HYDROGEN IMPORT SUPPLY CHAINS

A study on the influence of various supply chain configurations on the cost price of hydrogen for different hydrogen carriers, considering the entire supply chain from export terminal to end-user

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Hydrogen Import Supply Chains

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Preface

With the completion of this graduation thesis, my Master's degree in Civil Engineering, Hydraulic Engineering at the TU Delft has come to an end. The research was carried out in cooperation with the Port of Rotterdam. To do a research on a subject that is becoming increasingly more important in driving the energy transition was very exciting to me. It gave me the opportunity to work in a dynamic environment where no one yet knows exactly what the best or most promising opportunities are, but where everybody passionately wants to share their knowledge. I want to thank everyone who helped and supported me throughout my research, in particular, I would like to thank my graduation committee.

First of all, I would like to thank my supervisors from the TU Delft. I want to thank Mark van Koningsveld, the chairman of my committee, for his help, motivation and support throughout my thesis. His endless ideas and critical questioning helped me to take my research to the next level. Our brainstorming sessions on possible approaches to models have continuously challenged me to achieve the best results. Because I invested a lot of time in the development of models during my research, it was sometimes important to remember that a model is not an exact representation of what happens in reality. I would like to thank Ad van Wijk for sharing his knowledge about hydrogen and the current and future developments in the energy transition, this has helped me a lot in gaining a better understanding of the current situation and the future possibilities. The meetings with Ad were full of challenging questions and I would like to thank him for always taking the time to explain everything to me in detail. I also want to thank Poonam Taneja for her support and confidence in my approach and her positive outlook. It was very nice to talk to her, not only about the content of my research but also about my process and planning. My meetings with her helped me a lot in having a structured approach during my research and in remaining motivated.

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Abstract

In 2015, the Paris Agreement was established with the aim of ensuring that the global response to the threat of climate change is strengthened (UNFCCC, 2020). To achieve this objective, greenhouse gas emissions must be at least 40% below 1990 emission levels by 2030 (European Commission, 2020). Hydrogen is an energy carrier that can be stored for long periods and transported over long distances. Hydrogen produced by electrolysis of water, powered by renewable energy, is seen as the key to enabling the energy transition and creating a new green economy. The result will be a trade market for low-carbon hydrogen where the trade routes will be determined by natural, technical, cost and geopolitical factors (Notermans et al., 2020). However, to transport or store hydrogen, it must be compressed, liquefied or attached to a carrier due to its low energy density per unit volume (IEA, 2019). The challenge of this is that the transport of hydrogen is expensive and still at an exploratory stage. More research is needed into the most cost-effective opportunities for the emerging hydrogen transport supply chains.

Several studies have examined the differences that arise with various forms of hydrogen transport in terms of energy efficiency, carbon footprint and costs. However, these studies often assume fixed export and import locations, a fixed demand, a fixed end-use and/or a fixed supply chain structure. Furthermore, most studies examine the supply chain between the export and import terminal in great detail and hardly any research is done into the effect of the interaction between the export and import supply chain and the supply chain to the hinterland. Based on this literature review, the influence of different end-uses, distances and required volumes on the supply chain structure and costs and on the form of hydrogen transport remains inconclusive. Therefore, the main objective of this research is to develop a method that provides insight into the effects of hydrogen supply chain configurations on the cost price of hydrogen at the end-use location. The method should provide a better understanding of the influence of different distances and required volumes on the supply chain structure and on the type of hydrogen transport. In addition, by connecting supply chains, it should become clear how the interaction of supply chains affects the cost and throughput. This results in the main research question:

"What is the influence of the required volumes, transport distances, the type of hydrogen carrier and the structure of the entire hydrogen transport supply chain on the cost price of hydrogen at the end-use location and what will be the most cost-effective supply chains?"

Firstly, research has been carried out into all the elements that can be present in the supply chain configurations under consideration. This study examines the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the end-user. The hydrogen carriers that are included in this study are liquid hydrogen (LH_2), ammonia (NH_3) and Liquid Organic Hydrogen Carriers (LOHCs, of which MCH and DBT are included in this research). Transport between the export terminal and the import terminal is limited to vessels, and for the transport between the import terminal and the hinterland, a choice can be made between pipelines, trucks, rail and barges. The supply chain can be structured in such a way that the reconversion to hydrogen takes place at the import terminal (centralized), resulting in transport to the hinterland in the form of compressed gaseous hydrogen (CGH_2). Alternatively, hydrogen reconversion can take place at the end-user (decentralized), in which case there is transport to the hinterland in the form of the chosen hydrogen carrier. In order to increase the reliability of the applied data, low, medium and high scenarios have been made for the investment costs regarding the elements.

To answer the main research question, a multi-echelon supply chain model has been created that is able to estimate all the costs that each echelon contributes to the total cost. This model can be used for a single supply chain, but is also capable of connecting multiple supply chains to clarify the influence of supply chain interactions. This is of great value as the literature review has revealed that this is an important topic that has not yet been adequately researched. In the model it is possible to modify distances, volumes, commodities and the structure of the supply chain in order to compare alternative supply chain configurations. The elements are parametrically aligned with each other to ensure that the loss of each element is included in the final throughput. In this way, the model takes into account that

for more losses, more elements may be required in a supply chain to meet a demand.

To investigate the influence of different supply chain configurations on the cost price, the individual supply chains were examined first. Initially, the supply chain from the import terminal to the hinterland was investigated, followed by the supply chain from the export terminal to the import terminal. After studying both supply chains, the entire supply chain from export to import to end-use was analysed. All considered supply chain configurations have been compared in such a way that graphical representations like Figure 1 were created. In this figure the overseas distance is variable, but besides this, the hinterland distance or the supply chain volumes have also been made variable in this study.

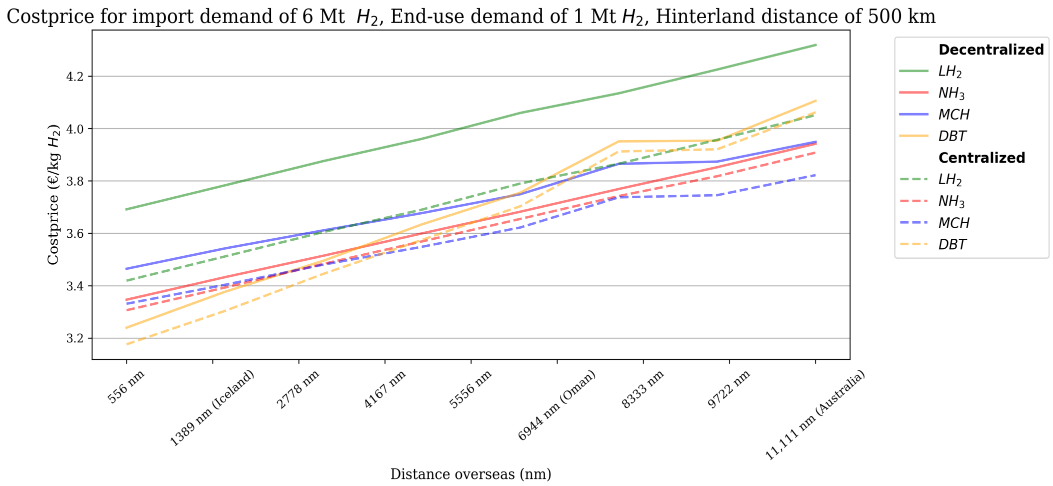

Figure 1: Cost price for the supply chain for a variable overseas distance

Eventually, it is concluded that if the overseas distance is made variable, DBT will be the most economical option for shorter oversea distances and that for longer oversea distances MCH and ammonia will be the most cost-effective options. This tipping point is around 3500 - 4500 nm (6500 - 8400 km), depending on the volume of the supply chain, the distance to the end user and whether the supply chain configuration is centralized or decentralized. However, it is important to note that the cost price of MCH and DBT is highly dependent on the procurement and selling price of the LOHCs. The centralized option will be more cost effective than the decentralized option for all the carriers. However, this may change for Ammonia in case of a large distance to the hinterland. It should be stressed, however, that the transport of large quantities of Ammonia by barge to the hinterland raises social and environmental concerns as Ammonia is a highly flammable and toxic substance. As a result, transporting large quantities of Ammonia to the hinterland may not be a realistic future scenario in some countries, or it may entail many additional costs that will increase the cost price significantly. It can also be concluded that the cost price of each carrier will approach a some what constant value at large supply chain volumes. From the sensitivity analysis, it can be concluded that the eventual cost price is very sensitive to the WACC and to the price at which the hydrogen is purchased in the export country. In addition, the cost price of LH_2 is highly sensitive to the number of storage tanks. All hydrogen carrier options are also relatively sensitive to the energy price.

Furthermore, some of the limitations of the research should be addressed in order to identify the shortcomings in this research and make recommendations for future research.

The results of this study are very sensitive to the input data, however, the reliability of this information is not very high as many technologies are still in the development phase. More research on the input data and on technological and cost developments within these supply chains is needed to increase the accuracy of the results. In addition, this study does not take into account any possible increase in costs due to issues related to safety, social or environmental aspects. Including these factors in the future will give a better perspective of reality and increase the trustworthiness of the results. This research also assumes that the transport in a supply chain is done solely by one transport modality. In reality, however, there is a high probability that this is not true. By including multi-modal transport in supply chain configurations in future research, a more realistic cost price can be estimated. Moreover, the cost price can also change significantly if the specific end-use is included. For example, when gaseous hydrogen is not needed as an end product but instead one of the carriers can be used directly, the cost price of this carrier will become increasingly attractive.

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1 Introduction

1.1 Background

Climate change has major consequences for humanity, nature and the environment. If greenhouse gas emissions continue to increase at the same rate, the temperature on Earth will keep rising. Scientists claim that this increase will continue for decades, largely due to the greenhouse gases produced by human activities (NASA, 2020). The Paris Agreement was drawn up in 2015, with the aim to ensure that the global response to the threat of climate change is strengthened by keeping the temperature rise below 2°C this century (UNFCCC, 2020). To achieve this goal, it has been said that by 2030, greenhouse gas emissions must be at least 40% less than those in 1990 (European Commission, 2020).

Hydrogen can play an important role in achieving a carbon-free future (Van Wijk & Wouters, 2019). The role of hydrogen has many similarities with that of electricity, as both are energy carriers and no greenhouse gases are produced when electricity or hydrogen is used. The production of hydrogen and electricity can, however, have a high CO_2 intensity, as these can be produced from fossil fuels (Wijk et al., 2019). Hydrogen produced from fossil fuels is called 'grey' hydrogen. Hydrogen can also be produced with reduced CO_2 emissions by applying Carbon Capture, Utilisation and Storage (CCUS), this is called 'blue' hydrogen. When hydrogen is produced by renewable electricity it is called 'green' hydrogen (IEA, 2019). In contrast to electricity, hydrogen can be stored for long periods and transported over long distances. In this way the energy system does not have to match demand and supply in real time and hence it is less vulnerable to disruptions of energy supply (IEA, 2019). However, to transport or store hydrogen it needs to be compressed, liquefied or attached to a carrier because of the low energy density per unit volume (IEA, 2019).

Hence, hydrogen can be the energy carrier that enables worldwide transport and large-scale storage of carbon-free and renewable energy (Wijk et al., 2019). It additionally provides the promise of the emergence of new jobs and economic activity in a sustainable and globally relevant sector (Wang et al., 2020). Hydrogen can contribute to this carbon-free future in two ways; (1) Hydrogen produced with cleaner production methods can be used in existing hydrogen applications and (2) hydrogen can be used in its pure form or it can be converted to hydrogen-based fuels, in this way hydrogen can be used as an alternative to current fuels and inputs (IEA, 2019).

Hydrogen produced through water electrolysis powered by renewable energy is thus seen as the key in enabling the energy transition and realizing a new, green economy. However, there will be regions with excess cheap renewable energy sources because of available space combined with positive wind and solar conditions, allowing for a surplus of green hydrogen production (Van Wijk & Wouters, 2019). These regions will trade hydrogen with regions willing to pay for this energy, hydrogen production, and its transport because of its regional energy scarcity, due to less favorable climatic conditions, density of population, and energy intensity of industry (Notermans et al., 2020). Areas such as Japan and Northwest Europe will simply run out of space for renewable energy production to meet their energy demand (Notermans et al., 2020). Hence a trade market for low-carbon hydrogen will emerge where the trade routes will be determined by natural, technical, cost and geopolitical factors (Notermans et al., 2020).

1.2 Research Problem

Most applications for low-carbon hydrogen are not cost-competitive without direct government support (IEA, 2019). There are many potential costs to be considered in the hydrogen supply chain due to the need for chemical conversion, liquefaction and compression, all of which are high-cost processes (IEA, 2019). The manner in which transport is organised will be strongly influenced by these high costs. Minimizing costs in the supply chain will lead to different forms of transport (Notermans et al., 2020). By looking at the distance, a choice will be made between transport via pipelines (up to 3000 km) or, where possible, energy can also be imported as electricity for direct use. For long distances, transport via shipping will be the dominant transport mode (Notermans et al., 2020). In addition to the transport costs, the end-use will also determine the form in which hydrogen is transported. However, at this moment it is not yet clear what the most cost-effective form of hydrogen transport is for different end-uses (Notermans et al., 2020).

The Netherlands is currently not only importing energy for its own use, but also for export. Wijk et al. (2019) concluded that a volume of about 10,500 PJ was imported in The Netherlands in 2017, of which about 9,500 PJ was transshipped. From this import volume, about 7,700 PJ was imported in the Port of Rotterdam of which 6,800 PJ was transited and exported, 520 PJ was used for bunker fuel and 370 PJ for own use. Most of these imports consist of oil and oil products (Wijk et al., 2019). Due to the Port of Rotterdam's dominant position in the trade of fossil fuels, the port is a successful industrial cluster (Notermans et al., 2020). If the Port of Rotterdam wants to maintain its unique position as an energy hub, the port will have to import comparable amounts of sustainable energy in the future, including green hydrogen in the form of liquid hydrogen, ammonia and/or hydrogen attached to a carrier (Wijk et al., 2019). To fulfill the most important potential of the Port of Rotterdam, namely becoming a hydrogen production and user hub and an import and trade hub for low-carbon hydrogen, the port must invest in acquiring knowledge about hydrogen transport, infrastructure and supply chains (Notermans et al., 2020).

In other words, the challenge is that the transport of hydrogen is expensive in comparison to today's oil and gas and still in the exploratory stage. More research needs to be carried out on the most cost-effective supply chains for the transport of hydrogen. The Port of Rotterdam must take steps within the hydrogen sector in order to remain the energy hub that the port currently is.

1.3 Research Gap

In this section, the research gap is defined by reviewing relevant literature for this study. First, insights obtained from various studies with a similar topic are described. Next, the actual research gap drawn from this literature review is discussed.

