thus depends on a scenario and is still mostly based on the assumption that the hydrogen demand in the model comes from the road transport sector.

Konda et al. (2011) implement the model of the second paper by Almansoori and Shah for the case of the Netherlands, which is particularly relevant for this thesis. Here, they include blue as well as green hydrogen production options, truck transport and fueling stations. However, the model excludes storage facilities and transportation by pipeline. This is a problem, as storage is a vital part of the chain to account for demand fluctuations. Furthermore, it expected that most transport will be done by pipeline in the future (Netbeheer Nederland, 2021). Furthermore, similar to Almansoori and Shah (2009) the model's hydrogen demand is modeled by assuming that 10% to 50% of the road vehicles will switch to hydrogen fuel.

Furthermore, Almaraz et al. (2013) extend the original model from Almansoori and Shah by including global warming and total risk of the total supply chain into the objective function next to total cost. Moreover, they select an optimal solution for the same case of the UK by using a Pareto front which balances total cost, pollution and safety risk of the supply chain. Their demand estimation for hydrogen is not discussed and is used from Almansoori and Shah (2006). Later Almaraz et al. (2015) deploy their same model and multi-objective methodology on the national level of France. In particular they extend their analysis and model by switching from dividing the country into square grids to GIS based analysis where each location of production and storage is determined exactly. This time they estimate their demand also on hydrogen adoption in road vehicles for 2050.

2.2 Contribution to the literature

Given the existing literature, the aim of this thesis is to expand on this research. Our contributions are threefold. First, existing literature makes large assumptions on future hydrogen demand. The main problem is that is assumed that all hydrogen demand will come from road vehicles. Yet, the largest future hydrogen consumption will come from industrial processes and from electricity production (Gas For Climate, 2021; Berenschot, 2020; Netbeheer Nederland, 2021). Excluding a realistic hydrogen demand estimate in the model will render the results of the model powerless as the spatial heterogeneity in demand locations is not taken into account and fixed cost barriers for production, storage and transport are harder to overcome with less demand. This all means that production and storage sites will be placed in possibly inefficient locations and transport volumes are significantly underestimated. In this thesis we try to model the future Dutch hydrogen demand for 2050 as realistic as possible using credible data sources. Moreover, we will use spatial data to divide the estimated national demand into regional demand.

Secondly, as most work is based on Almansoori and Shah (2006) the flexibility of the model also does not change. The most striking is that in each demand region a storage facility must be placed. This is done to take into account the variation in hydrogen demand over the year. While storage locations are needed in the supply chain (Netbeheer Nederland, 2021), requiring a storage facility in every region might not be needed as neighbouring regions can also be supplied from large scale storage facilities. Therefore, we make the model more flexible by letting storage facilities be able to serve other multiple regions.

Lastly, it is important to answer our hypotheses in the light of the Dutch case. Consequently, our aim is to make the model as realistic as possible for the Dutch context. As most research is focused on the UK, Germany and France (Wickham et al., 2022), it is worthwhile to add these specific features to the Dutch setting. These details include the locations at which it is feasible to produce and import large amounts of hydrogen. Moreover, we incorporate the existing Dutch gas network for re-using existing pipelines and the availability of salt caverns for storage into the model.

2.3 Hypotheses

2.3.1 Hydrogen supply chain costs

Our first hypothesis concerns the costs of each element in the hydrogen supply chain. Knowing the cost of each supply chain element could help governments focus on subsidizing and giving more incentive to the parts of the supply chain with the greatest start-up costs. In addition, as hydrogen is a new fuel there will be no hydrogen demand before there is supply. This consumption barrier of final users could make more expensive parts of the supply chain even more troublesome. Therefore, due to the initial demand and supply mismatch barrier it becomes even important to know the cost of hydrogen supply chain elements. Helping the most expensive parts namely could help hydrogen become more competitive against fossil fuel alternatives.

More specifically, especially the production of hydrogen can be characterized by large fixed capital expenditures due to its complexity (PwC, 2021). Moreover, the electricity needed for electrolysis is also a significant part of the costs. For example, Konda et al. (2011) estimate the feedstock plus production costs to be over 70% of the total supply chain costs for a case in the Netherlands. Moreover, Niermann et al. (2021) confirm this for the case of Germany with a cost of production often over 60% for most of their scenarios. This is also the case in Reuß et al. (2019). In both the last two papers, the supply chain is modelled in detail including storage, distribution, conditioning and compression of hydrogen.

Nevertheless, the model of Konda et al. (2011) includes pro-dominantly blue hydrogen using natural gas and oil instead of green energy. Therefore, using only renewable energy the production costs could be even greater. On the other hand, Niermann et al. (2021) and Reuß et al. (2019) do apply their case in Germany using green hydrogen. Nevertheless, as the production of hydrogen is mostly concentrated in northern Germany, transmission costs could be quite a lot higher compared to the Netherlands. In other words, the costs of each supply chain element could differ between the two countries. To assess whether production costs also take up the largest amount of total costs for the case of the Netherlands using green hydrogen, we formulate the following hypothesis:

H1: Production of Dutch hydrogen takes up the largest part in the supply chain costs in 2050.

2.3.2 Pipeline vs. truck transportation

Next, the transportation of hydrogen from production to demand locations is another vital part the supply chain. As there exist multiple alternatives for transporting hydrogen in form of truck and pipeline distribution, it is important to know which transport mode will be the most efficient for the Dutch case. Yet, little research is focused upon comparing the two modes. Older literature such as the ones from Almansoori and Shah (2006) and Almaraz et al. (2015) mainly focuses on truck transportation. Moreover, in a survey from Wickham et al. (2022) only three out of eighteen papers include both truck and pipeline transportation in their analysis. These have generally the same conclusion: small demand regions should be served by trucks while high demand regions are served in the most cost-effective way by pipeline (Yang and Ogden, 2007; Moreno-Benito et al., 2017; Reuß et al., 2019). Outside this literature, Niermann et al. (2021) and Bloomberg (2020) confirm that each transportation mode has its own niche where it is most competitive: truck for low demand and pipeline for high volumes. Moreover, we note that demand size is the only important factor in this choice. Transport distance seems not to be important for the choice of mode.

Nevertheless, while most research have found that truck and pipeline can compliment each other, the rest of the literature in the review of Wickham et al. (2022) seems to focus solely on gas pipeline infrastructure. More specifically, these papers focus on the spatial aspect of using gas networks for hydrogen (Johnson and Ogden, 2012; Samsatli et al., 2016). Moreover, Wickham et al. (2022) itself finds that trucks are not selected in their model for the case of the UK. They explain this by the fact that existing gas infrastructure can be re-used at a very low cost to transport hydrogen instead of natural gas. Indeed, re-using existing infrastructure also seems to be the way multiple agencies and gas infrastructure authorities see the future, as the most countries already have a strong gas network it can build on or transform (Netbeheer Nederland, 2021; PwC, 2021).

From the literature we therefore draw two conclusions. First, the choice of using truck or pipeline is very specific to the size of the demand per region. Secondly, although papers find a mix of trucks and pipeline use, some recent research slightly favors pipeline through re-using existing infrastructure. As both national demands and existing pipeline networks differ per country, we give the following hypothesis to see what this means for the Dutch case:

H2: Pipeline transport of Dutch hydrogen is economically more attractive than truck transport in 2050.

2.3.3 Pipeline infrastructure

In the previous hypothesis we expected that re-using pipeline infrastructure in the Netherlands is more cost-efficient than using trucks for hydrogen transport. When this would be the case, this would mean the majority of transport would be done by pipeline. A relevant question would then be whether the capacity of the existing pipeline infrastructure would be large enough for transport of hydrogen in the future.

One argument is that the existing gas network is now used for industrial processes, power generation and household heating. The general expectation is that all these three application of natural gas will be taken over by hydrogen (Gas For Climate, 2021). However, it is also expected that large buses, trucks, airplanes and boats will make use of some sort of hydrogen variant (PwC, 2021). The extra demand on top of the old three application for gas could create a burden on the pipeline infrastructure. Nevertheless, as will be treated in Section 3 it is expected that the size of the demand for transport will be relatively small compared to the other three existing application (Netbeheer Nederland, 2021). Therefore, we expect that the current Dutch pipeline infrastructure is sufficient to handle future hydrogen transport when the network is transformed. Morever, Netbeheer Nederland (2021) also expects that the general pipeline infrastructure will not be a bottleneck. Therefore, we can formulate the following hypothesis:

H3: The capacity of the Dutch gas pipeline network is sufficient to facilitate national hydrogen demand in 2050.

3 Data

In this section we treat the data for the input of the mixed integer linear program. First, we discuss Dutch national hydrogen demand estimates for 2050 in Section 3.1. Then in Section 3.2 we divide this national demand into four main energy sectors. Section 3.3 divides the national demand into smaller regional demand by using these four sectors. Finally, Section 3.4 discusses the other parameters such as costs and storage capacities of the model.

3.1 National hydrogen demand

To obtain our national demand forecast for hydrogen in 2050, we discuss multiple sources. First, Gas For Climate (2021), which is an initiative between the biggest gas transport companies in Europe, estimates the Dutch national hydrogen demand in 2050 to be 138.5 TWh per year. Next, the Institute of Sustainable Process Technology (ISPT), which connects different sectors of the sustainable energy sector together, estimates this demand to be somewhat higher with around 200 TWh per year. This report is based on a collection of dozens of studies which estimate the Dutch hydrogen demand including Gas For Climate (2021). Lastly, the main source is the series of estimates from CE Delft (2017), Berenschot (2020) and Netbeheer Nederland (2021) which builds upon one another. First CE Delft, a consulting company specialized in energy demand, made an estimate in 2017. Then consulting firms Berenschot and experts from the industry built on this in 2020. Then this report was used to develop on by Netbeheer Nederland in 2021, the company responsible for the gas network and infrastructure in the Netherlands. The last estimates are thus the ones that gas infrastructure are building on for the upcoming years.

We note that estimations of hydrogen demand is complex and subject to numerous assumptions. These include how well hydrogen thrives and how much sustainable energy is created in the coming years. Nevertheless, we believe the last three sources are the best current available estimate available for the Netherlands. The estimates are quite close to each other, but they are also developed by industry experts and were tested by various industry stakeholders and the Netherlands Environmental Assessment Agency (Netbeheer Nederland, 2021). More specifically, we use the estimates as given by Netbeheer Nederland (2021) as they build upon the series of estimates and as it is the most recent estimate. More detailed national forecasts can be seen in Appendix F.

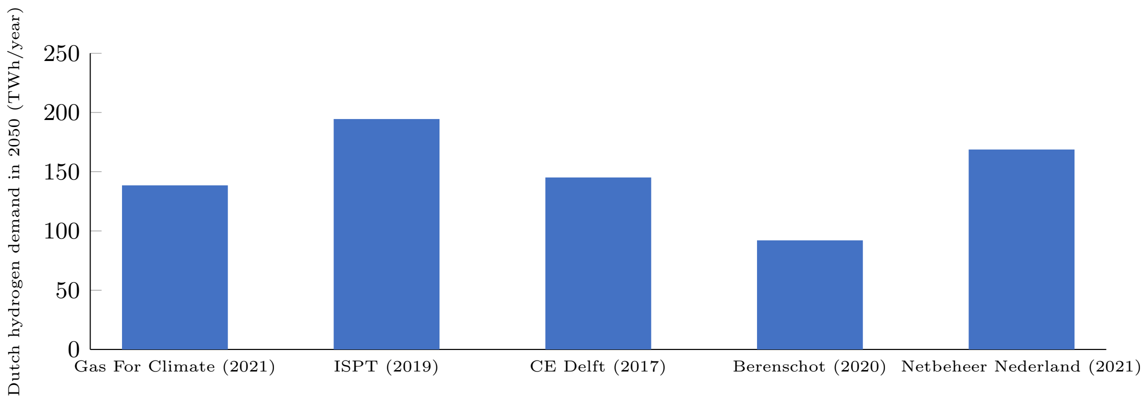


Figure 1: Estimated Dutch hydrogen demand per sector in 2050 (TWh/year) as given by multiple sources.

3.2 Sectoral hydrogen demand

Next, we wish to divide this national hydrogen demand into regional demands. To do this, we first inspect the demand for four main sectors with energy needs: the heavy industry such as chemicals and metals, the transport sector, electric power generation and for building heating sector. The demands as estimated by Netbeheer Nederland (2021) for each of these four sectors are given in Figure 2. As shown in the figure, the national demands are estimated for four different scenarios. The Regional and National scenarios mean that hydrogen demand is mostly met by region and national supply. In the European and international scenarios, the country leans more on cheap import of hydrogen from Europe and other countries in Africa and the Middle East. For further detail on these scenarios we refer to Netbeheer Nederland (2021).

For our hypotheses, we make use of the National scenario as this is closest to the previous total hydrogen demand of around 150 TWh per year. It also seems most realistic as the European scenario assumes a heavy reliance on the biomass in all sectors (Netbeheer Nederland, 2021).

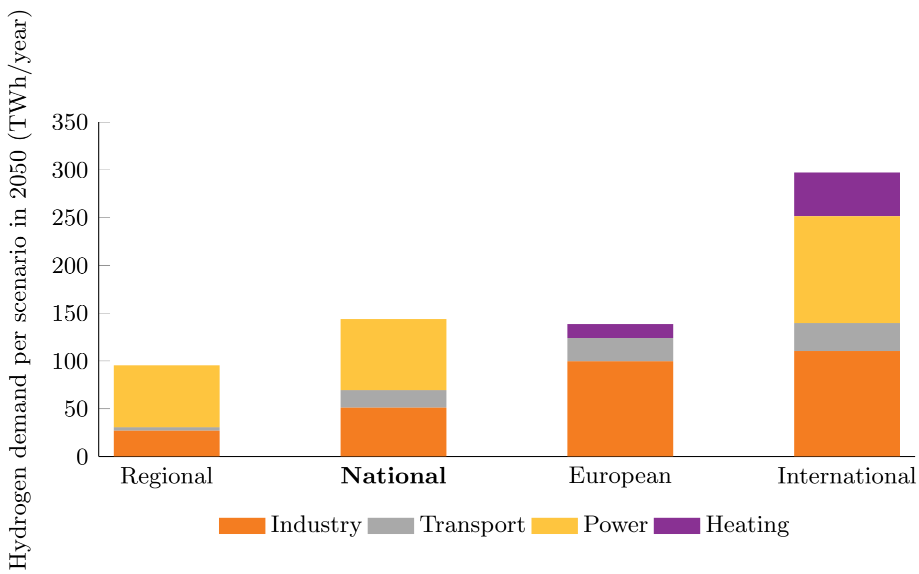


Figure 2: Estimated hydrogen demand per sector in 2050 (TWh/year) as given by Netbeheer Nederland (2021).

3.3 Regional hydrogen demand

In this section we proceed with dividing the Dutch national hydrogen demand in 2050 per sector into regional NUTS3 level demand. To obtain the demand D_i^s of region $i \in I$ for hydrogen in sector $s \in S$, we use hydrogen demand proxies p_i to divide our given estimated national demand D^s as shown in equation (1). Therefore, we only have to make assumptions on the validity of the spacial heterogeneity of the used proxy p_i instead of the absolute national sector demand. This is because our division will always sum up to our estimate:

$$D_i^s = \frac{p_i}{\sum_{i \in I} p_i} D^s. \tag{1}$$

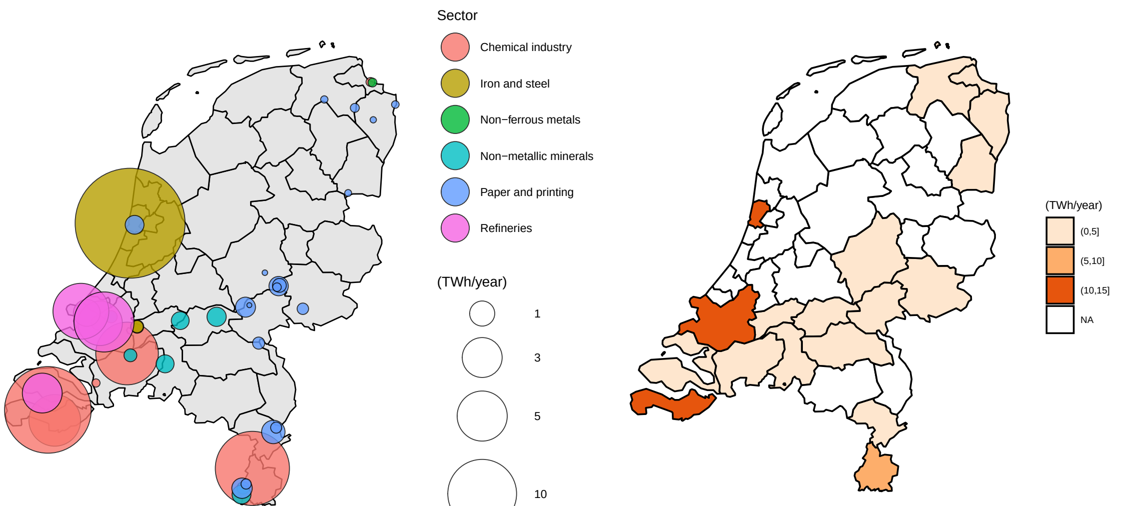
More detailed levels such as neighbourhood and municipality levels would allow for a finer analysis. However, our aim is to strategically make an optimal supply chain so too much detail would restrain the model from solving. Moreover, NUTS3 level data is more readily available compared to neighbourhood and municipality data. NUTS2 levels are not used as these areas are too large for our strategic analysis as we want to know the positions of production and storage on a region level instead of a province level.

First we divide the demand for hydrogen in the heavy industry in Section 3.3.1. Then, we proceed with the demand for electricity power in Section 3.3.2. Finally, we estimate the demand on NUTS3 levels for transport and building heating in Section 3.3.3. Again all figures of regional hydrogen demand is based upon the National scenario.

3.3.1 Industry

First, we derive the NUTS3 level regional demand for hydrogen in 2050 for the heavy industry. To to this, we perform an adjusted approach to Neuwirth et al. (2022) usign data from sEEnergies (2022). This is an open data set funded by the European Union which collects data on industrial sites and energy consumption within Europe. More specifically, we obtain the location, industry sector and total energy demand per year (excluding electricity) of each large industrial site within the Netherlands. The data is shown in Figure 3a, where one can clearly see the industrial clusters in IJmuiden, Roermond, Zeeland and Limburg.

The energy demand of all locations is then used to divide the national industrial hydrogen demand into the NUTS3 regions as shown in Figure 3b. Note that there are some assumptions we make. First, we assume that the energy demand of each site is directly proportional to its future hydrogen demand. It could be that some sites or sectors will need proportionally more hydrogen than other sites/sectors. Secondly, we assume that the energy demand of all sites will remain constant until 2050. This is not likely due to increasing demand due to economic growth while on the other hand it could decrease due to achievements in process efficiencies. Thirdly, following Berenschot (2020) we assume that the refinery sector will not make fuel for road, air and water transport anymore. It would still make products for the chemical industry, in which case we assume the demand of each refinery to be 40% of the original demand. Therefore, the pink refinery data points in Figure 3a are 40% of its original size.



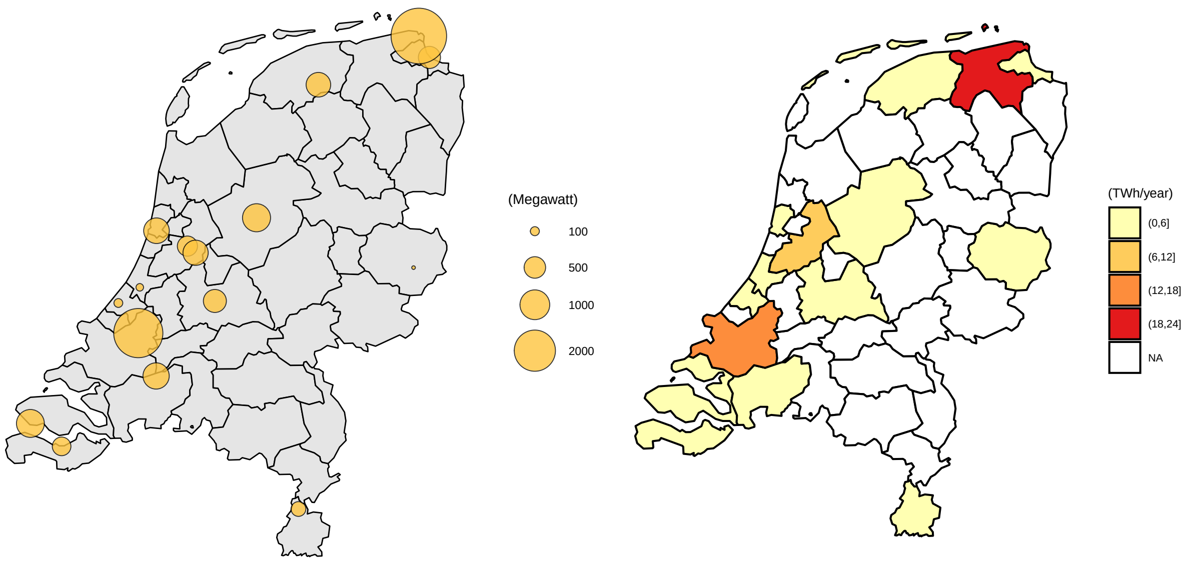
(a) Industry locations energy demand for hydrogen in 2050.

(b) Resulting hydrogen demand per NUTS3 (TWh/year) for the National scenario.

Figure 3: Hydrogen demand of heavy industries.

3.3.2 Power

Next, we derive the regional NUTS3 hydrogen demand for electricity power. To divide the sector hydrogen demand, we use the locations of all large (>1MW) natural gas powered power stations in the Netherlands as gathered via various internet sources and inspected via Open Infrastructure Map (2022) and Netbeheer Nederland (2021) shown in Figure 4a. We use gas-powered eletricity production only, as coal electricity production is almost phased out in the Netherlands (CBS, 2021a). Moreover, it is likely that the division over the electricity generation in 2050 is similar as gas-powered stations can be converted into hydrogen powered stations (Netbeheer Nederland, 2021). The resulting demand estimate for hydrogen in TWh per year for the National scenario can be seen in Figure 4b. Herein, we assume that all power stations will remain active in the same proportion it is now. It could however be that less power stations are needed as sun and wind energy will become the main source of direct electricity. This would result in the proportion of hydrogen needed for power being different.



(a) Assumed gas powered electricity production locations energy demand for hydrogen in 2050.

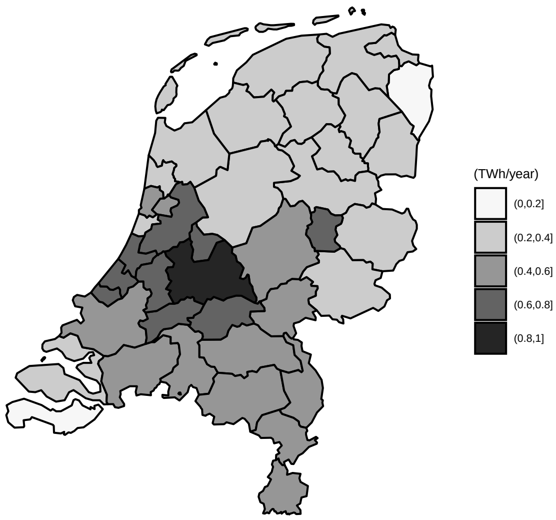
(b) Resulting hydrogen demand per NUTS3 (TWh/year) for the National scenario.

Figure 4: Hydrogen demand for electricity power.

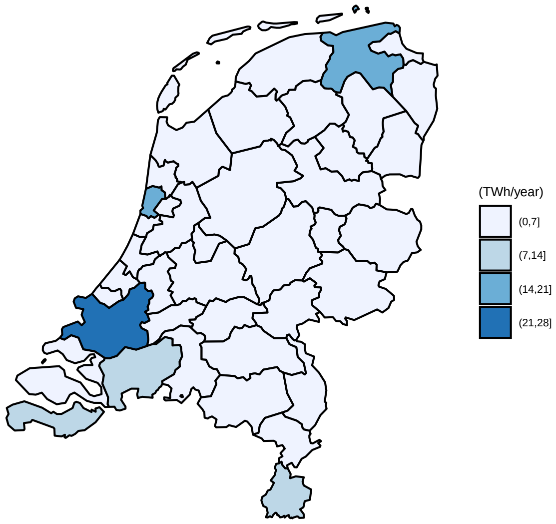
3.3.3 Transport and heating

Lastly, we divide the hydrogen demand for the building heating and transport sector. For the transport sector, we gather NUTS3 level data so the direct results in hydrogen demand is shown in Figure 5a. To divide the transport hydrogen demand we make use of traffic intensity data of CBS (2021b) on NUTS3 level, which is a proxy for where hydrogen will be needed in refuelling stations. This means we assume that traffic intensity is a valid proxy for hydrogen fuel demand. Secondly, we do not take into account the demand for shipping and aviation fuel. We deem this specific demand within transport to be negligible with respect to the industrial and power demand in the National scenario as seen in Figure 2.