Research has been carried out on various forms of hydrogen storage and transport. Liquid hydrogen (LH_2), methylcyclohexane (MCH) (which is a Liquid Organic Hydrogen Carrier (LOHC)) and ammonia (NH_3) are considered the most promising hydrogen carriers in terms of their characteristics, economic performance and feasibility of applications (Wijayanta et al., 2019). This is especially assumed in Japan, one of the main movers in the world in the global introduction of hydrogen (Wijayanta et al., 2019). However, these three hydrogen carriers still have their challenges. Firstly, hydrogen liquefaction takes place at a temperature of -253°C, which means that a lot of energy is needed in the liquefaction process (Aziz et al., 2019). In addition, the shipping of liquid hydrogen is more disadvantageous due to complex storage and low volume density (Tijdgat, 2020), moreover hydrogen is lost during storage through evaporation (boil-off) (Tijdgat, 2020). Another challenge for liquid hydrogen is that the design of a ship capable of carrying liquid hydrogen is still in its early stages (IEA, 2019). The world's first liquid hydrogen carrier was just launched by the Kawasaki Heavy Industries in December 2019 (Recharge, 2019). However, additional conversion steps in other parts of the supply chain are reduced if liquid hydrogen is used (Tijdgat, 2020) and, compared to ammonia and MCH, the highest price reduction can be achieved in the case of liquid hydrogen due to technological developments (Aziz et al., 2019). Ammonia already liquefies at -33°C and it contains 1.7 times more hydrogen per cubic metre than liquid hydrogen (IEA, 2019). In addition, ammonia already has an established international transport and distribution network (IEA, 2019). Both synthesis and decomposition are processes that require a significant amount of energy, thus increasing the cost (Aziz et al., 2019). Additionally, ammonia cannot be used in some end-use sectors because it is a toxic chemical. Moreover, the escape of unburned ammonia can lead to the formation of fine dust and acidification (IEA, 2019). MCH is a LOHC, the properties of LOHC's are very similar to those of crude oil and oil products, which ensures that hydrogen storage and transport in the form of LOHC systems can make use of the already existing infrastructure of oil and oil products. LOHC's can therefore be transported as liquids without having to be cooled (IEA, 2019). However, the conversion and reconversion processes still consume a lot of energy because high temperature heat sources (at temperatures above 300°C (Wulf & Zapp, 2018)) are needed (Brigljević et al., 2020), which results in high costs (IEA, 2019). In addition, the carrier molecules in a LOHC are often expensive and when the hydrogen is extracted from a LOHC, the LOHC is not used up and has to be shipped back to its place of origin (IEA, 2019).

Conclusions have been drawn from reports as to which type of transport would be the most cost effective looking at the distance. From IEA (2019) it can be concluded that the transport of hydrogen as a gas via a pipeline is the most economical delivery option when the distances are below 3500 km. If the distance is greater, transporting hydrogen as ammonia or as a LOHC is probably more cost-effective. Transporting hydrogen as liquid hydrogen is always more expensive than transporting hydrogen as ammonia or as a LOHC. These are costs that are obtained from a supply chain starting with production and ending at a location for end-use. A hydrogen production cost of 3 USD/kg H_2 is assumed. In case of transport by ship, a reconversion to hydrogen plant is situated at the import terminal and a distribution of 100 tpd in a pipeline to an end-use location 50 km from the receiving terminal is assumed (IEA, 2019). Lanphen (2019) states that gaseous hydrogen is preferred for distances up to 3500 nm (Nautical Miles, about 6500 km). When the distance increases the preferred transport choice will be the transport of hydrogen as ammonia. Lanphen (2019) also shows that the difference between the cost of ammonia, MCH and liquid hydrogen is very small. Lanphen (2019) looks in more detail at the supply chain from production to import terminal and the cost price depends on the export and import country. Considering the export and import terminals, IEA (2019) calculates the price by taking the required storage into account, but other important elements, such as the number of jetty's, are excluded in this report. Looking at end-use, IEA (2019) takes into account a constant end-use at a location 50 km from the receiving terminal. Lanphen (2019) includes jetty's in the cost calculations for the import and export terminal, however the end-use is not included and the end of the supply chain is the import terminal. The conclusions and assumptions from IEA (2019) and Lanphen (2019) are summarized in Table 1.1. In addition, the existing energy infrastructure can be used for pipeline transport. (Wang et al., 2020) presents a vision of the future hydrogen pipeline network in Europe. It concludes that the European hydrogen market will be large enough in the future that the investment in such an energy infrastructure will be modest. In addition to a European backbone, it may also be possible in the future to construct new hydrogen gas pipelines allowing for intercontinental connectivity, as investigated in (Van Wijk & Wouters, 2019) for Africa and Europe.

	IEA (2019)	**Lanphen (2019)**
Assumptions	- Supply chain from production to end-use location - Carriers: H_2 , LH_2 , NH_3 , MCH - Fixed hydrogen production costs (3 USD/kgH_2) - Fixed end-use location at 50 km from import terminal - Conversion plant at import terminal - Import & export terminals costs determined with storage	- Supply chain from production to import terminal - Carriers: H_2 , LH_2 , NH_3 , MCH - Hydrogen production costs depend on export country - Conversion plant at import terminal - Import & export terminal costs determined with storage and jetty's
Conclusions	- distance <3500 km: hydrogen transport as gas via pipeline is best - distance >3500 km: best to ship hydrogen with NH_3 or MCH - LH_2 is always more expensive than NH_3 and MCH	- distance <6500 km: hydrogen transport as gas via pipeline is best - distance >6500 km: best to ship hydrogen with NH_3 - There is no big difference between the costs for NH_3, LH_2 and MCH

Table 1.1: comparison of conclusions and assumption from IEA (2019) and Lanphen (2019)

Various articles have been published on hydrogen supply chains. The conclusions of the most important articles relating to this study presented in Table 1.2. These are the articles that are the most recent and/or most relevant with regard to the scope of this research. The supply chains and their assumptions which were considered in the rest of the reviewed articles are presented in Appendix A.

In Wijayanta et al. (2019) it is predicted that ammonia will have the highest total energy efficiency, followed by liquid hydrogen and MCH, the higher the energy efficiency, the lower the overall energy expenses. Ammonia which can be used directly (without conversion back to hydrogen) is predicted to be the most feasible option for large-scale acceptance, as it shows the lowest cost. However, if very high purity hydrogen is needed, e.g. for a fuel cell, liquid hydrogen seems more feasible compared to MCH and ammonia (Wijayanta et al., 2019). In Ishimoto et al. (2020), the supply chain from hydrogen production in Norway is examined, where liquid hydrogen and ammonia are compared. Ishimoto et al. (2020) concludes that a liquid hydrogen chain is more energy efficient and has a smaller CO_2 footprint than an ammonia supply chain. In addition, it has been found that the costs for the liquid hydrogen chain are lower than for the ammonia chain when it has to be supplied to Rotterdam. If it is transported to Japan, the costs of the two chains will be close to each other (Ishimoto et al., 2020). The findings of Seo et al. (2020) show that the costs of the supply chain are reduced if the storage structure is centralized because this favours the phase transition of the production plants. For local distribution, IEA (2019) concludes that pipelines become more cost-competitive with trucks as the distance increases. How much hydrogen is required by the end-user is important in the choice of the form of distribution. However, compressed gas pipelines and liquid hydrogen tanks are likely to remain the most important distribution modes in the next decade (IEA, 2019). Reuß et al. (2017) shows that, for reduced demand for hydrogen and if competition in storage in salt caverns is eliminated, the LOHC-based pathways are very promising, although these pathways generate more greenhouse gases. In addition, Reuß et al. (2017) shows that storage in liquid hydrogen does not offer any advantage over LOHC's or cavern storage. This is because the investment costs of the required liquefaction plants are so significant that the lower electricity prices cannot balance this out (Reuß et al., 2017). Wulf & Zapp (2018) conclude that from an environmental point of view the transport of liquid hydrogen is favourable and from a cost point of view the transport via LOHCs is favourable (Wulf & Zapp, 2018). Table 1.1 shows the assumptions regarding the hydrogen supply chains examined in IEA (2019) and Lanphen (2019). Table 1.2 and Appendix A show the assumptions made in the supply chain studies analysed in this literature review. In June 2019, a model was developed by Kalavasta Industries in cooperation with various partners to evaluate the import costs of hydrogen. The model has a greenfield approach, 2050 as a reference year, and can determine the costs of importing renewable electricity, hydrogen and hydrogen carriers from almost all countries in the world to the Netherlands. In the part of the model that looks at the transport of hydrogen carriers over water, the supply chain starts with the production of hydrogen and ends with storage at the import terminal. This model does not take end-use into account. In addition, the study does not clearly explain how the costs of the import and export terminal are determined (Terwel & Kerkhoven, 2019).

In summary, there have been many studies that examine the differences that occur in various forms of hydrogen transport in terms of energy efficiency, CO_2 footprint and costs. However, these researches often assume fixed export and import locations, a fixed demand, a fixed end-use and/or a fixed structure of the supply chain. In addition, most studies examine the supply chain between the export terminal and the import terminal in great detail and almost no research is done on the effect of the interaction between the export and import supply chain and the supply chain to the hinterland. Based on this literature review, the influence of different end-uses, distances and required volumes on the structure and cost of the supply chain and on the form of hydrogen transport remains inconclusive.

This causes the need for a more insightful research or model regarding these influences. A model should be created that not only looks at the supply chain from the export to the import terminal but also at the supply chain from the import terminal to the hinterland and the interaction between these two supply chains. This model must have the flexibility to select different hydrogen carriers and to adjust the distance and demand of both the import terminal and the end-user. In addition, it must be possible to choose between various transportation possibilities in this model and to take the countries in which the elements are situated into account. This should give the advantage of quickly comparing alternative supply chain configurations. The model should be designed in such a way that it can be used for a specific duration in which a fluctuating demand can be applied. By implementing this, the model also shows the influence of the construction time of elements on the throughput and thus the final cost price. By running the model over several years, the costs of elements can also be paid off over multiple years, which gives a more accurate overview of the costs.

	Supply Chain Assumptions
Wijayanta et al. (2019)	Hydrogen produced in Australia and transported to Japan. It compares the hydrogen carriers LH_2, NH_3 and MCH. The begin of the supply chain is storage in Australia near the seaport and the end is the H_2 release process in Japan which is also assumed to be near the seaport. The demand is fixed (demand in Japan in 2030 and 2050) and a distinction is made between NH_3 for direct use and NH_3 with decomposition.
Ishimoto et al. (2020)	Hydrogen produced in Norway is transported to Tokyo and Rotterdam. Hydrogen is produced from natural gas with CCUS and from electrolysis based on renewable power. It compares the hydrogen carriers LH_2 and NH_3 and assumes a fixed demand in each country for each hydrogen carrier. The supply chain ends at the end-use for Fuel Cell Vehicles (FCVs), delivery to end-use takes 1 hour.
Seo et al. (2020)	Hydrogen is produced from the energy of byproduct hydrogen from petrochemical complexes, natural gas (NG), coal, biomass, and electricity from solar and wind power. It compares H_2 and LH_2. Transportation is via tube trailer, railway tube car, pipeline, tanker truck or railway car. The end-use is FCVs and the locations considered are a on-site refueling station or off-site refueling station.
Reuß et al. (2017)	Analyses renewably-produced hydrogen as transportation fuel for FCVs. The hydrogen is produced by electricity from renewable energy sources and the fuel is hydrogen compressed to 700 bar. It compares H_2 and LOHC's. The supply chain consists of the production, storage, transport and fueling at the fuel station. Transport is considered to be with pipeline or trailer. The fueling station stage includes to reconversion to gaseous hydrogen. The investigated hydrogen demand ranged from 0.4 to 100 t/day and the transport distance from 2 to 500 km.
Wulf & Zapp (2018)	Considers the transport of LOHC's and LH_2. Hydrogen production is from alkaline water electrolysis powered by wind electricity. The end-use of hydrogen is hydrogen for FCVs at the refueling station. The assessment is done for the German market in 2050. The transport is assumed to be done by trucks over a distance of 400 km.
Roobeek (2020)	Considers the transport of $LH_2$from Oman to The Netherlands. Hydrogen production is from solar pv. The supply chain takes into account storage, liquefaction and LH_2-shipping. It determines the price of a kg $H_2$when it arrives in The Netherlands.

Table 1.2: comparison of scopes and assumptions made in hydrogen supply chain studies

From the conclusions of the above-mentioned studies (Table 1.2) it can be deduced that the cost of losses for various hydrogen carriers play a major role in their supply chains, it is necessary to be able to identify this as well. The model must be constructed in such a way that the throughput can be parametrically linked to the losses of a particular element. By including this, it will be incorporated that if more losses occur in a supply chain, more elements are needed to meet the demand. Furthermore, a geographical representation of the supply chain in the model would be very helpful in order to get a more realistic understanding of the supply chain under investigation. In addition, the model should be structured in such a way that it is easily adaptable to apply any changes or improvements. As hydrogen supply chains are still in the development phase, technology and cost development of elements in the supply chain will most likely take place in the future. Furthermore, it would also be very beneficial if the space requirements with respect to the number of elements could be included. Besides, most studies have been done for greenfield scenarios. The possibility of integrating the model into a brownfield scenario would also be a very valuable improvement.

1.4 Objective and Scope

In this paragraph the purpose and the field of this research are defined. The objective of this research derives from the research problem and the research gap.

1.4.1 Objective

The main objective of this research is to develop a method that creates insight into the consequences of hydrogen supply chain configurations on the costs of hydrogen at the end-use location. The method should provide a better understanding of the influence of different distances and required volumes on the supply chain structure and on the type of hydrogen transport. In addition, by connecting supply chains, it should become clear how the interaction of supply chains affects the cost and throughput. The first step is to define the different elements in the supply chain and summarize these in such a way that a supply chain model can be developed. The model must be constructed in such a way that a single supply chain can be analysed, as well as coupled supply chains. The model must be able to compare different supply chain configurations by making the distances, the volumes, the commodities and the structure of the chain variable. Through optimisation and comparison of supply chain configurations, it should be possible to determine the most cost-effective supply chains.

1.4.2 Scope

The two supply chains investigated in this research are the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the hinterland. Four types of hydrogen carriers will be included in the supply chain research: liquid hydrogen, ammonia and MCH and DBT which are both LOHCs, as these are currently considered to be the most promising hydrogen carriers (Wijayanta et al., 2019). The supply chain model created in this research will be based on the model developed by Lanphen (2019), this model is based on these three specific hydrogen carriers as well. The study of the supply chains will only consider hydrogen transport by ship for the transport between the export and import location. For the local transport between the import terminal and the end-use location transport via pipelines, trucks, train and inland shipping will be considered. The study compares supply chain configurations where the reconversion plant can be located at the import terminal (centralized) or at the end-user location (decentralized). The option that the reconversion is located in between the import terminal and end-user location is not taken into account. In addition, it is assumed that the conversion is always at the export terminal and not at the location of H_2 production in the export country. In this research, each supply chain can be examined individually, however, the supply chains can also be connected in order to find out what the influence is of the interaction between the supply chains. The overseas distance, the hinterland distance and the volumes of both supply chains can be adjusted. This research mainly focuses on supply chains in which large volumes are transported, for example this research does not take into account the small volume flows towards gas stations.