To divide the demand for building heating we again use the open data sets from sEEnergies (2022). More specifically, we obtain heating energy demand for each NUTS3 region in the Netherlands for 2015. We tested this against a proxy of NUTS3 population density, which yielded similar regional heterogeneity. The result in hydrogen demand for 2050 for heating is given in Appendix B as it is not used for the National scenario but for the International scenario in robustness tests. Again, the spatial heterogeneity could change due to population growth and decreases in for example cities and country sides.



(a) Road transport hydrogen demand per NUTS3 (TWh/year) for the National scenario.



(b) Estimated total hydrogen demand per NUTS3 in the Netherlands in 2050 (TWh/year).

Figure 5: Hydrogen demand for road transport and total hydrogen demand for all sectors.

3.3.4 Total hydrogen demand

Using the regional estimates as distributed in this section, we are able to obtain the total regional hydrogen demand for the Netherlands in 2050 in TWh per year. This is shown in Figure 5b. What can be seen is that most hydrogen demand is concentrated near Rotterdam, Zeeland, IJmuiden, Limburg and Groningen. This is mainly due to the industry demand in Rotterdam, Zeeland IJmuiden and Limburg as well as power generation in Groningen.

Lastly we note that we require the import size of hydrogen to be 75,000 GWh/year for the National scenario and 291,300 GWh/year for the International scenario, following the scenarios as given by Netbeheer Nederland (2021). This part of the demand therefore has to be satisfied by import and the other demand can be satisfied by national production. Using these demand estimates and import requirements, we continue with the parameters for the model.

3.4 Model parameters

Finally, we present the input parameters for the model by using existing literature. An overview of all gathered parameters can be found in Table 7. In Section 3.4.1 we first go through the feedstock prices for the production of hydrogen. Then in Section 3.4.2 we discuss the cost parameters of hydrogen production and import. Then, we treat the parameters for the transport of hydrogen via pipeline and truck in Section 3.4.3. Lastly, the storage parameters are presented in Section 3.4.4.

3.4.1 Feedstock

Before we discuss the general production costs a considerable part of hydrogen production costs consists of electricity consumption, as electricity is transformed into hydrogen. To come up with a variable cost estimate, we use the production efficiency of alkaline electrolysis, which three sources in Table 1 estimate to be around 70-80%. Then, the same three sources estimate the electricity price per GWh for industry to be around 50,000 euros per GWh. Therefore, by using Table 1 we conclude that the price of hydrogen feedstock is 70,192 euros per GWh of hydrogen.

3.4.2 Production and import

For the production cost of hydrogen there are numerous papers and reports which indicate the current cost of production as well as future forecasted production prices. While most sources agree on the current price of production, forecasted prices seem to diverge quite significantly. Therefore, we use a list of five sources which we aggregate in Figure 6.

More specifically, we refer to capital expenditure costs (CAPEX), which are one-time fixed costs to set up production of hydrogen. We choose to use alkaline electrolysis (AEC) costs, as most data is available for it. Moreover, the future costs of this technology seems similar with other less mature unproven technologies such as polymer electrolyte membrane (PEM) and solid oxide electrolyzer cell (SOEC) electrolysis (Schmidt et al., 2017). Current CAPEX prices for alkaline electrolysis (AEC) range from 800 to 1,100 per kilowatt (kW). Using a simple least squares regression line in Figure 6, the forecasted CAPEX by 2050 for hydrogen electrolysis by AEC is 415.9 euros/kW.

As a kW is a unit of power and not of energy, we convert this figure into a price per energy unit of gigawatt-hour (GWh). This is also the unit we choose to work with in our model. Using Table 2 we first convert our CAPEX estimate into GWh per year using a capacity rate of 20%, the fact that there are 8760 hours in a year and a lifetime of 20 years for production. This brings our yearly CAPEX to 11,869 euros per GWh. Furthermore, we assume that the operational expenditures per year (OPEX) are 8% of the CAPEX costs. When we add the CAPEX and OPEX together we get a yearly variable cost of 30,680 euros per GWh. Using a list of production plans for the Netherlands, the smallest size of production is 1 MW. Therefore we use a fixed cost of 1 MW of production (IEA, 2021).

Lastly, we use an import price of 0.8 euros per kg hydrogen as given by Gas For Climate (2021). When we convert this using the fact that one kg hydrogen contains 33.3 kWh of energy per kg, we arrive at a cost estimate of 24,024 euros per GWh of hydrogen, which is lower than our production cost estimate.

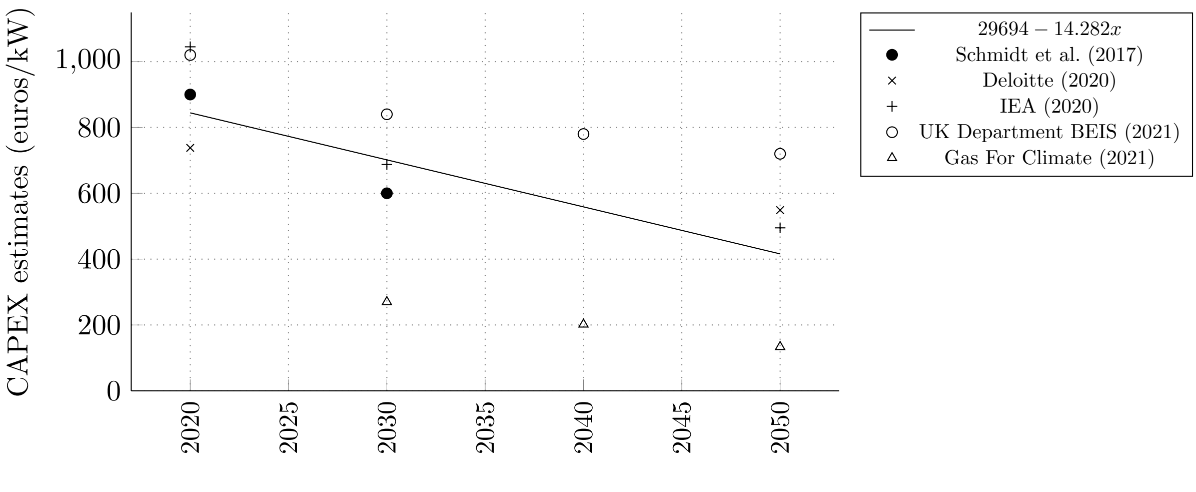
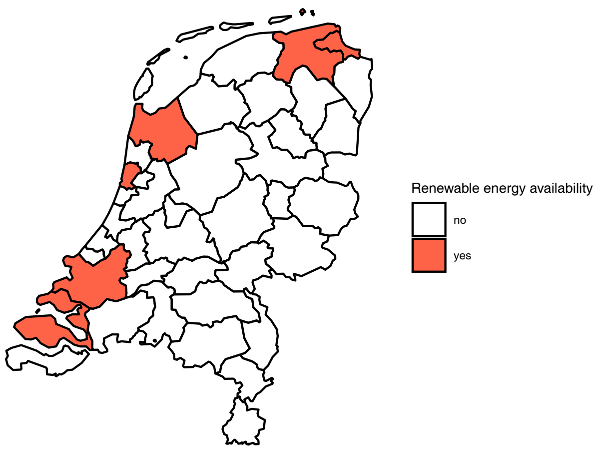


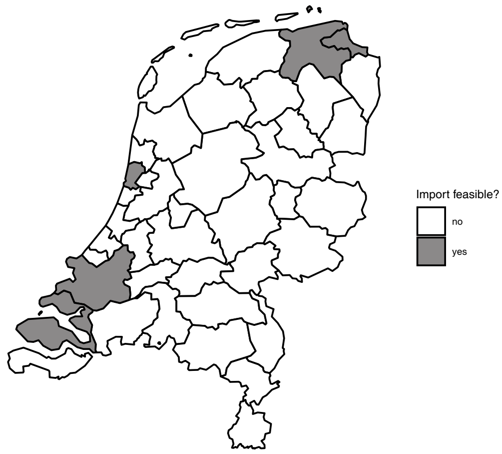
Figure 6: AEC electrolysis CAPEX estimates of hydrogen by different sources.

Next to production and import cost estimates, we also implement Dutch geographically specific restrictions to our model. First, electricity transport is 4 to 5 times more expensive per energy unit than hydrogen transport. Therefore we restrict our model to locate sources of production closer to large renewable energy sources, because the transporting hydrogen is cheaper than transporting electricity (Netbeheer Nederland, 2021; PwC, 2021; Gas For Climate, 2021). For the Netherlands these are the coastal regions indicated in Figure 7a in red. The regions in set V^R have close proximity to off-shore wind electricity via existing electricity transport (Netbeheer Nederland, 2021; PwC, 2021). For our model, this means that the red regions are restricted in production to 10 GW while the white regions are restricted to 0.1 GW. These numbers are based on current and expected sizes of hydrogen production in the Netherlands, which range from 0.01 GW to 1 GW (IEA, 2021).

Secondly, not all regions are able to import hydrogen, as existing pipelines and coastal infrastructure for natural gas are already in place in certain regions which is not expected to change in the future (Netbeheer Nederland, 2021). In Figure 7b the regions that are able to import hydrogen are coloured grey. For the model this thus means that import is only allowed in these NUTS3 regions. In all white regions, no import is allowed.



(a) Renewable energy availability with regions $i \in V^R$.



(b) Import feasibility of hydrogen with regions $i \in V^I$

Figure 7: Renewable energy availability for hydrogen production and import feasibility for each NUTS3 region.

3.4.3 Transport

For the transport of hydrogen we consider truck and pipeline transport. More specifically, trucks can transport both gaseous and liquid hydrogen, while pipeline can only transport gaseous hydrogen. Most importantly, the costs and carrying/throughput capacities will be discussed of both transport modes.

Truck

For the costs and characteristics there are numerous reports and papers which make use of truck estimates. To check the validity of these figures we compare multiple sources. We choose to compare three sources as they have the same general cost structure and data available which make them applicable for comparison. The results can be seen in Table 3 and Table 4 for both liquid and gaseous hydrogen carrying trucks respectively. For each cost estimate and characteristic, we make use of an average on the right side of the table.

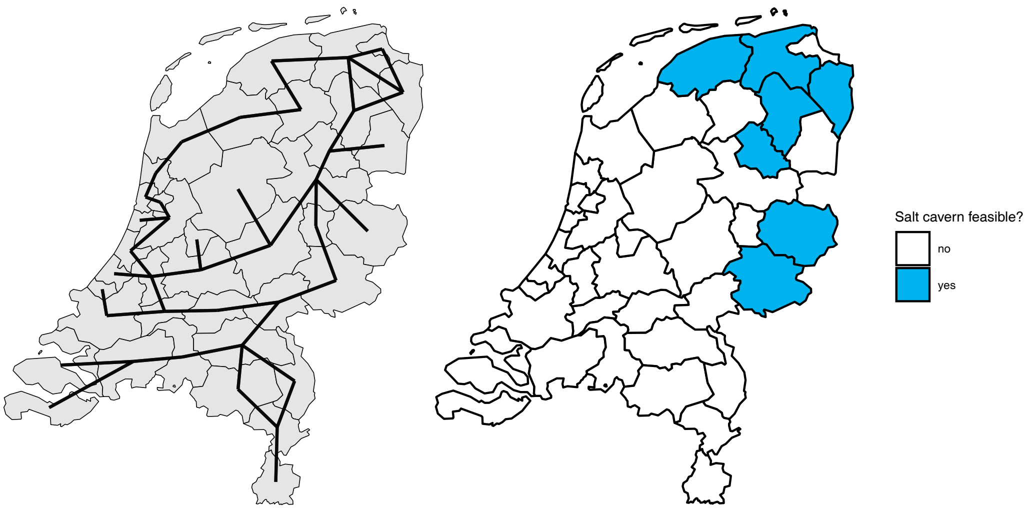
For the liquid trucks in Table 3, the CAPEX of one truck is comparable over all sources and has an average of 1,075,000 euros. Meanwhile, the yearly OPEX of one truck is also comparable, as well as the conversion costs to convert gaseous hydrogen into liquid hydrogen for truck transport. By dividing by the CAPEX by a truck's lifetime and adding the yearly OPEX, we arrive at an average yearly fixed cost for a liquid carrying trucks of 141,165 euros per year. Meanwhile, by using Table 4 for gaseous carrying trucks, this comes down to only 108,311 euros per year. However, the carrying capacity is much lower for gaseous trucks, as gas is less dense than liquid hydrogen. Therefore, liquid trucks seem to outperform gaseous trucks in terms of fixed cost per GWh of capacity (970,806 vs. 4,736,776 euros/GWh). This is in line with conclusions of other papers such as Almansoori and Shah (2006) which use a more specific type of cost estimate. Therefore, we choose to only use liquid trucks in our supply chain model, as gaseous trucks are not competitive.