1.5 Research Question

Now that the research problem is formulated, the research gap is determined and the objectives and scope of the research are established, the research question is defined. In view of the main objective, the main research question is formulated as follows:

"What is the influence of the required volumes, transport distances, the type of hydrogen carrier and the structure of the entire hydrogen transport supply chain on the cost price of hydrogen at the end-use location and what will be the most cost-effective supply chains?"

The study addresses various sub-questions in order to answer this research question. These sub-questions are divided into three different categories; sub-questions relating to information and data collection, the method and the supply chain costs:

1. **Information and data collection**
    - What information about the components of the hydrogen supply chain is needed to determine the influence of supply chain configurations on the eventual cost price?
2. **The method**
    - How can a method be developed that can not only analyse a single supply chain but can also connect multiple supply chains and what is the added value of this approach?

- What requirements are imposed on the fundamental structure of the software by the possibility of making the distances, volumes, commodities and structure of the supply chain variable?
- How can the calculation of the final cost price best be incorporated into the resulting model?

3. **The supply chain costs**
    - How does the cost price of hydrogen evolve for different supply chain configurations for the supply chain from the import terminal to the hinterland?
    - How does the cost price of hydrogen evolve for different supply chain configurations for the supply chain from the export terminal to the import terminal?
    - How does the cost price of hydrogen evolve over for different supply chain configurations for the entire supply chain?

1.6 Research Method

The aim of this research is to develop a method to gain insight into the effects of supply chain configurations on the costs of hydrogen. A mathematical model can assist in this process, because it can describe a system and study the effects of different components. In addition, Y. H. Lee et al. (2016) states that the complexity of managing and controlling supply chains is increasing as supply chains become more and more globalised. As a result, the experience and intuition currently available is not sufficient. Mathematical models are necessary to overcome these shortcomings.

This study aims to develop a multi-echelon supply chain model that can estimate all the costs that each echelon contributes to the total cost. A suitable method for modelling this is a parametric model, this is a method in which the solution only depends on the values of the parameters. Parametric modeling is a useful approach as the project parameters or variables can be adjusted in a parametric model during the project simulation. Because the parameters can easily be changed, the influence of different parameters and variables becomes transparent. However, this introduces the challenge of determining to which aggregation level the model will be extended. This aggregation level can best be defined by investigating the most promising possibilities from literature and expert knowledge. For instance, the hydrogen carriers LH_2, NH_3, MCH and DBT were chosen for this research because studies show that they are the most promising (see Section 1.3). In addition, on the technical levels, no detailed investigation was carried out into what specific techniques are used for the processes that take place within the supply chain (such as hydrogen conversion and reconversion). The decision was made to focus mainly on price and capacity in order to be able to examine the entire supply chain at a high level.

Moreover, a reliable cost estimate is needed to predict the influence of the various echelons on the cost price. Methods of cost estimation include: expert appraisals, 3-point estimations, comparative estimations, parametric estimations and bottom-up estimations. The methods are arranged in such a way that they increase in accuracy, detail and reliability (Dashore, A, 2020). A parametric approach for cost estimation is therefore an appropriate method for obtaining reliable cost estimates. The bottom-up estimates, which gives more accurate, detailed and reliable results, is not applied in this study because the approach is more complex and time consuming. In addition, hydrogen supply chains are still in the developing stages, so an initial estimation of costs is needed and a more detailed approach is not yet necessary. Lastly, parametric models are used extensively nowadays, often as the primary (or even as the only) basis for estimates. Especially in the early stages of designs for which detailed information is not yet available (Camargo et al., 2003). For this study, where supply chains are examined that are currently not yet operational, parametric modelling can be a suitable tool for establishing an initial baseline for cost estimates.

Hence, to gain more insight on the influence of end-use, volume, distance, carrier type and supply chain structure on the cost price of hydrogen, a parametric model is developed. To obtain reliable results from this model, it must be provided with the right input. Therefore, a literature study is first carried out that provides a deeper understanding of all elements of the supply chain and also serves as a source for quantitative data that can be used in the model. Second, a multi-echelon parametric supply chain model is created from which it is eventually determined how much each element in the supply chain contributes to the cost price of hydrogen at the end-use location. In this model it should be made possible to change the required volume, the type of carrier, the distance and the structure of the supply chain. The structure of the supply chain indicates the elements present in the supply chain and the location of these elements in the supply chain.

The supply chain model created in this report links two supply chains; the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the end-user. In this report, two models are created; The first one models the supply chain from the import terminal to the end-user, called the End-Use Model. The second model is called the Supply Chain Model, this model makes it possible to model not only one supply chain (f.e. the supply chain from the export terminal to the import terminal) but to also link two (or more) supply chains to each other (f.e. the supply chain from the export terminal to the import terminal to the end-user). This makes it possible to identify the influence of the interaction of supply chains on the final cost price.

Lanphen (2019) presents two models that together determine the cost price of hydrogen for the supply chain from the export terminal to the import terminal; a generic supply chain model and a terminal investment model. However, the generic supply chain model was made in Excel and the terminal investment model with the programming language Python. The costs in the generic supply chain model and the terminal investment model are calculated with a pre-tax, pre-finance cash flow model. In this research the general supply chain model of Lanphen (2019) will be converted to Python allowing it to be combined with the terminal investment model into a complete cash flow supply chain model. The terminal investment model will not just be used for the import terminal as in Lanphen (2019), but will be modified in such a way that it can also be used for the export terminal. In addition, Lanphen (2019) did not include the supply chain to the hinterland in the models (import terminal - end-use). This supply chain will be included in this research, in order to get a clear understanding of the costs over the entire supply chain. In this report all costs will be calculated with a pre-tax and pre-finance cash flow model.

In this research, both models are made using the programming language Python. For the End-Use Model, the open source package Open Source Terminal Investment Simulation (OpenTISim) is used which is available at the Github of the TU Delft Hydraulic Engineering Department (M. Van Koningsveld, 2019). This package is modified in such a way that it is now also possible to model not only the terminal investment decisions but also the transport investment decisions (see Chapter 3). For the Supply Chain Model the OpenTISim package is also used to simulate the terminal investment decisions of the export and import terminal. In addition, the open source package Open Source Complex Logistics Simulation (OpenCLSim) is used which is available at the Github of the TU Delft Hydraulic Engineering Department (M. Van Koningsveld, J. Den Uijll, F.Baart, and A.Hommelberg, 2019). This package is used to simulate the transport of the supply chains.

The model will be constructed in in a manner that allows the comparison of four different hydrogen carriers, being MCH, DBT, liquid hydrogen and ammonia. The transport from export to import terminal will be limited by shipping and the local transport from the import terminal to the location of end-use will be limited to pipelines, trucking, trains and inland shipping. The model shall be designed in such a way that it is possible to situate the hydrogen retrieval plant at the import terminal or at the location of end-use. Various end-uses will be applied to this model differing in required volume and the distance from the import terminal. In the Supply Chain Model, the commodity, the distance, the required volume, the location of end-use and the structure of the supply chain (which is the type of local transport and centralized/decentralized conversion installations) can thus be adapted. This enables the influence of each of these variables on the cost price to be determined. Once the influence of the various variables on the cost price is clear, conclusions can be drawn about the most cost-effective supply chains for different end-use locations, thus answering the main research question.

1.7 Reading Guide

This section briefly discusses the structure of this report. Chapter 2 focuses on the supply chains that are investigated in this report. The scope of the study becomes more clear when reading this Chapter. All elements that are included in the scope of the study are discussed here. Chapter 3 explains the method that is applied in the research. This is where the structure of the two models created in this study is explained. In Chapter 4, an overall analysis is carried out for both models. This analysis should clarify the impact of a varying distance and demand on the cost price of a certain supply chain configuration. Chapter 5 shows the application of the Supply Chain Model to a case study, to determine the most cost-effective supply chain configurations for this case study. The results of the study are interpreted and discussed in Chapter 6, in which the limitations of the study are also addressed. Chapter 7 concludes with the answer to the main research question and recommendations for future research.

2 | The Supply Chain

This research will first examine the supply chain from the import terminal to the end-user and will subsequently consider the entire supply chain from export terminal to import terminal to the end-user. In this chapter, first the elements of the supply chain from import terminal to end-user (The End-Use Supply Chain) are described and second the elements in the supply chain from export terminal to import terminal (The Export - Import Supply Chain). By linking these two supply chains, it is made clear which elements are present in the entire supply chain (Figure 2.1).

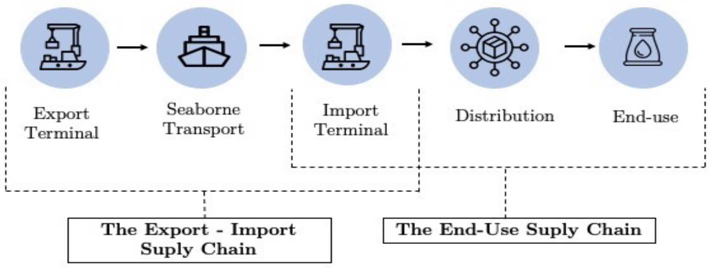


Figure 2.1: The entire supply chain from the export terminal to the import terminal to the end-user

2.1 The End-Use Supply Chain

The supply chain that will be examined in the first part of the research is called the End-Use Supply Chain. This supply chain starts at the storage facilities at the import terminal and ends at the location of end-use. In between these two locations the hydrogen is transported as NH_3, LOHC, LH_2 or Compressed Gaseous Hydrogen (CGH_2) and converted back to gaseous hydrogen, if needed. The described supply chain is depicted below in Figure 2.2. The supply chain starts at the storage facilities at the import terminal, which will be described in paragraph 2.2.1.2. The next element is the reconversion to hydrogen plant. This element is coloured orange in the figure because it can be positioned in two placed in the supply chain; it can be placed at the import terminal (centralized) or at the end-use location (decentralized). In addition, the retrieval plant can also be absent from the supply chain when the carrier is required for direct use. In addition, distribution is needed in the supply chain to transport the carriers or the gaseous hydrogen to the location of end-use. In this chapter, first the forms of hydrogen transport that this report will focus on are discussed. After this the reconversion plants for these forms are discussed and lastly the local distribution modes for these forms of transport are discussed.

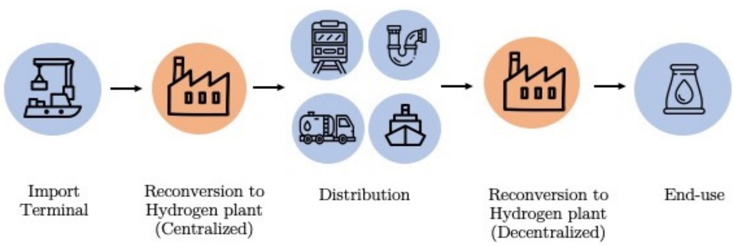


Figure 2.2: The supply chain from the storage at the import terminal to the location of end-use

2.1.1 Hydrogen Forms of Transport

Due to the low energy density of hydrogen, it is required to compress, liquefy or attach hydrogen to a carrier, in order to be transported over long distances and stored for long periods of time. Hydrogen can be attached to a carrier and converted into a fuel, such as synthetic methane, synthetic liquid fuels and NH_3 (IEA, 2019). This report will look at three different forms of hydrogen transport: LH_2, NH_3 and LOHCs, all of these are briefly explained below. The most important advantages and disadvantages of these forms of transports have been briefly discussed in Section 1.3 and these are summarised in Table 2.1. In Appendix B a table is presented with all the characteristics of the various forms of transport considered in this report.

Carriers	Advantages	Disadvantages
LH_2	- Supply chain is comparable with LNG supply chain - Additional (expensive) conversion steps in other parts of the supply chain reduced - Compared to MCH and NH_3 highest price reduction can be achieved for LH_2	- Liquefaction takes place at temperature of -253°C, hence a lot of energy needed for this process, around 6100 kWh/ton H_2 - Hydrogen is lost during storage through evaporation (boil-off) - Design of a LH_2-ship still in the early stages
NH_3	- Liquefaction at -33°C and has higher energy density than LH_2 - Already established supply chains for NH_3	- Lot of energy needed for synthesis and decomposition around 6100 and 5890 kWh/ton H_2, respectively - NH_3 is a toxic chemical, hence there can be restrictions in the supply chains - Escape of NH_3 can lead to formation of fine dust and acidification
LOHC	- Properties are similar to oil(products), hence the (elements in the) supply chains are comparable - Transported and stored as liquid, no cooling is needed	- Dehydrogenation consumes a lot of energy, around 7000 - 9500 kWh/ton H_2(requires high energy heating) - Carrier molecules in a LOHC are often expensive - When H_2 extracted from an LOHC, the LOHC is not used up and needs to be shipped back to the place of origin to use it again

Table 2.1: Most important advantages and disadvantages of the three hydrogen carriers

2.1.1.1 Liquid Hydrogen

The energy density of hydrogen is very low, more energy can be transported or stored by liquefying the hydrogen, thus increasing the energy density (van Wijk et al., 2017). However, hydrogen must be cooled down to -253°C to become liquid. Transport and storage of LH_2 can be compared to liquefied natural gas (LNG) which must be cooled down to -162°C (Wijk et al., 2019). Liquefied hydrogen, however, has different safety characteristics than (compressed) gaseous hydrogen. If gaseous hydrogen leaks into the open air, it will quickly evaporate and disappear. LH_2 on the other hand, will become a heavy gas in the open air because the surrounding air freezes and because it becomes a heavy gas it will accumulate on the ground. This is relevant for LH_2 transport and storage (Wijayanta et al., 2019). The process for LH_2 that is considered in this report is shown in Figure 2.3.

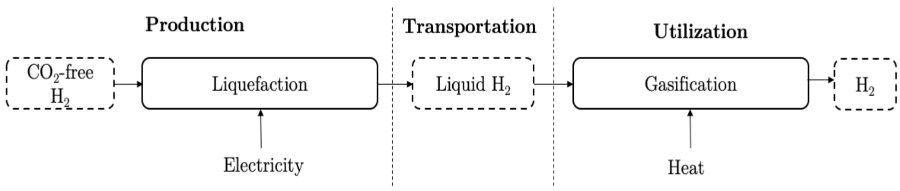


Figure 2.3: LH_2 as a carrier (based on (Aziz et al., 2019))

2.1.1.2 Ammonia

By binding hydrogen (H_2) and nitrogen (N_2), ammonia (NH_3) is produced, therefore there are no CO_2-emissions during combustion. The process of making NH_3 from hydrogen and nitrogen is called the

Haber-Bosch process. This is an accessible process because the nitrogen can be obtained from the air, which means that no carbon source is necessary (van Wijk et al., 2017). NH_3 is a gas under normal conditions, but can be liquefied when cooled down to -33°C. In addition, liquid NH_3 has a higher energy density than LH_2. As NH_3 is already traded as a product globally, distribution and storage of NH_3 is already technologically mature. NH_3 is not only an energy carrier but can also be used directly as a raw material or as a fuel (van Wijk et al., 2017). NH_3 does, however, have a high toxicity which means that it must be treated with care by professionally trained people and additionally its synthesis and dehydrogenation (if necessary) requires a lot of energy (IEA, 2019). Figure 2.3 shows the process for NH_3 that this research focuses on.

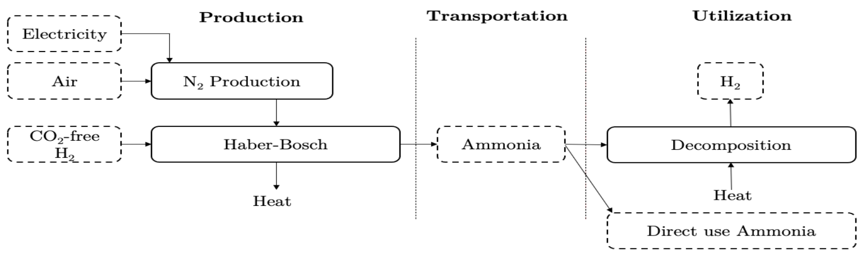


Figure 2.4: NH_3 as a carrier (based on (Aziz et al., 2019))

2.1.1.3 LOHC

Hydrogen can also be bonded to a Liquid Organic Hydrogen Carrier (LOHC). LOHCs have properties similar to oil and oil products (IEA, 2019). The biggest advantage of an LOHC is that it can be transported and stored without cooling. However, as with NH_3, there are high costs associated with the conversion and reconversion processes. A potential LOHC is Methylcyclohexane (MCH), MCH requires toluene for its production which is a toxic substance and MCH itself is flammable and dangerous to inhale. As a liquid, however, MCH is less dangerous compared to gasses that can be inhaled. Next to MCH, Dibenzyltoluene (DBT) is also an LOHC option, which proves to be safer than MCH; however, MCH is the cheaper option (IEA, 2019). Nevertheless, economies of scale could allow DBT to be competitive with MCH. A disadvantage of an LOHC is that the LOHC is often expensive and has to be transported back to the place of conversion after the reconversion process. Various companies in the world have started with the production, transport and storage of LOHCs, for example; The Japanese company Chiyoda is working on hydrogen transport on the basis of MCH (Wijk et al., 2019) and the company Hydrogenious is working on hydrogen transport on the basis of DBT (Schneider, 2015). Appendix B provides a longer explanation of what an LOHC is and highlights the differences between MCH and DBT. In this research, MCH and DBT are considered as LOHCs, see Figure 2.5. What is also notable about LOHCs is that the product is shipped back to the exporting country to be reused. This will result in additional loading time, fuel costs etc., however these costs outweigh the otherwise high investment costs if the LOHC is not reused.

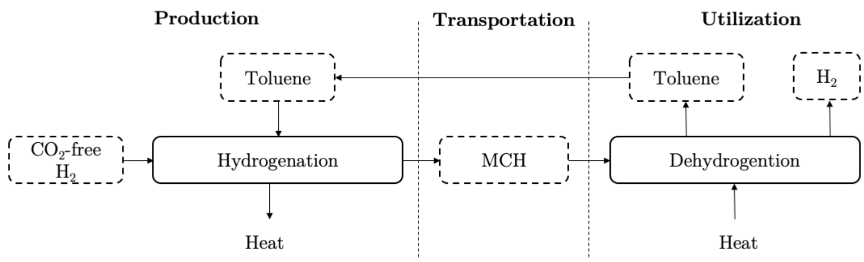


Figure 2.5: MCH as a carrier (based on (Aziz et al., 2019))

2.1.2 Reconversion to Hydrogen Plant

A reconversion plant is necessary to turn the carrier back in to gaseous hydrogen at a certain pressure. This is needed because most of the end-uses need gaseous hydrogen and not the carrier. However, some end-uses demand NH_3 and reconversion plants are thus not necessary in such a supply chain. The reconversion plant can also be located at different locations. In Figure 2.2 the reconversion plant is located at the import terminal and CGH_2 is transported to the end-use location. However, the reconversion plant can also be situated somewhere along the route to the hinterland or at the location of end-use. In these supply chains the hydrogen is firstly transported as NH_3, LOHC or LH_2 from the import terminal to the location of the reconversion plant.

The reconversion process is different for the various carriers. LH_2 is reformed by evaporation, also called regassification. Regassification of LH_2 produces gaseous hydrogen with a high purity, allowing it to be used immediately in fuel cells. NH_3 MCH and DBT are endothermic processes. Temperatures between 350 and 900°C are required for the release of hydrogen from NH_3 and temperatures between 200 and 400°C for MCH and DBT (Wijayanta et al., 2019). The energy required for the decomposition of NH_3 is approximately equal to 7-18% of the energy contained in the released hydrogen and for MCH and DBT it is even equal to 24-40%. The H_2 recovery rate is 90% for MCH and DBT and 99% for NH_3. In addition, after this reconversion, the purity of the H_2 is sufficient for H_2 which is used in combustion. If the H_2 is to be used in fuel cells, another purification step has to be added. In this purification step hydrogen is lost, for LOHC this is 2% and for NH_3 this is 15% if Pressure Swing Adsorption (PSA) is used for purification (Wijayanta et al., 2019). The purity of the hydrogen after regassification is very high and thus good to be used in fuel cells without an extra purifying step. The data for the reconversion plants used in the model are presented in Appendix C in Table C.2.

2.1.3 Distribution Modes

The LH_2, NH_3, LOHCs and CGH_2 can be transported to the hinterland in various ways. This report looks at transport by pipeline, barge, rail and trucks. The advantages and disadvantages of the transport options are briefly explained below.

2.1.3.1 Pipeline

A pipeline is an efficient way to transport large volumes over long distances to the hinterland. A disadvantage, however, is that once the pipeline is in place, there is little room for flexibility towards the point of delivery (Nayak-Luke et al., 2021). A pipeline could be built for CGH_2, NH_3 and LOHCs. However, building a pipeline for an LOHC is not a realistic scenario for the future. The reason for this is that LOHCs have to be transported back to the place of origin, which would require the construction of a second pipeline, thereby increasing the costs considerably. Another disadvantage of a pipeline is that it is often challenging to find a suitable route to install the pipeline. Especially for flammable and toxic substances such as hydrogen and NH_3 the environmental and social issues are significant and the pipeline route is restricted to specific areas (Elishav et al., 2020). In the Netherlands, for example, there are designated pipeline tracks that have been approved, which makes the trajectory of the pipeline inflexible. This report therefore looks at CGH_2-pipelines and NH_3-pipelines. NH_3-pipelines can be found all over the world, especially in the United States there is a large NH_3-pipeline network. In the Netherlands there are two NH_3-pipelines, one with a length of 5,8 km and one with a length of 1 km (Zomer, 2019). At present, there are also several hydrogen pipelines in the Netherlands. In the Netherlands there is a hydrogen pipeline network of about 140 km managed by the company Air Products (Gasunie, 2021b). The company Gasunie is currently working on realising a dedicated hydrogen infrastructure in the Netherlands by 2030, based on the existing natural gas infrastructure. This network (also called the Hydrogen Backbone) will link five industrial clusters in the Netherlands to each other, to foreign countries and to hydrogen storage sites (Gasunie, 2021a). The data used in the model for the NH_3 and hydrogen pipelines is presented in Appendix C, Table C.6.

2.1.3.2 Barge

Inland shipping is, alongside pipelines, also a way of transporting large volumes to the hinterland. Here too, the disadvantage is that this form of transport is not flexible with regard to the location in the hinterland. However, environmental and safety aspects play a smaller role for transport by ship than for pipeline transport (Elishav et al., 2020). Additionally, the fuel efficiency of a barge is much better than that of a truck. Different types of ships are required for the transport of the carriers. For example, there are no ships specifically built for the transport of NH_3. Since NH_3 has almost the same boiling temperature and condensation pressure as propane, LPG vessels are used for the ship transport of NH_3 (Zomer, 2019). An LOHC has the same characteristic properties as oil products, therefore it will be transported in an oil tanker (Reuß et al., 2017). An LH_2-barge is currently not yet in use, but the values can be estimated by looking at LNG barges. LNG needs to be cooled to -162°C and LH_2 to -253°C, it is expected that a LH_2-barge will cost 3.5 to 4 times as much as a LNG barge (Amos, 1998). In this model inland navigation is included for LH_2, NH_3 and LOHCs, the data used in this report is shown in Appendix C, Table C.5.

2.1.3.3 Train

Besides inland navigation, a train can also bring large volumes to the hinterland, again with the disadvantage of inflexibility. However, many ports and industrial areas already have a good connection by rail. In addition, the fuel efficiency of a train is much better than that of trucks (Nayak-Luke et al., 2021). Trains can run on electricity but also on diesel and in the future even on H_2 or NH_3, although these technologies are still being developed. The assumptions in this report regarding the fuel are presented in Appendix C.1.1. Trains also require different rail tankers for the different carriers. NH_3-rail tankers are already in use all over the world (Elishav et al., 2020). For LOHCs, rail tankers carrying oil products are being considered (Reuß et al., 2017). LH_2-rail tankers are still at the development stage, so the existing LNG rail tankers are looked at instead. Again, an assumption is made that the LH_2-rail tanker is 3.5 to 4 times more expensive than the LNG rail tanker, similar to the barge.

2.1.3.4 Truck

Trucks are also often used to transport commodities to the hinterland. The advantage of trucks is that there is flexibility in the place of delivery. A big disadvantage of truck transport, however, is that emissions are much higher than with other distribution modes. In addition, trucks are usually expensive when large volumes have to be transported over long distances (Nayak-Luke et al., 2021). Trucks are therefore often used as last-mile transport. This means that large volumes are first transported via pipe, barge or rail and that the last section of the delivery is done by trucks. Most trucks currently run on diesel, but in the future trucks may also run on hydrogen or be electric. The assumptions that have been made in this report regarding the type of truck and fuel are presented in Appendix C.1.1. Again, different trailers are needed for the carriers. NH_3-trailers are already in use all over the world (Elishav et al., 2020). For LOHCs, trailers are considered that are already used for the transport of oilproducts (like diesel and gasoline) (Reuß et al., 2017). LH_2-tankers are currently already in use, the LH_2 is transported in super-insulated, cryogenic tanker trucks (Office of Energy Efficiency & Renewable Energy, 2021b). For distribution with trucks this report also considers truck transport of CGH_2. The gaseous hydrogen is compressed into steel tube cylinders, these cylinders are than stacked on a truck trailer (Office of Energy Efficiency & Renewable Energy, 2021a). The data for the trailers used in the model is presented in Appendix C, Table C.3.

2.2 The Export - Import Supply Chain

In order to examine the entire supply chain from export terminal to import terminal to end-user, it must first be established which elements are present in the supply chain from the export terminal to the import terminal. Figure 2.6 shows this supply chain and the corresponding elements. The export terminal consists of a hydrogen conversion plant, tanks for the storage of the hydrogen carriers and a jetty with a pipeline. The transport is limited to sea transport by ship. The import terminal also consists of a jetty with a pipeline and storage tanks to store the LH_2, NH_3 or LOHC's. A reconversion plant to convert the carrier back to gaseous hydrogen can also be present at the import terminal. This plant is also present in the End-Use supply chain that was described before (paragraph 2.1.2). In the paragraphs below, the rest of the elements are briefly explained.

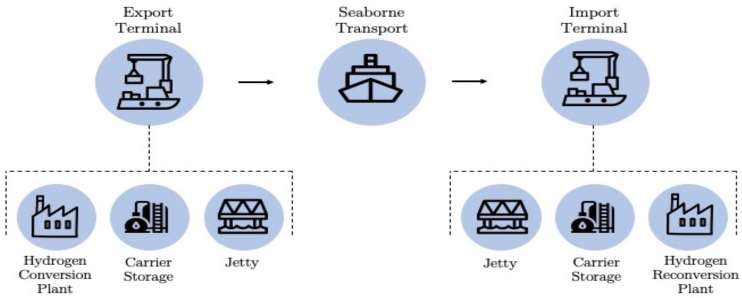


Figure 2.6: The supply chain from export terminal to the import terminal

2.2.1 Terminal Elements

The export terminal and the import terminal both consist of a jetty with a pipeline and storage tanks. In addition, there are hydrogen conversion plants at the export terminal and hydrogen reconversion plants at the import terminal. The design of the jetty, pipeline and storage tanks is the same for the export terminal as for the import terminal. All elements are briefly described below. The data used for these elements in this report is presented in Appendix D.

2.2.1.1 Terminal Jetty

The terminal covered by this model is designed for liquid bulk carriers (LOHCs, NH_3 and LH_2). For the loading and unloading of liquid bulk, no quay wall is required, instead this can be done by a relatively small platform, a jetty. The jetty consists of an approach bridge, a jetty head consisting of the platform with the necessary (un)loading equipment, and breasting and mooring dolphins (Ligteringen & Velsink, 2012). In this report an L-shaped jetty is taken into account, based on (Lanphen, 2019). It is taken from (Ligteringen & Velsink, 2012) that liquid bulk can be (un)loaded rather quickly. For ships carrying less than 200,000 to 250,000 tons, loading or unloading can be done with a net hourly capacity of 10% of the carried weight.

In addition, the loading is done with shore based pumps located at the jetty and the unloading is done with ship based pumps(Ligteringen & Velsink, 2012). Hence, no unloading equipment is needed at the jetty at the import terminal. However, in the case of an LOHC, the LOHC must be loaded back on the the ship again, requiring the use of loading arms at the jetty at the import terminal. Furthermore, there is also a pipeline present at the jetty that ensures that the liquid bulk is brought from the storage tanks to the loading arms or that the discharged liquid bulk can be transported back to storage tanks. For the terminal jetty and terminal pipeline, this study assumes that the same equipment can be used for all hydrogen carriers, however, this may not be accurate in practice.

2.2.1.2 Storage

This study takes into account the storage of LOHCs, NH_3 and LH_2. Different types of storage tanks are required for these commodities. The storage that is present at the import terminal is a temporary storage before the product is transported to another location or to the reconversion plant. Seasonal and long term storage are not included in this report, it is assumed that this storage will take place in salt caverns (Lanphen, 2019). If the reconversion plant is located at the import terminal, the released gaseous hydrogen does not need to be stored but can be transported directly through pipelines.