Then, we need the variable cost of using trucks. For the labor costs, we use an estimate of 0.76 euros/km. This is based on a truck driver's wage of 38 euros per hour (Eurostat, 2021) divided by the average speed of 50 km per hour. Next, for fuel costs we make use of an estimate for future electric trucks as given by Gao et al. (2017). By using these estimates the variable cost (the costs per km driven) comes down to 0.95 euro per kilometer. Moreover, we use a carrying capacity of 0.1454 GWh per truck, a loading/unloading time of three hours, an average availability per year of 31% and an average speed of 50 km/hour.

Pipeline

For hydrogen transport by pipeline we only have variable costs consisting of CAPEX and OPEX as these two expenditures both depend on the pipeline length. In Table 5 the costs and characteristics are given for pipelines as given by five sources. The CAPEX for both repurposed and new pipelines are given in euros per km. As we can see from the table, re-using existing natural gas infrastructure is much less expensive (Gas For Climate, 2021; PwC, 2021). Morever, the yearly OPEX is also listed in euros per km. When we divide the CAPEX by the average pipeline lifetime and add the OPEX to it for every source, we get an average variable cost of 88,779 euros per kilometer for new pipelines and of 42,143 euros per kilometer for repurposed pipelines. For the characteristics we use an average throughput of 40,922 GWh per year and lifetime of 37.5 years.

To know when to use the new or repurposed pipeline costs, we use the national gas network map of Gas Unie (2018). To let this map work with our NUTS3 regions in our model, we simplify the network as seen in Figure 8a. Where there is a connection with a black line in this figure, there is already an existing pipeline infrastructure, which means we can use the repurposed cost estimate. When there is no connection between regions, we use the new pipeline cost estimate.



(a) Simplified existing pipeline infrastructure for natural gas.

(b) Import feasibility of hydrogen for each NUTS3 region.

Figure 8: Hydrogen salt cavern storage and import feasibility.

3.4.4 Storage

Lastly, we discuss estimates for storage facilities of hydrogen. In Table 6 the costs and lifetime of storage by salt cavern, cryogenic tank (CT) and high-pressure tanks (HPT) are shown for different sources. As multiple studies point out, salt caverns seem a very cost-efficient solution for hydrogen storage. With a cost of only 33,819 euros per GWh, salt caverns indeed seem to be the best solution for hydrogen storage. Nevertheless, there is a large but limited capacity in the Dutch soil for this type of storage (PwC, 2021). Therefore, we also include CT storage as an alternative to salt caverns, as this storage is not limited by capacity per region. Storage by HPT will be disregarded as this is more expensive than CT.

Lastly, salt caverns are only available in certain provinces in the North and East of the Netherlands. For the model, we used the sources of PwC (2021) and Netbeheer Nederland (2021) to indicate that the blue regions in Figure 8b are suitable for hydrogen storage in salt caverns. In the other white regions, salt cavern storage is not possible. Furthermore, using the information on salt caverns availability by PwC (2021), we assume maximum of 10,000 GWh per storage size per region. Also, using the total existing storage capacity for natural gas of 9 billion cubic meters and a yearly demand of 40 million cubic meters, we assume that 9/40=23% of the hydrogen demand should be stored as safety storage factor (CBS, 2022; NAM, 2022).

Table 1: An overview of feedstock costs.

	Unit	IEA (2019)	Reub et al. (2017;2019)	Niermann et al. (2021)	Average
Production efficiency	%	74%	70%	82%	
Electricity price	euros/GWh	47,000	60,000	50,000	
Variable cost	euros/GWh production	63,514	85,714	61,350	**70,192**

Table 2: An overview of estimated production costs and characteristics.

		Production	Import	Conversion paramaters
CAPEX	euros/kW	415.9		
CAPEX	euros/GW	415,900,000		1,000,000 GW/kW
CAPEX	euros/GWh	237,386		8760 hours/year, 20% capacity rate[a,b]
Yearly CAPEX	euros/GWh	11,869		20 year lifetime[a,b]
Yearly OPEX	euros/GWh	18,990		8% of CAPEX[a,b]
Yearly variable costs	euros/GWh	**30,860**	**24,024**	0.8 euros/kg H2[c]

[a] Planbureau voor de Leefomgeving (2011),
[b] UK Department BEIS (2021),
[c] Gas For Climate (2021)

Table 3: An overview of estimated liquid truck transport costs and characteristics.

Parameter	Unit	IEA (2019)	Reub et al. (2017;2019)	Niermann et al. (2021)	Average
CAPEX	euros	1,185,000	1,020,000	1,020,000	1,075,000
Yearly OPEX (General and maintanence expenses)	euros/year	42,200	36,400	36,400	38,333
Yearly OPEX (conversion)	euros/year	1,886	1,973	1,886	1,915
Yearly fixed cost	euros/year	142,836	140,373	140,286	**141,165**
Driver cost	euro/km	-	-	-	0.76[a]
Fuel	euro/km	-	-	-	0.19[b]
Variable cost	euro/km				**0.95**
Lifetime	years	12	10	10	11
Capacity	kg H2	4300	4500	4300	4,367
Capacity	GWh H2	0.1432	0.1432	0.1499	**0.1454**
Loading/Unloading Time	hours	3	3	3	**3**
Availability	%	-	40%	23%	**31%**
Speed	km/h	50	50	50	**50**

[a] Eurostat (2021),
[b] Gao et al. (2017)

Table 4: An overview of estimated gas truck transport costs and characteristics.

Parameter	**Unit**	**IEA (2019)**	**Reub et al. (2017;2019)**	**Niermann et al. (2021)**	**Average**
CAPEX	euros	835,000	710,000	710,000	751,667
Yearly OPEX (General and maintanence expenses)	euros/year	35,200	30,200	30,200	31,867
Yearly fixed cost	euros/year	104,783	118,950	101,200	**108,311**
Driver cost	euro/km	-	-	-	0.76[a]
Fuel	euro/km	-	-	-	0.19[b]
Variable cost	euro/km				**0.95**
Lifetime	years	12	8	10	10
Capacity	kg H2	670	720	670	687
Capacity	GWh H2	0.02231	0.02398	0.02231	**0.02287**
Loading/Unloading Time	hours	1.5	2	1.5	**2**
Availability	%	-	40%	23%	**31%**
Speed	km/h	50	60	50	**53**

[a] Eurostat (2021),
[b] Gao et al. (2017)

Table 5: An overview of pipeline transport costs and characteristics.

	PwC (2021)	Gas For Climate (2021)	IEA (2020)	Reuß et al. (2017)	Reuß et al. (2019)	**Average**
CAPEX 36 inch new (euros/km)	3,200,000	2,200,000	1,200,000	2,765,081	1,217,402	2,116,497
CAPEX 36 inch repurposed (euros/km)	840,000	400,000	-	-	-	620,000
Yearly OPEX (euros/km)	32,000	19,219	-	5,000	48,696	26,229
Yearly variable cost new (euros/km)	117,333	77,886	-	78,735	81,160	**88,779**
Yearly variable cost repurposed (euros/km)	54,400	29,886	-	-	-	**42,143**
Troughput (GWh/year)	79,444	32,000	11,322	-	-	**40,922**
Lifetime (years)	30	-	40	40	40	**37.5**

Table 6: An overview of estimated storage costs and characteristics.

	Gas For Climate (2021)	PwC (2021)	Niermann et al. (2021)	Reuß et al. (2019)	Le Duigou et al. (2017)	Almansoori and Shah (2009)	**Average**
Salt cavern (euros/GWh)	8,600	79,048	14,842	-	32,786	-	**33,819**
Depreciation period (years)	-	30	30	-	50	-	**37**
CT: cryogenic tank (euros/GWh)	-	357,269	780,781	-	-	92,557	**410,202**
Depreciation period (years)	-	50	20	-	-	-	**35**
HPT: high-pressure tank (euros/GWh)	-	-	-	750,751	-	833,150	**791,950**
Depreciation period (years)	-	-	-	20	-	-	**20**

4 Methodology

In this section we present a mixed integer linear programming to answer our hypotheses, which optimises the decision variables used to create a Dutch supply chain for hydrogen in 2050. The objective of this model is to minimise the total production, storage and transportation costs, given a set of constraints. Here the constraints mainly involve the flow, production, import and storage of hydrogen. Minimising the total costs given the set of constraints ultimately then results in a configuration of a cost-optimal hydrogen supply chain. The model is implemented in `Java` using the `CPLEX` library, which solves the model with a 0.1% optimality gap. This means we know that we are at most 0.1% away in terms of total cost from the optimal solution.

An inspiration for this model was Almansoori and Shah (2006), although this model is completely different in a sense that it focuses on comparison between pipeline and truck transportation and the way the pipeline network should be laid out in terms of locations and capacity. Moreover, storage and import requirements and feasibility are also modelled with more detail specifically for the case of the Netherlands. In Figure 9 a schematic overview of the supply chain is given with examples I and II.

First, hydrogen can either enter the supply chain via national production (red square) or via international import (grey square). Then, we note that in both I and II, there are both red and blue flows going to each demand region. This is because each demand region needs both direct demand (red) as well as a demand retrieved from the storage location (blue). Therefore, each region i receives hydrogen directly from production regions as well as from storage locations. Next, the difference between I and II is that both red and blue flows can travel directly to each demand region as well as through demand regions. In I, flows travel directly, while it is also possible in II that flows travel through demand regions. In this way a network of pipelines can be created which serve multiple regions by one extensive line.

For the truck transport we only work with example I where each truck can travel directly to each region. We choose to do this as otherwise we double count the number of trucks needed in the supply chain. In this case, we would overestimate the costs of truck transport. Therefore, case II only acts as a way to create a network for pipeline transport.

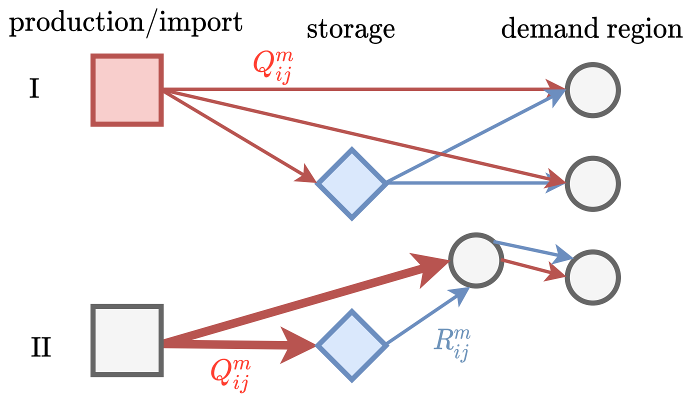


Figure 9: Schematic overview of the relation between production and storage sites and demand regions.

The parameters as discussed in the previous section can be seen in Table 7. We proceed with explaining the decision variables, constraints and objective function of the model. The table can thus be used as an overview for these equations.

Table 7: An overview of the input data.