Storage tanks are present at the export terminal, import terminal and if the reconversion plant is located at the end-user, storage tanks are also needed at the end-use location. From (Ligteringen & Velsink, 2012) it can be taken that for liquid bulk the operational storage capacity falls in the order of 1 month of consumption. Oil tanks are used for the storage of LOHCs. Ammonia can be stored in pressurised tanks, low temperature storage tanks or semi refrigerated storage tanks. Because of the large volumes that need to be stored, low temperature storage is used (Elishav et al., 2020). Liquid hydrogen is stored in cryogenic tanks (IEA, 2019).

2.2.1.3 Hydrogen Conversion Plant

At the export terminal there are conversion plants that convert the supplied hydrogen into one of the carriers. The carriers considered in this model are LH_2, NH_3 and LOHCs (MCH and DBT). The conversion processes are different for all carriers and are briefly explained below.

An LOHC can be generated through hydrogenation. MCH is made by the hydrogenation of toluene in the presence of a catalyst. This takes place under relatively moderate temperatures of 180 - 300 degrees and a pressure of 200 kPa (Wijayanta et al., 2019). The hydrogenation of DBT requires DBT that is referred to as perhydro-DBT after the hydrogenation. This process is again under a pressure of 200 kPa and an intermediate temperature of around 150 degrees Celsius (Schneider, 2015). The hydrogenation of MCH and DBT are both exothermic reactions, the resulting heat can be used in other processes within the H_2production facility, such as electricity generation, thus increasing the total energy efficiency and reducing the costs (Wijayanta et al., 2019).

Ammonia and hydrogen are produced via the Haber-Bosch process, which is a well known process throughout the world. This process takes place under high pressures (30 Mpa) and medium temperatures (300°C) in the presence of a catalyst (Wijayanta et al., 2019). NH_3-synthesis is an exothermic process, just like hydrogenation.

LH_2 can be obtained, just like LNG, through a liquefaction process. However, the boiling point of LH_2 is about 90 degrees lower than LNG, therefore more energy input is needed in this process and better insulation (Wijayanta et al., 2019). Since the elements of the supply chain of LH_2 are still in the development phase, there will be a lot of room for technological and cost developments in the future (Wijayanta et al., 2019). Hence, the production of these carriers require the purchase of hydrogen but also of other products, such as nitrogen for ammonia and toluene and DBT in the case of MCH and DBT. The data that is used in this report is presented in Appendix D.

2.2.1.4 Reconversion to Hydrogen Plant

See Section 2.1.2

2.2.2 Seaborne Transport

For the transport between the export terminal and the import terminal, this study only considers transport by ship. For the shipping of the various commodities, different types of vessels must be considered, described below. Appendix D contains the detailed data for the vessels that is used in this report.

- Ammonia is transported in vessels that are equipped to carry either LPG or ammonia (Elishav et al., 2020). This is due to the fact that ammonia and propane almost have the same boiling temperature and condensation pressure (Zomer, 2019).
- An LOHC has properties similar to oil products and therefore can be shipped in already existing oil tankers (IEA, 2019).
- LH_2 will be shipped in a new type of vessel that is based on LNG tankers (Tijdgat, 2020). However, the boiling temperature of LH_2 is even lower than that of LNG. As a result, cooling LH_2 on ships will be more challenging than cooling LNG on vessels, requiring different materials and technologies, and increasing the costs.

2.3 Conclusion

In the entire supply chain from export terminal to import terminal to end-user, a reasonable number of elements are present. This report focuses on three different hydrogen transport possibilities; liquid hydrogen, ammonia and LOHCs (where MCH and DBT are considered in this study). The transport between the export and import terminal is limited to shipping. For the transport to the hinterland, trucks, barges, trains and pipelines are considered. In addition, a hydrogen retrieval plant can be present at the import terminal, at the end-user or it may not be present at all in the supply chain.

3 | The Models

In this report, two models are established. The first model is called the End-Use Model, in which the supply chain from Chapter 2, Section 2.1, Figure 2.2 is modelled. The second model is called the Supply Chain Model, In this model, the End-Use Supply Chain and the Export-Import Supply Chain described in Chapter 2 are connected. Consequently, the entire supply chain from export terminal to import terminal to end-user is modelled. Below, it is described for both models what the model purpose and the model concept is. In addition, the structure, the boundary conditions and the model validation are described for both models.

3.1 The End-Use Model

The End-Use Model simulates the supply chain shown in Chapter 2, Figure 2.2. This is a supply chain that includes a hydrogen reconversion plant and a transport mode to the hinterland. In this supply chain, the reconversion plant can be located at the import terminal or at the end-user's location, however it can also not be a part of the supply chain. Transportation to the hinterland can also be done in various ways. The purpose of the model, the model concept and the structure of the model are explained below. Lastly, the system boundaries and the validation of the model are briefly discussed.

3.1.1 Model Objective

The objective of this model is to investigate what each element in the end-use supply chain contributes towards the final cost of hydrogen. This should provide a clear understanding of the influence of different supply chain configurations on the ultimate cost price of hydrogen. By analyzing the costs of different supply chain configurations, it should become clear which of the supply chain configurations are the most cost-effective and also which configurations increase the cost the most and for what reason.

3.1.2 Modelling Concept

To calculate the cost of the elements in the supply chain, it is necessary to know how many elements are present in the supply chain each year. This is modelled using the open source package Open Source Terminal Investment Simulation (OpenTISim), which is available at the Github of the TU Delft Hydraulic Engineering Department (M. Van Koningsveld, 2019). OpenTISim enables the translation of fluctuations in demand into expansions in the individual elements of a terminal in order to arrive at a terminal design (Lanphen, 2019). OpenTISim is designed in such a way that it looks at the demand of each year and assesses whether an increase in capacity is needed in order to meet that demand. This is done for each year in a given model time frame. In this research the OpenTISim package is modified in a way that it no longer looks at the expansions of the terminal elements (berths, jetties, storages), but only considers two elements; the hydrogen reconversion plant and the transport to the hinterland. Both elements have corresponding triggers that ensure their expansion at the appropriate time in the lifetime of the model to meet the demand.

The design of the End-Use Model is determined based on a number of assumptions that define the system boundaries, given in Section 3.1.4. The triggers that cause expansions of the elements are based on the capacity of the elements; when the demand exceeds the available capacity of the elements, an expansion of that element is required. An element has its own investment costs and operational costs. The investment costs are collected when the element is under construction and the operational costs are generated each year that the element is operational.

Figures 3.1 and 3.2 show the results of the model for an example with LH_2 with a retrieval plant at the end-user at a distance of 800 km and transport via barges. The demand in 2020 up to 2024 is 1 Mton H_2 and in 2025 up to 2029 the demand is increased to 2 Mton H_2. Figure 3.1 shows how many reconversion plants are present each year and Figure 3.2 shows how many transport elements (in this example barges) are online each year.

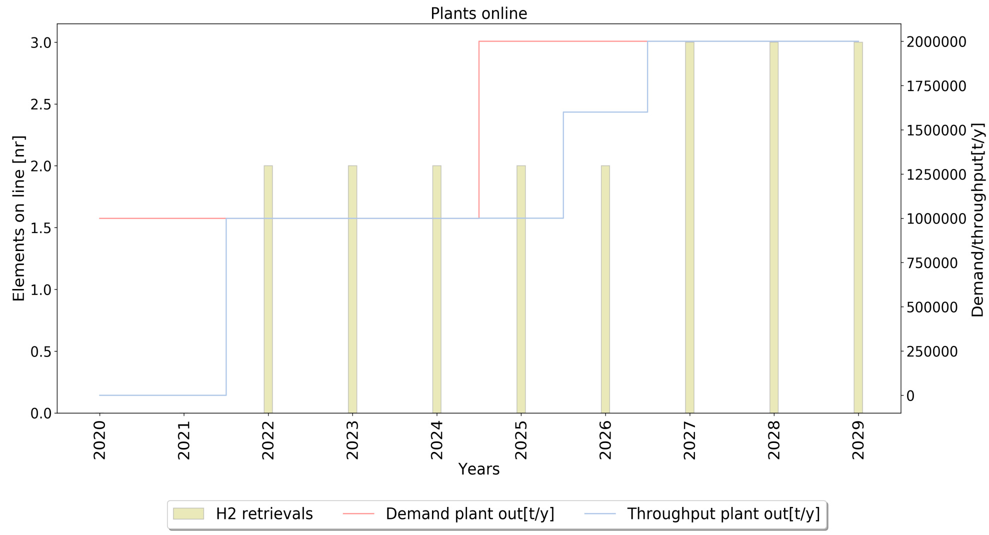


Figure 3.1: The number of plants over the years, with the throughput and the demand

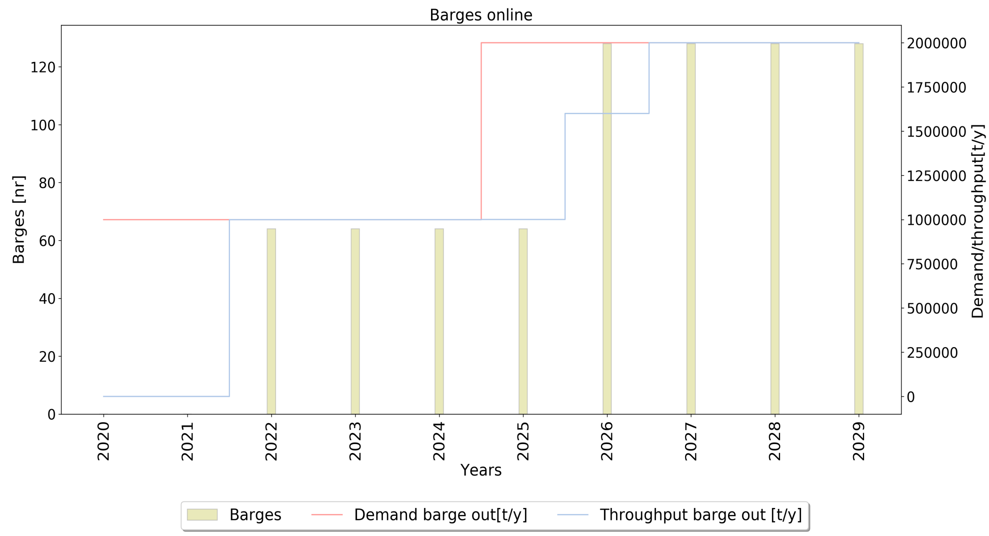
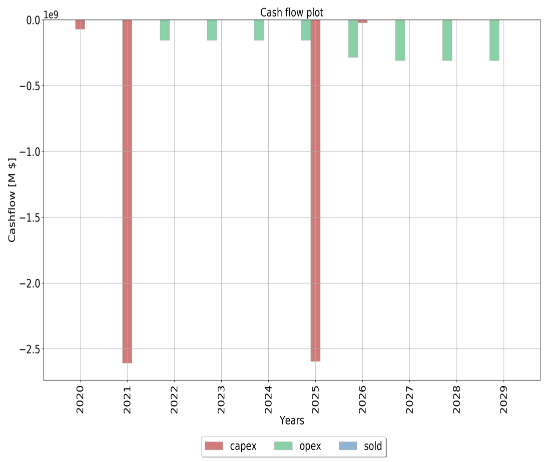


Figure 3.2: The number of barges over the years, with the throughput and the demand

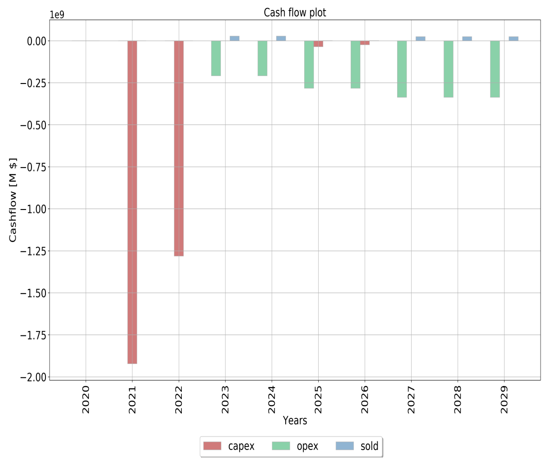
What is interesting about this supply chain is that the reconversion plant can be located in different places or not even be present in the supply chain at all. In this model, it is possible to choose whether the retrieval plant is at the import terminal (centralized), the end-use location (decentralized) or not present at all. The difference between a centralized and decentralized plant is that if it is located at the import terminal, the remaining capacity of the plant can be sold to other supply chains, which can make it more favourable for the final cost price. When the retrieval plant is located at the end-user, this is not possible. Therefore, if the supply chain configuration is such that the retrieval plant is located at the import terminal, there will not only be investment costs and operational costs but also a certain income generated by the sale of the unused hydrogen to other supply chains. These earnings are calculated every year that the retrieval plant is online, by considering the percentage of capacity that is not used that year by the given supply chain.

Cash flows are generated for each year by examining how many elements are active that year and by identifying the costs of those elements. A discount rate is applied to these cash flows to take into account that money is worth more in the future due to its potential earning capacity. The discount rate used in this model is based on the cost of capital and is called the WACC, a more detailed explanation of this method is presented in Appendix C. The resulting cost price is calculated by adding up all cash flows over the model time frame and dividing them by the total throughput generated by the model. By applying this concept, the cost price of hydrogen resulting from a given supply chain configuration can be computed relatively quick and in a simple manner.

Figure 3.3a shows the cash flows for all years for the example that is described above (LH_2 with decentralized reconversion and barge transport). In this example it concerns a reconversion plant at the end-user, hence the remaining capacity is not sold; therefore there is no additional income ('sold' in Figure 3.3a). Figure 3.3b shows the cash flows for each year if the LH_2-reconversion plant would be at the import terminal (centralized) and there would be CGH_2-pipeline transport to the hinterland. In this situation the remaining capacity will be sold to other supply chains, which means that there is an additional income ('sold' in Figure 3.3b).



(a) The cash flows over all the years for liquid hydrogen with a decentralized plant and barge transport



(b) The cash flows over all the years for liquid hydrogen with a centralized plant and pipe transport

Figure 3.3: Cash flow graphs

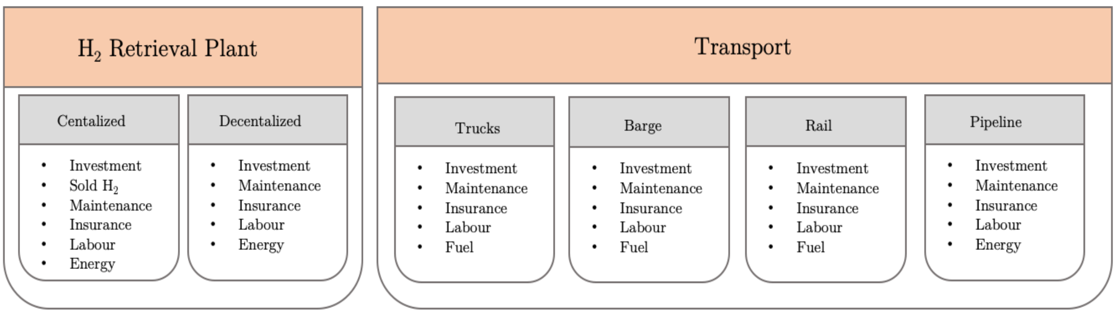


Figure 3.4: The costs of the elements in the End-Use Model

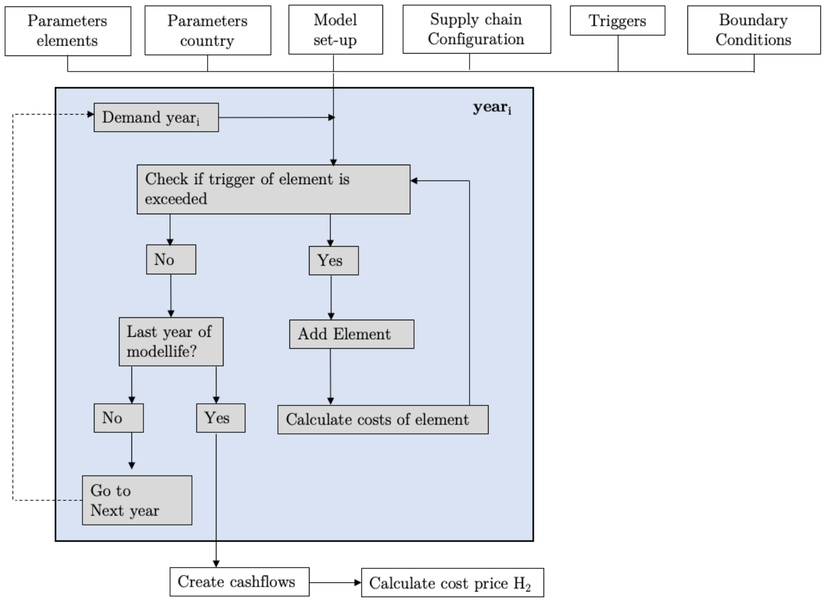


Figure 3.5: The structure of the End-Use Model

3.1.3 Model Structure

The structure of the model is shown in Figure 3.5 and the details of what is included in the costs of an element are presented in Figure 3.4. The input values of the model are the element dependent parameters, the country dependent parameters, the model set-up, the supply chain configuration, the triggers and a given set of boundary conditions. All input values are briefly discussed below and the boundary conditions are explained in Section 3.1.4.

- **Parameters elements**: These are all values related to the element under consideration, such as capacity and cost. They can be found in Appendix C.
- **Parameters country**: These are parameters that depend on the country that is being considered. Country-dependent parameters are the WACC, the energy price and the fuel price. A further description of these parameters can be found in Appendix C.
- **Model Set-up**: The model set-up consists of the start year of the model and the model time frame.
- **Supply Chain Configuration**: The supply chain configuration defines which supply chain is considered. It determines which carrier is selected, the location of the reconversion plant, the mode of transport to the hinterland and the distance to the end-use location.
- **Triggers**: The trigger of an element determines when an investment is made in a new element. A trigger is based on a certain temporal nature, i.e. the timing of an investment. From IJzermans (2019) it can be concluded that the trigger can be based on different temporal natures. A trigger can be based on a perfect foresight, in this situation, an investment is made in an element with a timing that ensures that the demand will always be met, i.e. one already know what the demand will be in the future. A trigger can also be based on the current performance, this is also called the reactive mode. In this mode, the current demand is examined and a decision is made whether an investment is needed at that moment in time. With this trigger, the demand will not always be met because investments are not made until the demand is greater than the available capacity. As a last option, a trigger can also be based on forecast volumes. In this model, the reactive mode was chosen for the trigger, because it reflects reality best.

Each year, it is checked whether the triggers of the elements are exceeded with the given demand of that year and the input parameters. If the trigger of an element is exceeded, a new element is added and the corresponding costs are calculated. This is repeated until the triggers of the elements are no longer exceeded. If the trigger is no longer exceeded the model moves on to the next year and the whole process is repeated. When the last year of the model is computed, cash flows are created for each year by looking at how many elements are online each year and their associated costs. The final cost price of hydrogen is calculated by adding up the cash flows from all the years and dividing them by the model throughput. All calculation are described in detail in Appendix E.

3.1.4 Boundary Conditions

Boundary conditions are needed to define the limits of a specific system. The same set of boundary conditions must be applied to the different supply chain configurations in order to be able to compare them. Below is a description of the boundary conditions and their assumptions which are applied in this model.

- It is assumed that there is an unlimited supply of the chosen carrier coming from the storage in the import terminal.
- It is assumed that the end-user has enough capacity to handle the supplied hydrogen.
- The model allows for the selection of four different carriers: DBT, MCH, NH_3 and LH_2.
- In the model, a choice can be made between three different locations for the retrieval plant; at the import terminal, at the end-user or not present at all.
- The model offers a selection of four transport distributions to the hinterland; trucks, barges, rail and pipelines.
  - For barge and rail, it is assumed that waterways/rails and rail stations/inland ports are already present.
  - For inland shipping one does not take into account the social carbon cost or the boil-off gas costs.
  - The diameter of the pipeline is determined from the maximum volume that can be present during the model period. An assumption must therefore be made for this maximum volume in the supply chain.
- The values of the country dependent parameters (WACC, energy price and fuel price) do not fluctuate over the model life time, but can be made country specific in the model or an average value can be used.
- Investment and operational costs do not fluctuate over the model life time.

3.1.5 Model Validation

The model has been validated by checking for a certain supply chain configuration whether the model outputs correspond with the expected results. The complete validation is shown in detail in Appendix G. The validation is done for a supply chain involving ammonia as the carrier and situated in the Netherlands. The reconversion is decentralized (situated at the end-user) and the ammonia is transported with barges to the end-user. From the validation in Appendix G it can be concluded that the model generates the same values in the amount of elements online each year, the corresponding throughput and the correct costs as would be expected.

3.2 The Supply Chain Model

The Supply Chain Model is a model that allows multiple supply chains to be linked together to determine the effect of supply chain interaction. In this study, the supply chain from the export terminal to the import terminal will be linked to the supply chain from the import terminal to the hinterland. The purpose of this is to better understand the influence of the interaction of these supply chains on the cost price. This model takes into account all elements discussed in Chapter 2. Figure 3.6 shows this supply chain with all its elements. Again, the reconversion plant is shown in orange because it can be located at different places; at the import terminal, at the end-user or not present in the supply chain at all. In addition, this model also takes into account that storage tanks are needed at the end-user location if the retrieval is located there. Therefore, storage is also possible at the end-user's location and is also shown in orange in Figure 3.6. The objective of the model, the modelling concept and the structure of the model are described below. Subsequently, the boundary conditions and the validation of the model are discussed briefly.

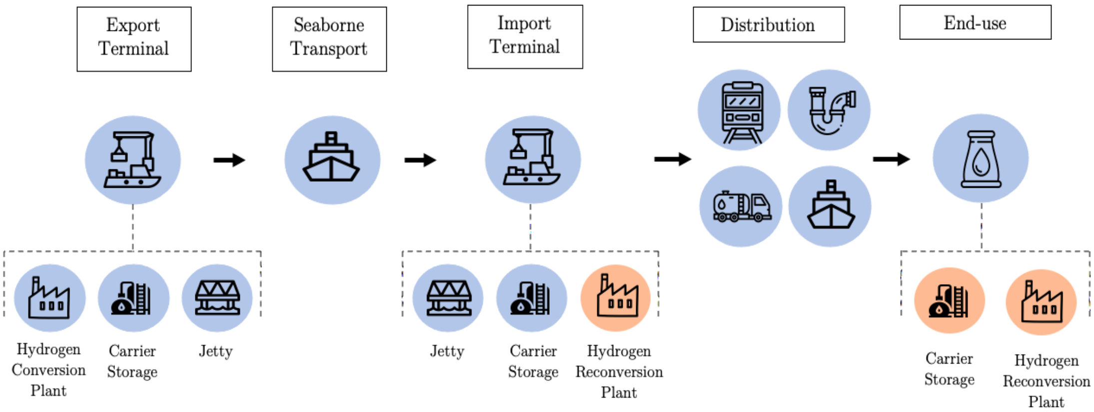


Figure 3.6: The entire supply chain that is modelled by the Supply Chain Model

3.2.1 Model Objective

As with the End-Use Model, the objective of the supply chain model is to assess the contribution of each element in the examined supply chain configuration to the final cost of hydrogen. The purpose of the Supply Chain Model is to not only identify the costs of a single supply chain but also to allow multiple supply chains to be linked together in order to examine the costs and the interaction of these supply chains. In the Supply Chain Model, it is possible to take into account many more elements than in the above described End-Use Model. By taking more elements into account and by connecting supply chains with each other, many more alternative supply chain configurations can be compared. By analysing the costs of the different supply chain configurations, it should become clear which of the supply chain configurations are the most cost-effective and also which configurations increase the costs the most and for what reason.

3.2.2 Modelling Concept

To calculate the cost of the elements in the supply chain, it is necessary to know how many elements are present in the examined supply chain configuration each year. As with the End-Use Model, the open source package Open Source Terminal Investment Simulation (OpenTISim) is used to translate the fluctuations in demand into expansions of the individual elements of a terminal in order to arrive at a terminal design. The OpenTISim is applied to the terminals that are present in the supply chain configuration. In this study, these are the export terminal, the import terminal and the end-use locations, with their associated elements, presented in Figure 3.6. For a given model time frame, supply chain configuration and terminal demand, it determines how many elements are required at each terminal each year. In addition, the transport between the terminals is simulated with the open source package Open Source Complex Logistics Simulation (OpenCLSim), which is available at the Github of the TU Delft Hydraulic Engineering Department (M. Van Koningsveld, J. Den Uijll, F.Baart, and A.Hommelberg, 2019). OpenCLSim enables the simulation of transport flows between two terminals with a given transport mode and throughput. This allows one to simulate the transport that is required between two terminals each year and thus determine how many transport modes are required each year for a given demand. By connecting supply chains to each other by means of OpenTISim and OpenCLSim, the terminals' throughput becomes correlated. This allows to include that the supply chain only becomes operational when the elements are operative in both terminals within a supply chain. By structuring the model in this way, the investments over the entire supply chain are consequently also coordinated. The structure of the model is discussed in more detail in the next section.

The design of the Supply Chain Model is based on a number of assumptions that define the boundaries of the system, as mentioned in Section 3.2.4. The triggers that determine the expansion of the elements are based on the capacity of the elements; when demand exceeds the available capacity of the elements, an expansion of that element is required. The triggers of all elements are explained in detail in Appendix F. Each element has its own investment cost and operational cost (given in Appendix D). The investment costs are collected when the element is under construction and the operational costs are generated each year that the element is in operation. Since OpenTISim and OpenCLSim determine how many elements are needed each year, cash flows can be constructed for all the elements with the associated capital and operational costs to determine the costs of all the elements over the entire model life. The final cost price can be determined by dividing these total costs by the summed throughput over the model life. The detailed calculations to determine the cost price are presented in Appendix F.

For example, a supply chain can be modelled for ammonia. It is given that the demand at the end-user is 2 Mt H_2, the distance between end-user and import terminal is 500 km and the distance between the import terminal and export terminal is 10,000 km. The hydrogen retrieval plant is situated at the end-user and the transport between the import terminal and the end-user is done by ammonia barges. This example is modelled for a model life time of 10 years with 2020 as the start year. The output of the Supply Chain Model is the number of elements that are present each year in the supply chain and their associated costs.

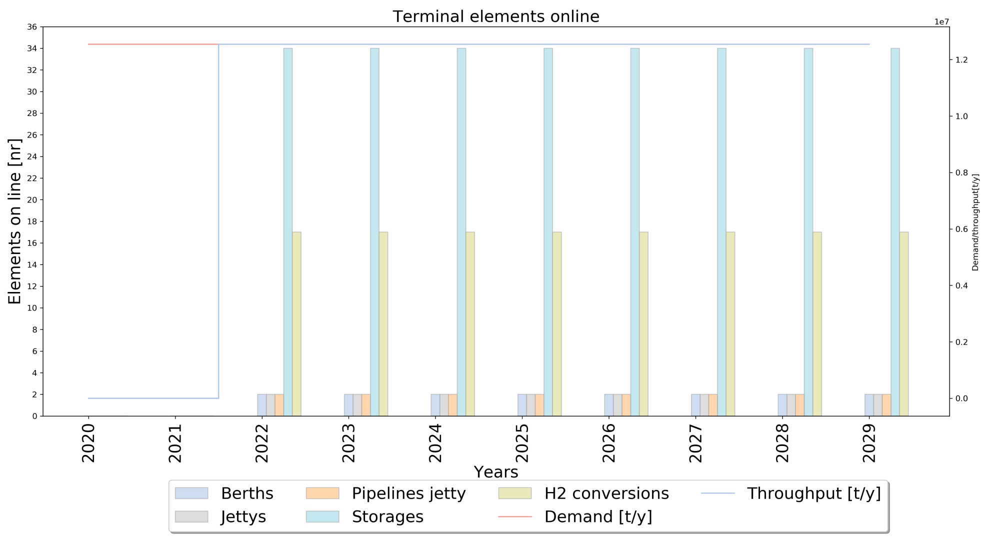


Figure 3.7: The number of elements over the years at the export terminal, with the throughput and the demand

Figure 3.7 shows how many elements are online at the export terminal each year. The model computes the number of elements that are present at the import terminal and end-user location in the same way. Figure 3.8 shows how many vessels are needed between the import terminal and export terminal. The model computes the number of transport elements needed between the import terminal and end-user location in the same way. As in the end-user model, the cash flows for each year are calculated with the number of elements that are present over the model life.