Input parameter	Value	Description
V	40 regions in the Netherlands	Set of NUTS3 regions
S	Salt caverns and cryogenic tank	Set of storage technologies
M	Pipeline and truck	Set of transport modes being pipeline and truck
$f^{\text{production}}$	Cost of setting up 1 MW production	Fixed cost of production (euros)
$c^{\text{feedstock}}$	70,192 euros/GWh	Variable cost of feedstock (euros/GWh/year)
$c^{\text{production}}$	30,860 euros/GWh	Variable cost of production (euros/GWh/year)
c_s^{storage}	33,819 and 410,202 euros/GWh	Variable cost of storage technology $s \in S$ (euros/GWh)
f^{truck}	141,165 euros	Fixed cost of truck transport (euros/truck)
c_{ij}^{m}	88,779/42,143 euros/km and 0.95 euro/km	Variable cost of transport by mode $m \in M$ (euros/km)
c^{import}	24,024 euros/GWh	Variable cost of importing hydrogen (euros/GWh)
a_{is}	Figure 9b	Equals 1 when storage technology is available in region $j \in J$,zero o.w.
D_i	Appendix F	Yearly demand for hydrogen in 2050 of region i (GWh/year)
β	23%	Safety storage factor
A_{ij}^m	-	Indicator being 1 when region i neighbours region j, zero otherwise
$Q_{\max}^m$	40,922 GWh per year or 0.1454 GWh/truck	Maximum allowed flow per truck or pipeline $m \in M$ (GWh)
M	-	Large arbitrary number
d_{ij}	-	Distance between centroids of region i and region j (km)
SP	50 km/h	Average speed of a truck (km/hour)
LUT	3 hours	Loading and unloading time (hours)
TA	$24 \cdot 365 \cdot 31\%$ (31% of the year)	Truck availability factor (hours)
$P^{\max}$	10 GW	Maximum production capacity of a production location (GWh/year)
$P'^{\max}$	0.1 GW	Maximum production of a region not having access to renewable energy (GWh/year)
I^T	75,000/291,300 GWh	Total required import of hydrogen
$S_s^{\max}$	10,000 GWh	Maximum storage capacity of a storage technology $s \in S$ (GWh)

First, we introduce the decision variables of the supply chain model in equations (2)-(4). In (2), P_i equals the production of hydrogen, I_i the import and S_{is} the storage in form $s \in S$ in region $i \in V$. Moreover, Q_{ij}^m is the hydrogen transport flow from region i to region j by transport mode $m \in M$ where M consists of either truck or pipeline. The same applies for R_{ij}^m, but this is the flow for the required storage to handle fluctuating demand. Next in (3), NTU stands for the used number of trucks for the supply chain and X_{ij}^m indicates the number of pipelines needed from region i to j for pipeline transport or the number of trips needed for truck transport. Then the binary variable Y_{ij}^m indicates whether there is flow from region i to region j via transport mode m. Finally, Z_i^P indicate whether or not there is production active in region i for the fixed costs in the objective function.

$$P_i, I_i, S_{is}, Q_{ij}^m, R_{ij}^m \geq 0 \qquad \forall m \in M, i, j \in V \tag{2}$$

$$NTU, X_{ij}^m \in \mathbb{N} \qquad \forall m \in M, i, j \in V \tag{3}$$

$$Y_{ij}^m, Z_i^P \in \{0, 1\} \qquad \forall m \in M, i, j \in V \tag{4}$$

Then, by equation (5) we model the transport flows for the direct yearly demand for hydrogen. In Figure 10 these flows are illustrated in red. Here, region i can consume hydrogen for storage $\sum_{s \in S} a_{is} S_i$ when storage technology s is available ($a_{is} = 1$) and consume direct yearly demand D_i. On the other hand, node i can produce P_i or import I_i hydrogen which then adds hydrogen to the supply chain. What a region i consumes should be equal to what it produces or imports plus any in- or outflows of hydrogen. Therefore, we also add the inflow of hydrogen $\sum_{j \in V} Q_{ji}^m$ to the consumption side of the equation, which does not include region i's consumption. We add the outflow of hydrogen excluding production or import of the same region to what the region produces on the right side of the equation as $\sum_{j \in V} Q_{ij}^m$. Overall, we have consumption plus any outflow equalling production plus any inflows.

$$\sum_{s \in S} a_{is} S_{is} + D_i + \sum_{m \in M} \sum_{j \in V} Q_{ij}^m = \sum_{m \in M} \sum_{j \in V} Q_{ji}^m + P_i + I_i \qquad i \in V \tag{5}$$

The same concept applies to the transport for storage requirements due to seasonal demand and variable production in equation (6). In Figure 10 these flows are illustrated in blue. A

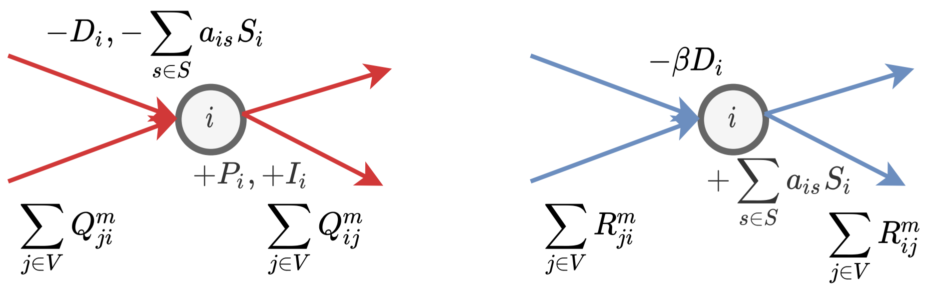


Figure 10: In out flow of demand and storage flows.

region i should consume a fraction of its demand due to seasonality βD_i, while it produces storage in the form of $\sum_{s\in S} a_{is}S_i$ when storage type s is available ($a_{is} = 1$). These should be equal to each other, plus any in- and outflows excluding this consumption and storage. In this case the inflow of hydrogen meant for hydrogen $\sum_{m\in M}\sum_{j\in V} R^m_{ji}$ plus what is consumed βD_i should be equal to the outflow of hydrogen $\sum_{m\in M}\sum_{j\in V} R^m_{ij}$ plus what is produced in terms of storage $\sum_{s\in S} a_{is}S_i$.

$$\beta D_i + \sum_{m\in M}\sum_{j\in V} R^m_{ij} = \sum_{m\in M}\sum_{j\in V} R^m_{ji} + \sum_{s\in S} a_{is}S_{is} \qquad i \in V \tag{6}$$

Next, to both make sure the capacity of a single transport unit m is not exceeded as well as limiting the number of regions j a region i is neighboured to, we use equation (7). Here, we add the transport flows for demand and storage together for each transport mode m as $Q^m_{ij} + R^m_{ij}$. For pipeline, this total flow from region i to j should be possible when region i and region j neighbour, that is when $A^m_{ij} = 1$. When they do neighbour each other, we are able to transport flows via pipeline. For trucks, we are able to transport hydrogen from region i to any other region j directly, so A^m_{ij} always equals 1 for truck transport. In this way, we model the pipeline flow as a network and the trucks as direct links. For trucks $Q^m_{\max}$ is equal to the capacity of one truck for which X^m_{ij} equals the number of trips from region i to region j. For pipeline, $Q^m_{\max}$ is equal to the yearly maximal throughput capacity, so therefore X^m_{ij} equals the number of pipelines needed from region i towards region j to handle the total flow $Q^m_{ij} + R^m_{ij}$.

$$Q^m_{ij} + R^m_{ij} \le A^m_{ij} Q^m_{\max} X^m_{ij} \qquad m \in M, i, j \in V \tag{7}$$

Then, we add two constraints (8)-(9) to make sure no flows are both imported and exported at the same time to and from region i. When this would happen, a circular flow could exist in the model which would unnecessarily enlarge the flow capacity in the chain. First we introduce a 'big M' constraint in (8), which makes sure that when X^m_{ij} is greater than zero, indicator variable Y^m_{ij} is equal to one. When X^m_{ij} is zero, Y^m_{ij} is allowed to be zero or one. In this way, when there is a flow going from region i to j we know this by variable Y^m_{ij} being equal to one. To make sure no flow is imported and exported at the same time we restrict the sum of import to region i (Y^m_{ji}) and export from region i (Y^m_{ij}) to be smaller than 1. This means import and export cannot happen at the same time.

$$X^m_{ij} \le M Y^m_{ij} \qquad m \in M, i, j \in V \tag{8}$$
$$Y^m_{ij} + Y^m_{ji} \le 1 \qquad m \in M, i, j \in V \tag{9}$$

For the transport of hydrogen via truck we finally need the number of trucks needed in the supply chain as given in equation (10). To do this, we first compute the number of trips as given by the total transport flow for both demand and storage requirements ($Q^m_{ij} + R^m_{ij}$) divided by the capacity per truck $Q^m_{\max}$. Then, we multiply the number of trips by twice the distances (back and forth) that need to be travelled for each active flow. In this way, we have the total number of kilometers that need to be travelled. When we divide this total distance by the average truck speed, we get the total travelling time for all trucks in the supply chain. Then we add the number of trips times the average loading and unloading time to get the total time needed for all trucks in the chain. As trucks are not always available we divide by the number of hours a truck is available per year, TA. In this way we arrive at the number of trucks needed in the supply chain, NTU.

$$NTU = \left(\sum_{m=\text{truck}} \sum_{i \in I} \sum_{j \in J} \frac{Q^m_{ij} + R^m_{ij}}{Q^m_{\max}} \right) \cdot \left(\frac{2d_{ij}}{SP} + LUT \right) \cdot \frac{1}{TA} \tag{10}$$

Then, we proceed with final constraints for the decision variables of production, import and storage. First, we introduce constraints (11)-(13) for the production of hydrogen. First, we use (11) again as a big-M constraint to measure whether a production has been set up in region i ($Z^P_i = 1$) or not i ($Z^P_i = 0$). This variable is then used for the fixed cost of production in region i in the objective function. Then, we limit the production of hydrogen to a certain amount with $P^{\max}$ as enough renewable energy has to be available in each region i for production. Lastly, in (13) the regions that do not have access to large renewable energy sources ($i \in V \setminus V^R$) are restricted even more in terms of production with $P'^{\max}$.

$$P_i \le M Z^P_i \qquad i \in V \tag{11}$$

$$P_i \le P^{\max} \qquad i \in V \tag{12}$$

$$P_i \le P'^{\max} \qquad i \in V \setminus V^R \tag{13}$$

Secondly, for the import of hydrogen constraints we introduce constraints (14)-(15). The first constraint states that the total imported hydrogen of all regions $\sum_{i \in V} I_i$ should be equal to what is given in the scenario of Netbeheer Nederland (2021) as I^T. The second constraint restricts the regions to only allow import where this is possible at coastal regions as given in Section 3.4.

$$\sum_{i \in V} I_i = I^T \tag{14}$$

$$I_i \le 0 \qquad i \in V \setminus V^I \tag{15}$$

Thirdly, for the storage decision variables we introduce constraints (16)-(17). The first constraint limits the storage with salt caverns to only the regions which can host these storage facilities ($i \in V^C$). The last constraint limits the maximum storage capacity for each technology $s \in S$ and region $i \in V$ as a limited space in salt caverns is available and limited space is available for the other two storage forms.

$$S_{is} \le 0 \qquad i \in V \setminus V^C, s = \text{salt caverns} \tag{16}$$

$$S_{is} \le S^{\max} \qquad \forall s \in S, i \in V \tag{17}$$

Finally we present the objective function given in equations (18)-(20). Here, $\sum_{i \in V} Z^P_i f^{\text{production}}$ and $\sum_{i \in V} P_i (c^{\text{production}} + c^{\text{feedstock}})$ are the fixed and variable costs for production and feedstock over all regions i. Then, $\sum_{i \in V} \sum_{s \in S} S_{is} c^{\text{storage}}_s$ is the variable cost over all storage forms $s \in S$

and in all regions i. Term $(NTU)f^{\text{truck}}$ represents the total fixed costs for the number of trucks in the supply chain. The final to last term represents the variable cost for both pipeline and truck transport. For pipelines, the number of pipelines from region i to region j times the distances times the variable cost per kilometer are given. For truck this amounts to the total number of trips times the distance times the variable unit cost per kilometer. Lastly, $\sum_{i \in V} I_i c^{\text{import}}$ represents the total cost of importing hydrogen over all regions $i \in V$.

$$\sum_{i \in V} Z_i^P f^{\text{production}} + \sum_{i \in V} P_i (c^{\text{production}} + c^{\text{feedstock}}) \tag{18}$$

$$+ \sum_{i \in V} \sum_{s \in S} S_{is} c_s^{\text{storage}} + (NTU) f^{\text{truck}} \tag{19}$$

$$+ \sum_{m \in M} \sum_{i \in V} \sum_{j \in V} X_{ij}^m d_{ij} c_{ij}^m + \sum_{i \in V} I_i c^{\text{import}} \tag{20}$$

A one-page overview of the hydrogen supply chain model can be seen in Appendix C.