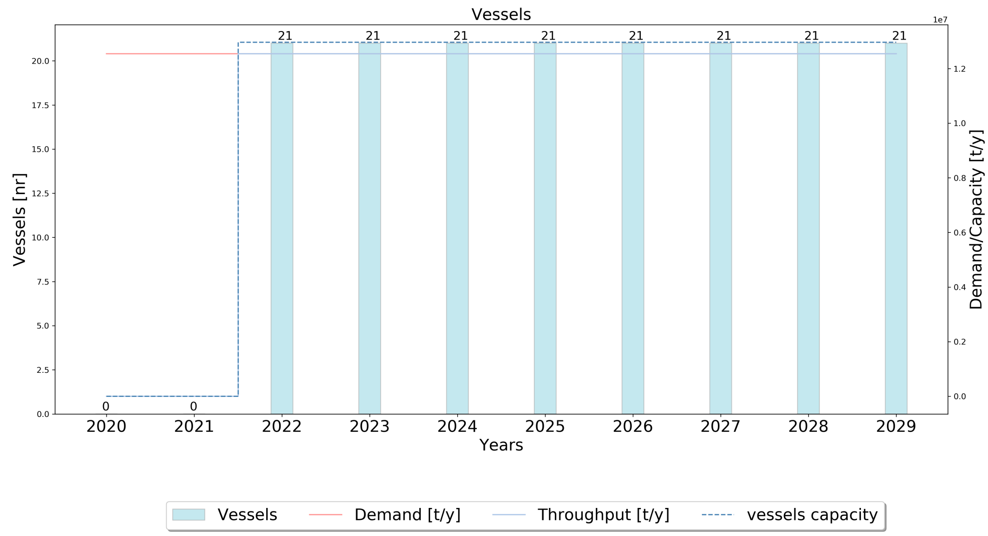


Figure 3.8: The number of vessels over the years for the transport between the export terminal and import terminal

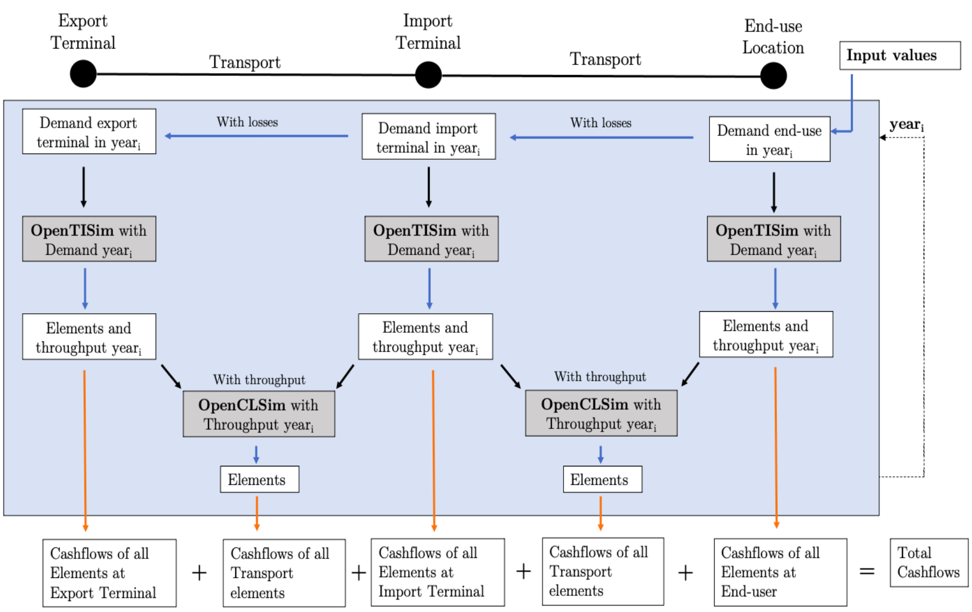


Figure 3.9: The structure of the Supply Chain Model

3.2.3 Model Structure

As described above, the number of elements that must be present in the supply chain each year are determined using OpenTISim and OpenCLSim. Each year OpenTISim calculates how many elements must be present at the terminals and OpenCLSim simulates the transport between the terminals. The complete structure of the Supply Chain Model is illustrated in Figure 3.9. The boundary conditions are discussed in Section 3.2.4, the input of the Supply Chain Model is:

- **Parameters elements**: These are all values related to the element under consideration, such as capacity and cost. They can be found in Appendix C en D.
- **Parameters country**: These are parameters that depend on the country that is being considered. Country-dependent parameters are the WACC, the energy price and the fuel price. The WACC, energy price and fuel price can be set up for each terminal. In addition, when the transport takes place between two countries, the most favourable value is chosen for the calculations of the transport. A further description of these parameters can be found in Appendix D.
- **Model Set-up**: The model set-up consists of the start year of the model and the model time frame.
- **Supply Chain Configuration**: The supply chain configuration defines which supply chain is considered. It determines which carrier is selected, the location of the reconversion plant, the mode of transport to the hinterland, the distance between the export terminal and import terminal, the distance to the end-use location and the hydrogen demand at the end-user.
- **Triggers**: The trigger of an element determines when an investment is made in a new element. As in the End-Use Model the reactive mode is chosen for each trigger. What the trigger of each element is, is described in detail in Appendix F.

With these input values, the model is executed for each year of the specified model time frame. Each terminal in the model is designed to meet a certain demand. The demand can be specified for each terminal as input value, but it is also possible to design the entire supply chain based on the demand of the end-user. If only the demand of the end-user is provided, it is calculated with the losses of each terminal and transport mode what the demand of each terminal needs to be to satisfy this end-user demand, see Figure 3.5. With the specified demand of each terminal, OpenTISim can be executed for each year to determine how many elements must be present at each terminal. This therefore shows how many elements are present at each terminal each year and what the throughput of each terminal is. The throughput is used as input for the openCLSim to simulate the transport that is needed each year. From this simulation it can be deducted how many transport elements are needed each year. When the model has completed for all years in the given model time frame, the cash flows of all the elements are added together to arrive at the total costs over the model. By dividing the total costs by the total throughput over the model time frame, a cost price can be derived. The costs that are taken into account for each element are shown in Figure 3.10.

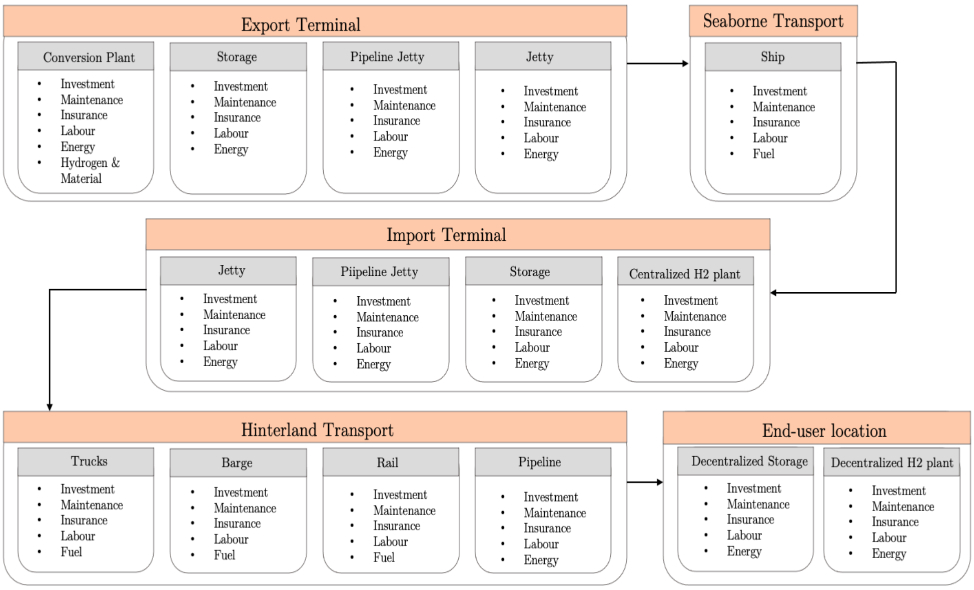


Figure 3.10: The costs of all the elements in the Supply Chain Model

3.2.4 Boundary Conditions

Boundary conditions are needed to define the limits of a specific system. The same set of boundary conditions must be applied to the different supply chain configurations in order to be able to compare them. Below is a description of the boundary conditions and their assumptions which are applied in the Supply Chain Model.

- **Export Terminal:**
  - It is assumed that there is an unlimited supply of hydrogen and material that is needed for the conversion to the chosen hydrogen carrier.
  - The terminal elements are limited to centralized conversion plants, storage tanks and jetties.
  - The jetty contains a dedicated pipeline that is the same for each carrier.
- **Overseas Transport:**
  - The overseas transport is limited to vessels. One type of vessel is chosen for each carrier.
- **Import Terminal:**
  - The terminal elements are limited to reconversion plants, storage tanks and jetties.
  - The jetty contains a dedicated pipeline that is the same for each carrier.
- **Transport to Hinterland:**
  - The model offers a selection of four transport distributions to the hinterland; trucks, barges, rail and pipelines.
    - For barge and rail, it is assumed that waterways/rails and rail stations/inland ports are already present.
    - For inland shipping one does not take into account the social carbon cost or the boil-off gas costs.

    * The diameter of the pipeline is determined from the maximum volume that can be present during the model period. An assumption must therefore be made for this maximum volume in the supply chain.

- **End-user location:**
  - It is assumed that the end-user has enough capacity to handle the supplied hydrogen.
- The values of the country dependent parameters (WACC, energy price and fuel price) do not fluctuate over the model life time.
- Investment and operational costs do not fluctuate over the model life time.
- The model allows for the selection of four different carriers: DBT, MCH, NH_3 and LH_2.
- In the model, a choice can be made between three different locations for the retrieval plant; at the import terminal, at the end-user or not present at all

3.2.5 Model Validation

The model has been validated by checking for a certain supply chain configuration whether the model outputs correspond with the expected results. The complete validation is shown in detail in Appendix H. The validation is done for a supply chain involving liquid hydrogen as the carrier. the country-dependent parameters are the same throughout the supply chain and equal to the global average. The reconversion is decentralized (situated at the end-user) and the liquid hydrogen is transported with barges to the end-user. The distance between the export terminal and import terminal is 10,000 km and the distance between the import terminal and end-user is 500 km. From the validation in Appendix H it can be concluded that the model generates the same values in the amount of elements online each year, the corresponding throughput and the correct costs as would be expected.

3.3 Conclusion

In this research two models have been created. The first model is called the End-Use Model and is used to gain insight into the costs of the supply chain from the import terminal to the hinterland. The second model is called the Supply Chain Model and links together two supply chains: the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the hinterland. This model should provide more insight into the costs over the entire supply chain from the export terminal to the import terminal to the end-user. Both models use OpenTISim to arrive at a terminal design that incorporates demand fluctuations over the specified model time. The Supply Chain Model also uses OpenCLSim to simulate the transport between terminals in more detail. The purpose of both models is to gain more insight into the costs of different elements in the supply chains and how these cost change for various supply chain configurations.

4 | Model Analysis

4.1 The End-Use Model Analysis

In this section, the End-Use Model will be analyzed. The different transport modes linked to a centralized or decentralized reconversion plant are plotted against each other over the distance to the end-user and over the demand of the end-user. It is assumed that the model time frame is 20 years, starting in 2020, and furthermore, it is assumed that the end-user demand grows each year by 4% (based on expert opinion), with the value in the starting year plotted on the x-axis. The supply chain is situated in The Netherlands. The data used in this model is shown in Appendix C. In the analysis a distinction is made between decentralized reconversion (at the end-user) and centralized reconversion (at the import terminal). The difference between the two is that when the reconversion plant is at the import terminal the unused capacity can be sold to other supply chains. When the reconversion plant is at the end-user location, this remaining capacity will not be sold. The selling price of the hydrogen in the case of a centralized reconversion plant is equal to the cost price of the hydrogen, looking only at the reconversion plant, not taking into account the transport to the hinterland, see Appendix E. In this general analysis of the End-Use Model only MCH is examined as LOHC and the pipeline scenario has been investigated for new pipelines only, not taking into account the already existing pipelines. After the analysis of the general model, a sensitivity analysis was also performed for the various parameters used in the model.

4.1.1 General Analysis

This section compares different transport modes linked to centralized and decentralized retrieval plants. When the retrieval plant is centralized (at the import terminal), transport of CGH_2 will take place, which is possible in this model using CGH_2-trucks or CGH_2-pipelines. When the retrieval plant is decentralized (at the end-user), transport of the carrier will take place (MCH, NH_3, LH_2 transport). This is possible in this model with trains, trucks and barges for all three carriers and with an NH_3-pipeline. The different possibilities are compared below.

4.1.1.1 Trucks vs. Trucks

First, the trucks are compared with each other. One option is that the reconversion plant is located at the import terminal and that the transport is done with CGH_2-trucks (in the graph denoted by 'Centralized trucks'). The second option is that the reconversion plant is located at the end-user's and that the transport is done with MCH, LH_2 or NH_3-trucks (referred to as 'Decentralized trucks' in the graph).

In the left graph, the cost price is plotted against the demand at the end-user in the starting year of the model, a fixed distance of 200 km to the end-use location is assumed. It can be observed from this graph that a reconversion plant at the end-user with carrier transport is for LH_2 always the cheapest option. For NH_3 centralized reconversion with CGH_2-truck transport is the cheapest option at first, but quickly decentralized reconversion and LH_2-truck transport become the cheapest option. For MCH the cheapest option for smaller volumes will be centralized reconversion with CGH_2-truck transport. Around a volume of 90,000 ton H_2 in the startyear the cheapest option becomes decentralized conversion with carrier truck transport. The cheapest option is always LH_2 with decentralized conversion and LH_2-truck transport.

The graph on the right shows the cost price versus the distance, assuming a fixed start-up demand of 200 kton H_2. From this graph we can again conclude that for each carrier decentralized reconversion with carrier truck transport is the cheapest option. Of all carriers LH_2-truck transport with decentralized conversion is again the most economical, however the rate of increase of the cost price of this option is faster over the distance than that of NH_3. It can be stated that around 400 km the cheapest option becomes NH_3-truck transport with decentralized reconversion. When increasing the volume in the right graph, the lines hardly change and the tipping point of LH_2 and NH_3 still remains around 400 km.

From these graphs it can be concluded that for LH_2-truck transport with decentralized conversion is the cheapest option up to 400 km. When the distance is greater than 400 km the cheapest option will become NH_3-truck transport with decentralized reconversion.

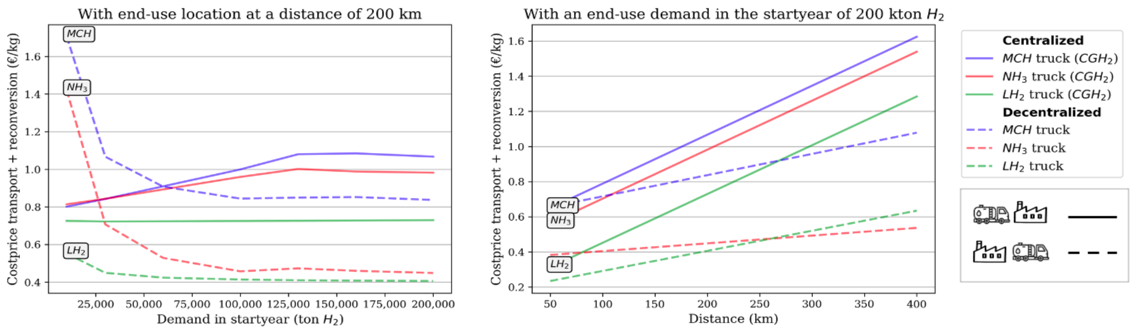


Figure 4.1: Decentralized reconversion with carrier truck transport vs. centralized reconversion with CGH_2-truck transport

4.1.1.2 Trucks vs. Barges

Now the barges are compared with the trucks. For the trucks, we look at decentralized reconversion with carrier truck transport ('Decentralized truck'), because the section above has shown that for longer distances and larger volumes, this option is cheaper than centralized reconversion with CGH_2-truck transport. For the barges, we look at decentralized reconversion with carrier barge transport ('Decentralized barge').