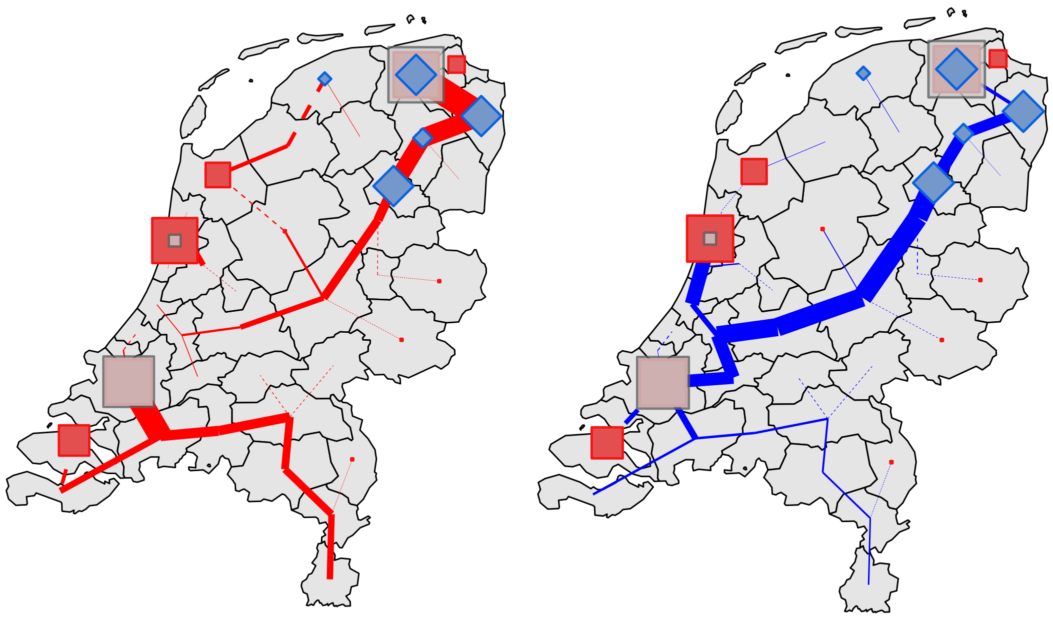
5 Results

In this section, we discuss the outcome of our hydrogen supply chain model and we treat the given hypotheses. We first discuss the general supply chain solutions in Section 5.1. Then, we will continue to answer our hypotheses in Sections 5.2-5.4. Lastly, we check our results against more extreme scenarios as a robustness check in Section 5.5.

5.1 Supply chain solutions

First, we show the solutions of our hydrogen supply chain model. In Figure 11a and 11b, the optimal solution of the hydrogen supply chain model is displayed. The symbols and flows are the same as given in the previous examples. The red and grey squares are the sizes of total production and import, respectively. The blue diamonds represent the size of the storage. In terms of transport, the red flows originate from production or import locations, while blue flows originate from storage facilities. Lastly, the solid lines represent the pipeline flows, while the dashed lines represent the truck transport.

First we note that almost all production and import is located in regions next to the sea with access to renewable energy. This result was already evident as only large amounts of production and import were allowed in this regions. However, we see that both import and production is quite evenly distributed over these regions. There exists import and production in Zeeland, Rotterdam, IJmuiden as well as in the North in Groningen. This is intuitive as spreading production and import locations over regions allows to relieve the pipeline network, saving in network costs. Moreover, these regions are also the locations with the highest demand for hydrogen. This means this demand does not have to be transported between regions.



(a) Solution showing the flow from production and import **(b)** Solution showing the flow from the storage facilities

Figure 11: Solutions of the hydrogen supply chain model with production (red square), import (grey square), storage (blue diamond) and demand flow (red) and storage flow (blue). Solid lines are pipeline transport, while dashed lines are truck transport.

In terms of storage, we see that all storage is located in regions where salt caverns provide a cheap option for long-term hydrogen storage. Most notably, we point at the blue flow coming from the North (Groningen), which has to provide in stored hydrogen especially for the

Rotterdam, IJmuiden and Zeeland region. Again, we note that these regions have the highest estimated hydrogen demand. We therefore conclude that while the production locations are able to be placed next to its ideal locations, the cheap alternative of salt caverns require us to transport hydrogen from northern regions to demand regions in the West. Next to the large blue flow from storage from the North, the other large flow is the red demand flow towards the South. Again we note that Limburg in the South also has a high hydrogen flow due to its industry.

Next to the sizes of the flows, we note that both pipeline and truck transport is used in the supply chain. For the bigger flows, pipelines are used while the smaller flows into low demand regions uses trucks. We see that for both the production and storage flows, most low demand regions are served by passing pipelines flows going to high demand regions. The other low demand regions that do not have a passing large pipeline are typically served by trucks. We go deeper into pipeline vs. truck transport in Section 5.3 where we answer Hypothesis 2.

Lastly, we show the model performance as listed in Table 8. We set the optimality gap to 0.10%, which `CPLEX` was able to solve in 53.91 seconds. As shown in the table, there exists a significant number of integer and binary variables, which could hinder the performance of the model. We note that for larger instances such as bigger countries, the model might take more time.

Table 8: An overview of model performance.

	Model output
Number of constraints	9,991
Number of integer/binary variables	6,599
Number of continuous variables	6,561
Optimality gap	0.10%
CPU time (s)	53.91

5.2 Supply chain costs

Next, we treat the supply chain costs to answer our first hypothesis. As can be seen in Table 9, all yearly costs within the supply chain are given. Most notably we see that most costs originate from the feedstock and production. More specifically, production and feedstock costs together form over 84% of the total costs of the supply chain. This accounts for the costs of the production facilities and the electricity costs of producing the hydrogen. Therefore, we accept our first hypotheses stating that the feedstock and production takes up the majority of the costs within the hydrogen supply chain.

In this research, 84% is higher than other papers in the field. This can be due to the fact that not all details of the supply chain are taken into account such as further local transportation and conditioning of the hydrogen. In this way, not all costs have been taken into account. Nevertheless, it confirms other academic findings that production of hydrogen is the largest bottleneck in the supply chain.

Another large cost element in the supply chain is the costs of importing the hydrogen. Furthermore, the costs of storage and transport via pipeline and truck are negligible compared to the other costs.

5.3 Pipeline vs. truck transport

Then we continue with our second hypothesis. We argued through previous literature and through the fact that there exist a gas network in the Netherlands that can be cheaply reused, pipeline transport would be more economically feasible than truck transport.

Table 9: An overview of the solution found by the hydrogen model.

	Costs	Share (%)		Solution characteristics
Feedstock	€7,150,739,808	58.78%	Total feedstock	101,874 GWh/year
Import	€1,801,800,000	14.81%	Total production	101,874 GWh/year
Production	€3,144,643,258	25.85%	Total import	75,000 GWh/year
Storage	€27,963,240	0.23%	Total storage	33,074 GWh/year
Pipeline	€33,718,478	0.28%		
Truck	€6,427,594	0.05%	Total demand flow pipeline	240,709 GWh/year
			Total demand flow truck	18,420 GWh/year
Total	€12,165,292,378	100%	Total storage flow pipeline	203,809 GWh/year
			Total storage flow truck	10,642 GWh/year
			Number of trucks (NTU)	304 trucks
			Number of pipelines (reused/new)	23 reused, 1 new

As our solutions in Figure 11a and 11b show, this is not always case. In Figure 11a and 11b, the competitiveness depends on the volume of hydrogen that needs to be transported. As said, smaller volumes are handled by truck while larger flows are transported by pipeline. To discover in which cases trucks are more competitive, we perform a cost analysis comparing truck and pipeline costs in Figure 12. Using a variable hydrogen volume and assuming an average distance of 110 km (average distance between each Dutch NUTS3 centroid), we compute the number of trucks needed by using equation (10). We use the number of trucks together with the assumed distance to compute the total costs of truck transport for each hydrogen volume as shown as the red line.

Meanwhile, the costs of reused and new pipelines are fixed for each hydrogen volume as it only depends on distance. When we plot both fixed lines together with the truck costs, we conclude that trucks are competitive against reused pipelines under around 1800 GWh/year. Against new pipelines, trucks are competitive under 4,000 GWh/year. This is indeed what we see in our solutions. All truck flows are under 1800 GWh/year, except a few which operate between regions where no old pipeline exists.

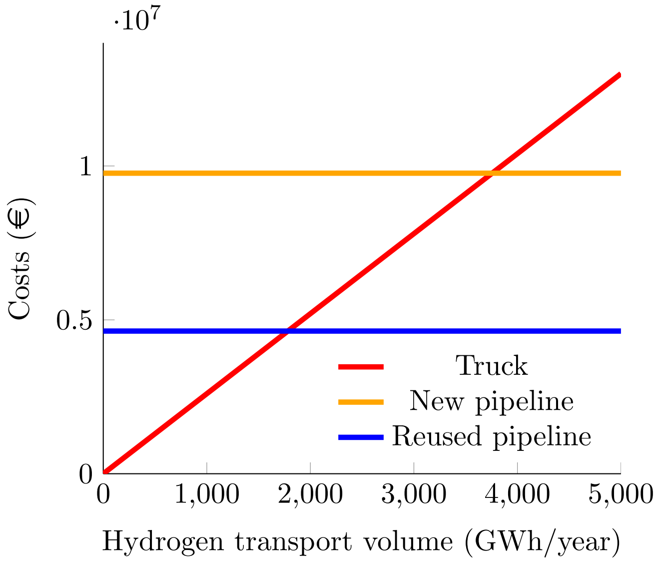


Figure 12: Total transport costs of the three different transport modes over the total distance.

Using our solutions of the model together with our analysis, we therefore reject hypothesis 2 stating that pipelines are economically more competitive than truck transport. The competitiveness of truck transport indeed depends on the hydrogen volume that needs to be carried.

This confirms the main findings of Bloomberg (2020) and Niermann et al. (2021) for the hydrogen volumes and typical distances in the Netherlands. Still, each country has different hydrogen volumes that need to be transported. Therefore, it is perfectly reasonable that other literature such as Wickham et al. (2022) finds that only using pipelines is the best alternative.

Finally, as an exercise we also let the supply chain model solve only using trucks to see how competitive trucks are against pipelines. The brief solution is shown in Table 10. Most notably, we see that that the total costs are only 30 million euros higher per year using only trucks. We conclude that therefore pipelines are not necessarily needed for a supply chain network in the Netherlands, as Konda et al. (2011) concluded earlier. Moreover, 2,050 trucks are needed in this supply chain which also seems feasible. The only advantage of pipelines are that they are reliable in delivery, but this is out of the scope of this thesis.

Table 10: An overview of the solution only using trucks as transport.

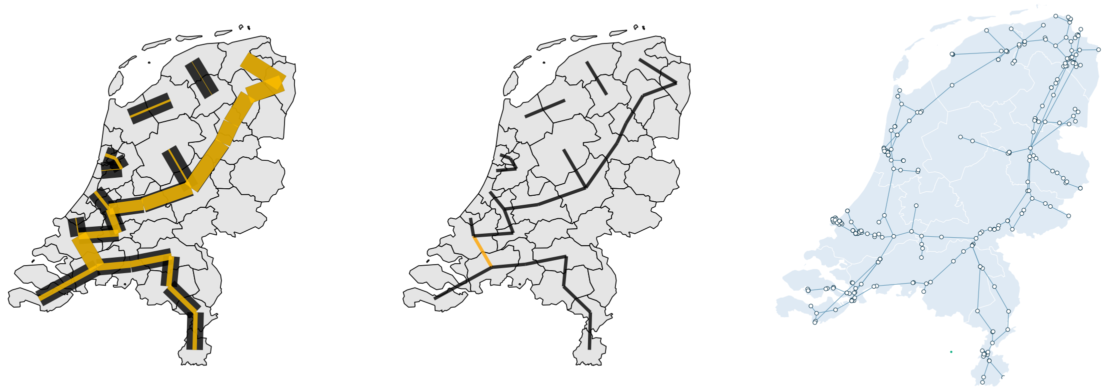
	Costs	Share (%)		**Solution characteristics**
Feedstock	€7,150,739,808	58.64%	Total feedstock	101,874 GWh/year
Import	€1,801,800,000	14.77%	Total production	101,874 GWh/year
Production	€3,146,266,494	25.80%	Total import	75,000 GWh/year
Storage	€27,964,440	0.23%	Total storage	33,074 GWh/year
Pipeline	€0	0.00%		
Truck	€68,421,429	0.56%	Total demand flow pipeline	0 GWh/year
			Total demand flow truck	100,766 GWh/year
Total	€12,195,192,171	100%	Total storage flow pipeline	0 GWh/year
			Total storage flow truck	44,163 GWh/year
			Number of trucks (NTU)	2,050 trucks
			Number of pipelines (reused/new)	0

5.4 Pipeline network capacity

Then, we answer our last hypothesis of whether the capacity of the existing gas network is sufficient to handle to future hydrogen pipeline transport. To do this, we aggregate the pipeline flows coming from production/import locations and from storage facilities. These flows together should not exceed the maximum throughput capacity per year for normal 36 inch pipelines of 40,992 GWh per year. The sum of the flows and the capacities of the pipelines are shown in Figure 13a. The yellow lines represent the sum of the flows between each region, where the black lines indicate the available capacity.

As can be seen in the figure, the combined flows often reach the maximum capacity of the network. Especially, in the flows from the North towards the West from storage locations this happens. Moreover, the production flow from Rotterdam to the South could create a bottleneck. More specifically, as shown in Figure 17 in Appendix D we note that that six out of the 24 pipeline connections achieve around the maximum yearly throughput capacity. Therefore, we just accept our last hypothesis that the pipeline network does not need to be extended. However, through the large flows from especially the storage facilities, the network could use expansion in the future.

Lastly, we compare the found pipeline network to the network as envisioned by Netbeheer Nederland (2021). In Figure 13b the found network is displayed with black lines the reused pipelines and orange the newly built connection. We compare this solution to the network in Figure 13c. We see that the found connections from the North to the West as well as the connection running the South-west towards the South-east are the same as Netbeheer Nederland envisions. Moreover, we note that our solution does not create a full loop in the West towards to North. This is due to the fact that in these areas trucks operate as an alternative. Nevertheless, our network resembles the plans from Netbeheer Nederland. This is mainly due to the fact that old pipelines can be reused as seen by the great number of black lines in Figure 13b.



(a) Sum of production and storage flows compared to pipeline capacities.

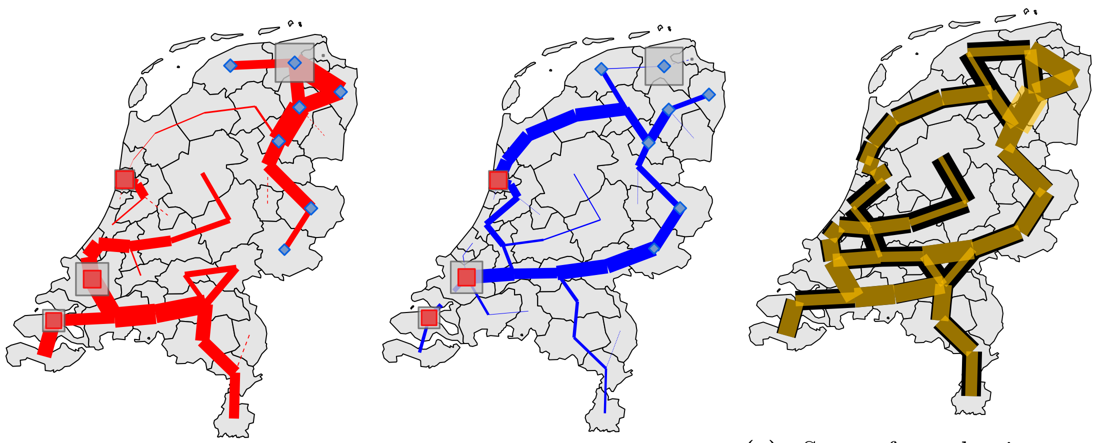
(b) Used pipelines of the solution that are re-used (black) and that are newly constructed (orange).

(c) Hydrogen pipeline network in 2050 as envisioned by Netbeheer Nederland (2021).

Figure 13: Pipeline network of the solution found by the hydrogen model and as envisioned by Netbeheer Nederland (2021).

5.5 Robustness checks

To check the validity of our second and third hypotheses we lastly perform two robustness checks. These robustness checks are in the form of varying our national demand. Next to demand, our results also heavily depend on the cost and performance parameters of truck and pipeline transport. However, as we have more data available on demand through the scenarios of Netbeheer Nederland (2021), we choose to test our results against varying scenarios. We note that we do not check our first hypothesis, as almost all hydrogen demand is imported in the International scenario. Therefore, less is produced in the final scenario which also lowers the production costs.



(a) Solution showing the flow from production and import

(b) Solution showing the flow from storage facilities

(c) Sum of production and storage flows compared to the pipeline capacities.

Figure 14: Supply chain network found by the hydrogen model using the International scenario.

First, we choose to test our results using the International scenario as treated in Section 3.2. In Figure 14, the flows from the production and import, storage facilities and the sum of the flows are displayed. For our second hypotheses we see that still there exist regions that are best served by truck. Therefore, even in this extreme scenario the flow do not become big enough to let pipeline be more competitive than truck transport. This means our second hypotheses is robust against more extreme scenarios. Nevertheless, we see that less truck connections are used as the flows in this scenario are bigger and thus better transported by pipeline.

We also see the trend of more pipeline use in the pipeline throughput map in Figure 14c. The pipeline network is used more extensively than in the National scenario and in two connections the capacity is exceeded. Therefore, in this scenario we reject our hypotheses that the pipeline infrastructure is sufficient to handle the future Dutch hydrogen demand.

To assess when our last hypothesis is rejected we run the model for the demand estimates varying from the National scenario until the size of the International scenario. For each in-between scenario, we use the the sector demand such that each of these scenarios is a perfect hybrid between the two as can be seen in Appendix E. This is done to account for the difference in sector demand between the two scenarios. For each demand size, we measure how many pipeline connections exceed the maximum throughput capacity. The results of this experiment are shown in Figure 15. We see that for total Dutch hydrogen demand up til 200,000 GWh/year, our hypothesis holds to some extent. That is, there is roughly enough capacity in the pipeline network to handle the demand. However, from 200,000 GWh/year until the extreme International scenario onward, we see that a significant number of pipeline connections needs to be expanded. We thus conclude that our hypothesis holds until this point. We note that the number of connections that have exceeding capacity varies through the plot. This is because for each scenario the pipeline network changes and with it the number of connections with exceeding capacity. Sometimes a network is used with more connections and other times less connections are used but using extra capacity.

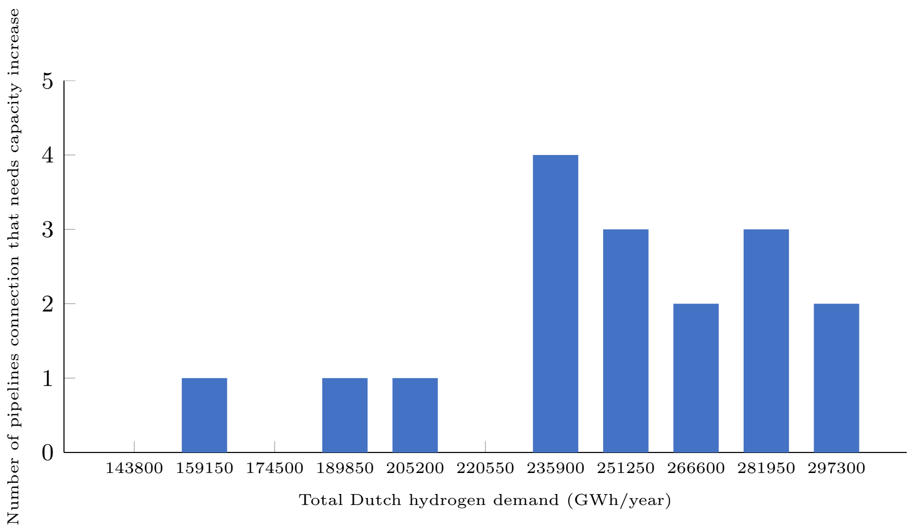


Figure 15: Number of pipeline connections that need expansion in each solution, depending on the demand size of varying scenarios (GWh/year).

6 Conclusion

In this thesis, we considered a hydrogen supply chain model for the year 2050 in the Netherlands. To improve the applicability of the model, we focused on collecting future hydrogen demand as well as adapting the model to the Dutch context. More specifically, we first discussed the future national Dutch hydrogen demand in 2050. Then, we distributed this estimate over Dutch NUTS3 regions using various data sources. Moreover, we collected cost and performance parameters of import, production, storage, pipeline and truck transportation for the model. Finally, we formulated a new model focusing on the transport flows as well as incorporating feasibility of production, import and storage within the Dutch context.

Our results showed that most hydrogen transport is required due to the industry in the South as well as hydrogen going to and coming from salt cavern storage locations in the North. Using the results, we accepted our first hypothesis stating that production and feedstock forms the greatest costs in the supply chain. This is particularly relevant for governments and stakeholders that can help alleviate the greatest bottleneck in a future hydrogen supply chain. Furthermore, we concluded for our second hypothesis that for the Dutch case, truck and pipeline transport of hydrogen are both competitive depending on the transport volume. More notably, truck transport also seems feasible for a future supply chain only using trucks. Therefore, Netbeheer Nederland has this option available next to its pipeline network. Trucks could for example be of use during the transition from gas to hydrogen network to accommodate large demands that the network cannot handle yet. Lastly, this conclusion is even more important as we concluded for our third hypothesis that the network is fully stressed in 2050. Therefore, we conclude that the pipeline network needs to be expanded to handle future hydrogen transport. Lastly, using two robustness checks we confirmed that trucks are still competitive in more extreme demand scenarios. Also, we concluded that the throughput capacity of the pipeline network is not sufficient for a national demand of 200,000 GWh/year onward. Therefore, our second hypothesis seems robust, while our last hypothesis depends on the hydrogen scenario.

Using the results we address three key recommendations for hydrogen supply chain stakeholders and governmental agencies. First, as the main costs of a future hydrogen supply chain are in the production side of hydrogen, we recommend first inspecting whether this part of the supply chain has sufficient incentive to produce. Especially in the starting phase of the supply chain, barriers to supply hydrogen should be alleviated as soon as possible to also stimulate hydrogen demand. This would in turn stimulate the supply of hydrogen, giving a kick-start to the economics of hydrogen. Secondly, as truck transport provides a viable alternative to pipeline distribution this mode can be used as a backup. We would recommend distribution stakeholders to consider this option in case the pipeline network is still in transformation or in case the network cannot handle unexpected demand. Lastly, as we showed that the pipeline network is close to its full throughput capacity in 2050, we recommend making plans beforehand to increase the capacity of the network. This is especially the case when more extreme hydrogen demand scenarios become more likely.

Finally, we address our key assumptions and shortcomings of this thesis and recommendations for future work. First, the main conclusions heavily depend on the cost estimates within the supply chain. When for example storage facilities other than salt caverns would be less expensive this also would mean less storage flow would have to be transported, saving in network costs. Cost estimates also influence the way in which trucks and pipeline were competitive and for which transport volume. These techno-economic parameters are often complicated figures subject to multiple assumptions. For future research, it could be worthwhile to make a study fully focused on these parameters and what effect they have on the results. Secondly, another assumption of our research is the size and spatial heterogeneity of hydrogen demand. Although we are comfortable in using the demands from Netbeheer Nederland (2021), dividing these estimates for each NUTS3 rests on multiple assumptions as discussed in Section 3. A wrong division of demand could for example mean that we underestimate hydrogen demand in low-demand regions. This would mean that we underestimate the need for hydrogen transportation, and thus the feasibility and costs of our transport network. Thirdly, our optimization model does not include all details within a hydrogen supply chain. This was to give more focus on our hypotheses. Nevertheless, using more details such as purification and final distribution within the region might add to the model, also possibly influencing its results and our conclusions. For example, some regions already have sufficient local distribution by pipeline, while other regions do not, which might require truck transport. In this case, transport to this region by pipeline might not be optimal. Fourthly, while it does not happen frequently, we note that in our model it is still possible to go from pipeline to truck and back to pipeline in terms of transport. While it is possible, these situations are not efficient in real life. Future research could work on improving the model such that these cases do not happen. Lastly, we note that our model is not solved to optimality. While 0.10% does not seem big, this is still a third of the total transport cost by pipeline and truck. This means there could exist a maximum reduction by 33% in transport costs. Therefore, it may be worthwhile to improve the performance of the model to more quickly come to an optimal solution.

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A National hydrogen demand 2050

Table 11 shows the national Dutch hydrogen demand in 2050 for each scenario and all sources discussed in the thesis. On the right side, the average of each scenario is given.

Table 11: Total hydrogen demand estimations for 2050 per scenario (TWh/year) as given by five main sources.

	Hydrogen demand 2050 per scenario (TWh/year)				
	Regional	National	European	International	**Average**
Gas For Climate (2021)	-	-	-	-	138.5
ISPT (2019)	-	-	-	-	194.4
CE Delft (2017)	115.9	185.3	-	134.5	145.1
Berenschot (2020)	33.6	73.9	116.9	143.9	92.1
Netbeheer Nederland (2021)	95.3	142.9	138.5	297.3	168.7

B Building heating hydrogen demand

In Figure 16 the hydrogen demand is displayed for building heating for the International scenario. These numbers are used for the robustness check in Section 5.5.

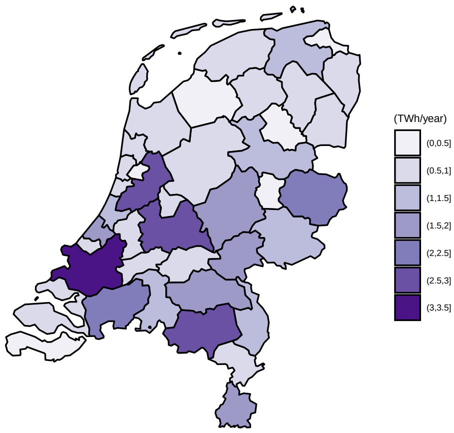

Figure 16: Resulting hydrogen demand per NUTS3 for building heating for the International scenario (TWh/year)

C Supply chain model

Below, the complete hydrogen supply chain as used in this thesis is given on one page as an overview. For a more extensive discussion on the constraints and decicion variables see Section 4.

Objective function

$$\min \quad \sum_{i \in V} Z_i^P f^{\text{production}} + \sum_{i \in V} P_i (c^{\text{production}} + c^{\text{feedstock}}) \tag{21}$$

$$+ \sum_{i \in V} \sum_{s \in S} S_{is} c_s^{\text{storage}} + (NTU) f^{\text{truck}} \tag{22}$$

$$+\sum_{m\in M}\sum_{i\in V}\sum_{j\in V} X_{ij}^m d_{ij} c_{ij}^m + \sum_{i\in V} I_i c^{\text{import}} \tag{23}$$

Production hydrogen in- outflow

$$\text{s.t.} \quad \sum_{s\in S} a_{is} S_{is} + D_i + \sum_{m\in M}\sum_{j\in V} Q_{ij}^m = \sum_{m\in M}\sum_{j\in V} Q_{ji}^m + P_i + I_i \qquad i\in V \tag{24}$$

Storage hydrogen in- outflow

$$\beta D_i + \sum_{m\in M}\sum_{j\in V} R_{ij}^m = \sum_{m\in M}\sum_{j\in V} R_{ji}^m + \sum_{s\in S} a_{is} S_{is} \qquad i\in V \tag{25}$$

Truck and pipeline availability and capacity

$$Q_{ij}^m + R_{ij}^m \leq A_{ij}^m Q_{\max}^m X_{ij}^m \qquad m\in M, i,j\in V \tag{26}$$

Circular flow restrictions

$$X_{ij}^m \leq M Y_{ij}^m \qquad m\in M, i,j\in V \tag{27}$$

$$Y_{ij}^m + Y_{ji}^m \leq 1 \qquad m\in M, i,j\in V \tag{28}$$

Number of trucks definition

$$NTU = \left(\sum_{m=\text{truck}} \sum_{i\in I}\sum_{j\in J} \frac{Q_{ij}^m + R_{ij}^m}{Q_{\max}^m} \right) \cdot \left(\frac{2d_{ij}}{SP} + LUT \right) \cdot \frac{1}{TA} \tag{29}$$

Production fixed cost and restrictions

$$P_i \leq M Z_i^P \qquad i\in V \tag{30}$$

$$P_i \leq P^{\max} \qquad i\in V \tag{31}$$

$$P_i \leq P^{'\max} \qquad i\in V\setminus V^R \tag{32}$$

Import requirement and availability

$$\sum_{i\in V} I_i = I^T \tag{33}$$

$$I_i \leq 0 \qquad i\in V\setminus V^I \tag{34}$$

Storage availability and restrictions

$$S_{is} \leq 0 \qquad i\in V\setminus V^C, s = \text{salt caverns} \tag{35}$$

$$S_{is} \leq S^{\max} \qquad \forall s\in S, i\in V \tag{36}$$

Decision variables

$$P_i, I_i, S_{is}, Q_{ij}^m, R_{ij}^m \geq 0 \qquad \forall m\in M, i,j\in V \tag{37}$$

$$NTU, X_{ij}^m \in \mathbb{N} \qquad \forall m\in M, i,j\in V \tag{38}$$

$$Y_{ij}^m, Z_i^P, Z_{is}^S \in \{0,1\} \qquad \forall m\in M, i,j\in V \tag{39}$$

D Pipeline throughput histogram

Figure 17 shows the number of pipeline connections with a specific throughput value the connections have as a histogram.

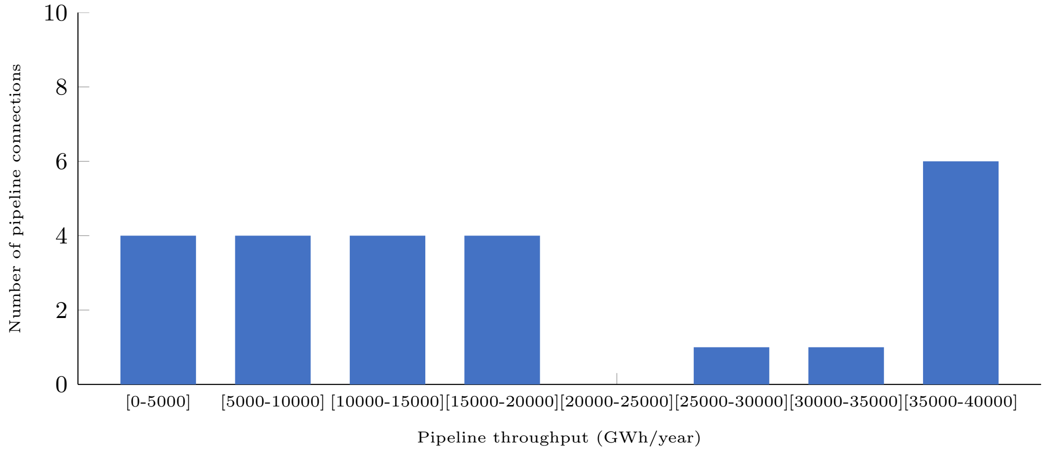

Figure 17: Histogram of the throughput through each pipeline connection given by the solution of the National scenario, where the throughput is in GWh/year.

E Hybrid scenarios

We use the scenarios between the National and International scenarios as hybrid to measure the impact between altering from scenario in Section 5.5. This is done by taking the difference between the left and most right scenario and step-wise increasing each sector until it reaches the International scenario.

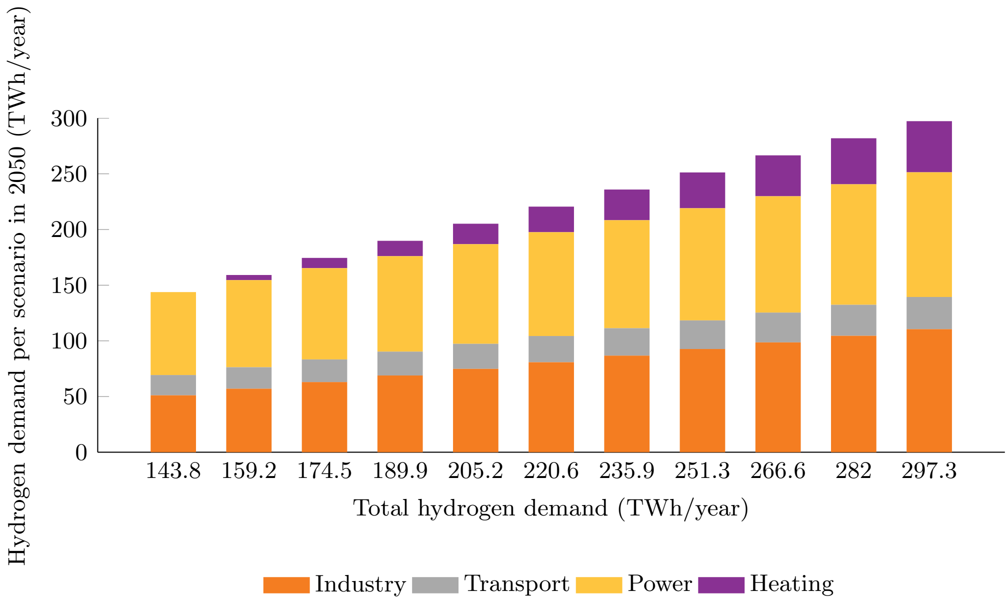

Figure 18: Hydrogen demand per sector in 2050 per scenario hybrid between the National scenario (left) and the International scenario (right) (TWh/year).

F Regional hydrogen demand 2050

In Table 12 the demand sizes for each NUTS3 region for the National scenario are displayed.

Table 12: Regional hydrogen demand for 2050 (GWh/year) estimated by using the three sectors and dividing the estimate of the National scenario.

NUTS3	**NUTS3 name**	**Hydrogen Demand (GWh/year)**
NL111	Oost-Groningen	181.15
NL112	Delfzijl en omgeving	3,139.03
NL113	Overig Groningen	20,822.63
NL124	Noord-Friesland	3,884.00
NL125	Zuidwest-Friesland	213.47
NL126	Zuidoost-Friesland	320.93
NL131	Noord-Drenthe	240.18
NL132	Zuidoost-Drenthe	210.09
NL133	Zuidwest-Drenthe	286.50
NL211	Noord-Overijssel	333.04
NL212	Zuidwest-Overijssel	621.21
NL213	Twente	606.48
NL221	Veluwe	552.62
NL224	Zuidwest-Gelderland	924.58
NL225	Achterhoek	679.28
NL226	Arnhem/Nijmegen	848.08
NL230	Flevoland	5,138.58
NL310	Utrecht	4,063.80
NL321	Kop van Noord-Holland	227.45
NL323	IJmond	18,996.38
NL324	Agglomeratie Haarlem	350.15
NL325	Zaanstreek	553.18
NL327	Het Gooi en Vechtstreek	667.12
NL328	Alkmaar en omgeving	359.75
NL329	Groot-Amsterdam	6,970.26
NL332	Agglomeratie 's-Gravenhage	1,327.68
NL333	Delft en Westland	620.38
NL337	Agglomeratie Leiden en Bollenstreek	1,160.07
NL33A	Zuidoost-Zuid-Holland	1,050.89
NL33B	Oost-Zuid-Holland	765.61
NL33C	Groot-Rijnmond	26,510.72
NL341	Zeeuwsch-Vlaanderen	13,590.60
NL342	Overig Zeeland	6,547.35
NL411	West-Noord-Brabant	9,047.45
NL412	Midden-Noord-Brabant	817.86
NL413	Noordoost-Noord-Brabant	612.47
NL414	Zuidoost-Noord-Brabant	561.74
NL421	Noord-Limburg	415.88
NL422	Midden-Limburg	1,015.35
NL423	Zuid-Limburg	8,566.00