In the left graph, the demand is variable and a fixed distance of 200 km is assumed. It can be seen from this graph that for this distance and decentralized reconversion, barge transport is always cheaper than truck transport, with LH_2 as the cheapest option. In the graph on the right the distance is variable and a fixed demand of 200 kton H_2 is assumed. The same conclusions can be drawn from this graph.

The conclusion is that when the retrieval plant is at the end-user barges are always cheaper than trucks, with LH_2 as the most economical option. However, it must be taken into account that trucks are a far more flexible method of delivery; no waterway or railway is needed. Calculating the cost of barge and rail assumes that the inland ports/rail stations and waterways/railways are already present.

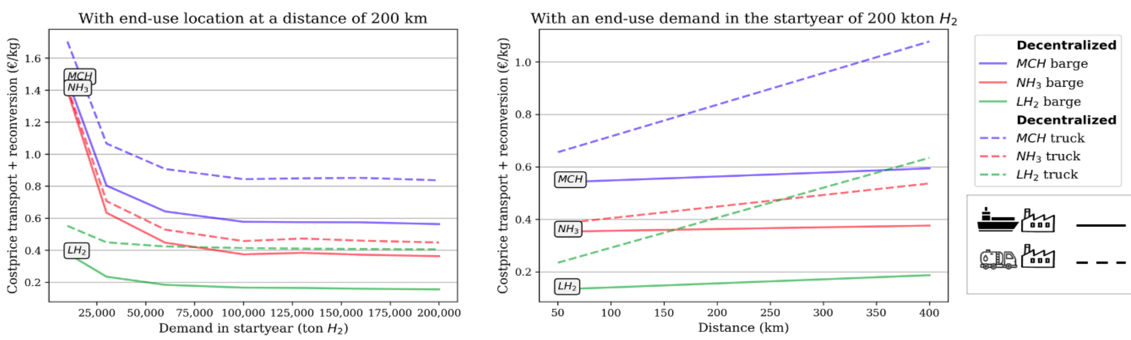


Figure 4.2: Decentralized reconversion with carrier truck transport vs. decentralized reconversion with carrier barge transport

4.1.1.3 Barges vs. Trains

This section compares barge and rail transport. For barge, decentralized reconversion with carrier barge transport ('Decentralized barge') is considered again. For rail this section considers decentralized reconversion with carrier rail transport ('Decentralized rail').

In the left graph, demand is variable and a fixed distance of 600 km is assumed. In the right graph, the distance is again variable and a fixed demand of 200 kton H_2 is assumed. From both graphs can be concluded that for a decentralized reconversion plant the cost price for rail transport is very close to that of barge transport. For MCH and NH_3-barge transport is the cheapest option and for LH_2-rail transport is more economical.

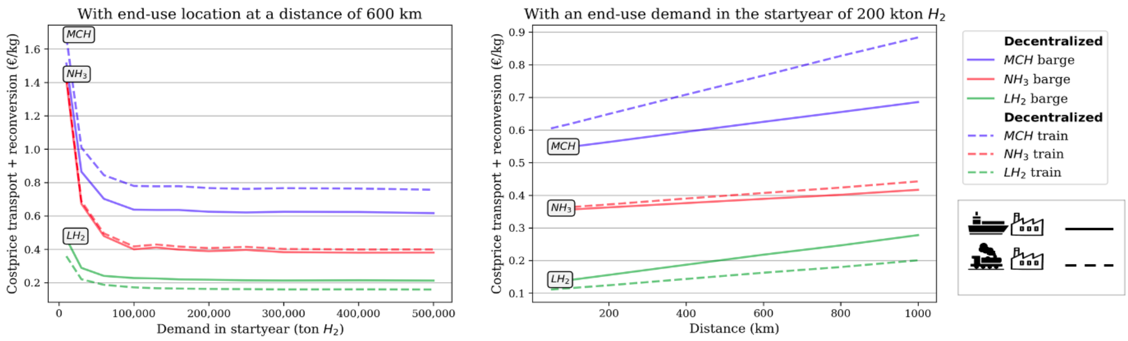


Figure 4.3: Decentralized reconversion with carrier barge transport vs. decentralized reconversion with carrier train transport

4.1.1.4 Barges vs. Pipelines

Now pipelines are compared with barges. For the barges, decentralized reconversion with carrier barge transport ('Decentralized barge') is again considered. For the pipelines, centralized reconversion with CGH_2 transport via pipelines ('Centralized pipe') is taken into account.

In the first graph, demand is variable and a fixed distance of 1000 km is assumed. It can be observed from this graph that when the supply chain volume increases the CGH_2-pipeline with a centralized plant becomes at some point the most economical choice for MCH and LH_2. However for NH_3 the barge transport will be cheaper than the CGH_2-pipeline with a centralized plant even for large supply chain volumes. The overall cheapest option for smaller volumes is a decentralized plant with barge transport for LH_2. When the volume becomes large the cheapest option will become a CGH_2-pipeline with a centralized plant.

In the second graph, the distance is variable and a fixed demand of 500 kton H_2 is assumed. It can be seen from this graph that for this supply chain volume, first a CGH_2-pipeline with a centralized retrieval plant is the cheapest, but for longer distances a decentralized power station with LH_2-barge transport becomes more economical.

The conclusion is that for small supply chain volumes a decentralized plant with LH_2-barge transport is the cheapest option. If the volume becomes large (400 - 500 kton H_2) then a centralized plant with CGH_2-pipeline transport will be the cheapest option. However, distance must also be taken into account; if the distance becomes too far ($>$ 1100 km), a decentralized plant with LH_2-barge transport will again be the cheapest option. In addition, it must be taken into account that this general analysis only looks at completely new pipelines. In a more realistic situation, it is highly likely that pipelines that already exist will be used, which will probably reduce the price of the pipeline option.

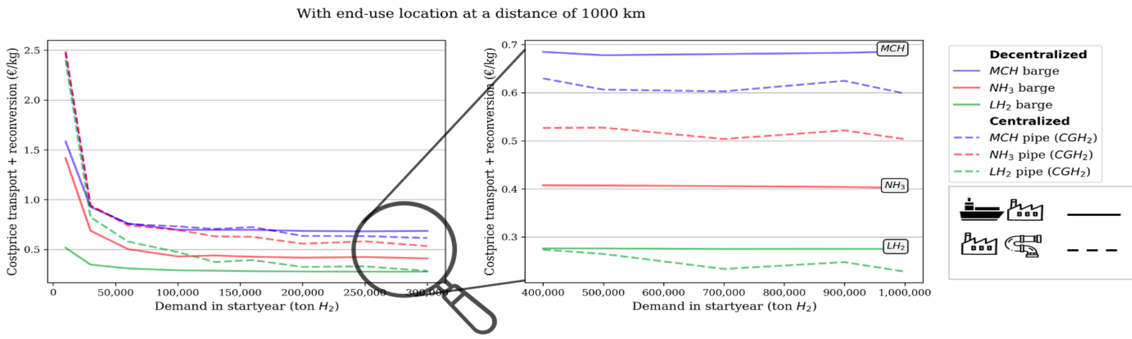


Figure 4.4: Decentralized reconversion with carrier barge transport vs. centralized reconversion with CGH_2-pipeline transport over the demand at the end-use location in the start year

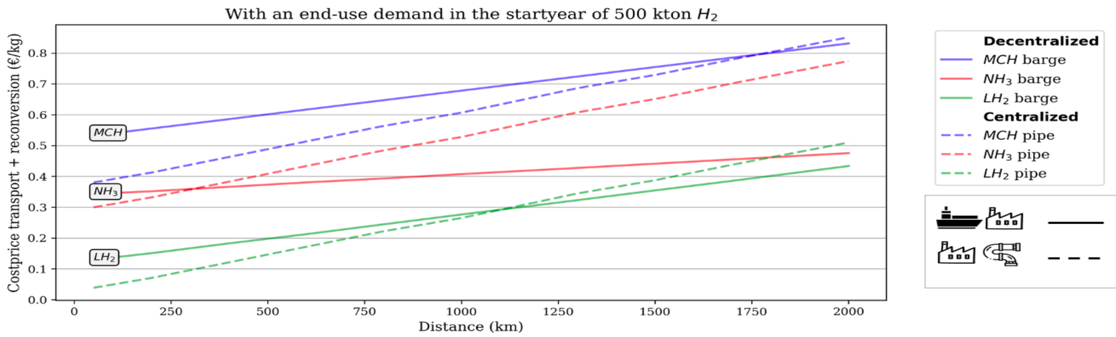


Figure 4.5: Decentralized reconversion with carrier barge transport vs. centralized reconversion with CGH_2-pipeline transport over the distance

4.1.1.5 Pipelines vs. Pipelines

In addition to a CGH_2-pipeline, an NH_3-pipeline can also be considered. Here, centralized reconversion with CGH_2 transport by pipeline ('Centralized pipe') is compared to decentralized reconversion of NH_3 with transport of NH_3 by pipeline ('Decentralized pipe'). It can be concluded from the graphs that centralized reconversion of LH_2 with CGH_2 transport remains the cheapest option. However, decentralized reconversion of NH_3 with an NH_3-pipeline is a cheaper option than centralized reconversion of NH_3 with CGH_2-pipeline transport.

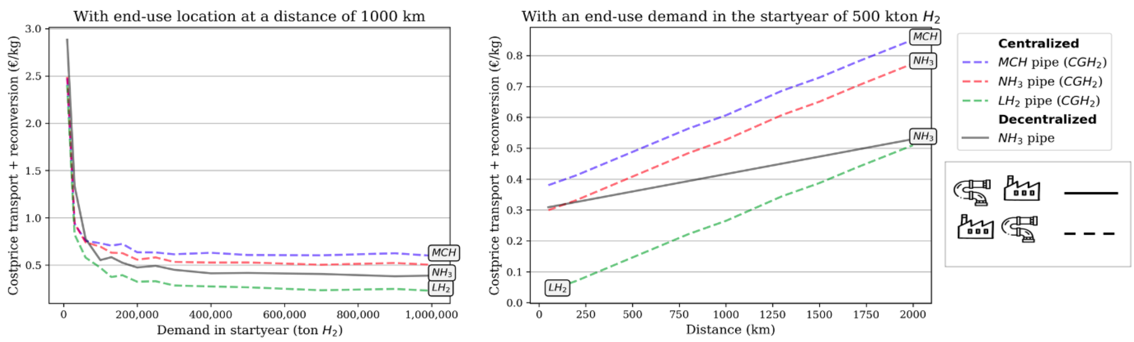


Figure 4.6: Centralized reconversion with CGH_2-pipe transport vs. decentralized reconversion with NH_3-pipeline transport

4.1.2 Sensitivity Analysis

A sensitivity analysis was carried out to see for which parameters the cost price is vulnerable. This was done for decentralized reconversion with carrier barge transport, centralized reconversion with CGH_2-pipeline transport and decentralized reconversion with NH_3-pipeline transport. In this analysis only barge is considered and not trucks and rail because the way the cost price is calculated is approximately the same for all three. The sensitivity that emerges for the barges will be similar for the trains and trucks. The sensitivity of a parameter is calculated by examining what happens to the cost price when the average parameter value (that is used in the general model) increases by 50% and decreases by 50%. The sensitivity of a parameter is indicated in percentages, this percentage indicates by how much the cost price changes when the parameter is adjusted. The parameters that the model is very sensitive to are shown in red and orange in Table 4.1.

	Decentralized with barge transport			**Centralized with CGH_2 pipe transport**			**Decentralized with NH_3 pipe transport**
	NH_3	MCH	LH_2	NH_3	MCH	LH_2	NH_3
Energy price	>30%	>30%	>5%	>30%	>30%	>15%	>30%
Fuel price	>5%	>5%	>5%	-	-	-	-
Grow of demand	>5%	>5%	>5%	>5%	>5%	>5%	>5%
CAPEX barge	>5%	>5%	>30%	-	-	-	-
CAPEX plant	>5%	>5%	>5%	>5%	>5%	>5%	>5%
CAPEX pipe	-	-	-	>5%	>5%	>30%	>5%
Boil-off losses	>5%	-	>5%	-	-	-	-
WACC	>15%	>15%	>15%	>15%	>15%	>15%	>15%
Labour costs	>5%	>5%	>5%	>5%	>5%	>5%	>5%
Selling price H_2	-	-	-	>5%	>5%	>5%	-

Table 4.1: Sensitivity of various parameters in the end-use model

4.1.3 Conclusion

The general analysis of the End-Use Model is intended to provide more insights into how different supply chain configurations affect the final cost price of hydrogen. It considers the supply chains of the hydrogen carriers NH_3, MCH and LH_2 from the import terminal to the end-user. In these supply chains it is possible to place the reconversion plant at the import terminal and thus have gaseous hydrogen transport to the hinterland or the reconversion plant is at the end-user and there is carrier transport to the hinterland with barges, rail or truck. From the analysis it can be concluded that for the different supply chain configurations, LH_2 is the cheapest option in terms of the supply chain to the hinterland. After LH_2, NH_3 is often the most cost-effective and MCH is usually the most costly option. This is due to the fact that the reconversion plant for LH_2 is a lot less expensive than the reconversion plants for NH_3 and MCH. However, a conversion plant for LH_2 (a plant that produces the supplied LH_2) is a lot more expensive than the conversion plants for NH_3 and MCH. It is therefore interesting to look at the entire supply chain from the export terminal to the import terminal to the end-user, this will be done in the next section.

4.2 The Supply Chain Model Analysis

In this section, the Supply Chain Model will be analyzed. In this study, the Supply Chain Model is applied to investigate the interconnection of the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the hinterland. First, the supply chain from the export terminal to the import terminal will be analysed, and thereafter the entire supply chain from the export terminal to the import terminal to the end-user. Again, one can choose to locate the reconversion plant at the import terminal or at the end-user. When the reconversion plant is at the import terminal, the gaseous hydrogen is transported through CGH_2-pipelines. When the reconversion plant is located at the export terminal, the transport is done by barges or rail. The difference with the End-Use Model is that this model includes the need for storage tanks at the end-user's site if the plant is located at the end-user's location. In addition, an extra carrier is being compared here, which is DBT. Moreover, it is assumed in the End-Use Model that, when a pipeline is used as distribution mode to the end-use location, the entire pipeline network is newly constructed. However, in the Supply Chain Model, a certain section of the pipeline network can be chosen to be part of an already existing hydrogen backbone. In this example, the hinterland is assumed to be in Europe and the values are taken from (Wang et al., 2020). It is assumed that 75% of the pipeline network is covered by the hydrogen backbone and that 25% needs to be newly constructed. The data that is used in this model is shown in Appendix D. After the analysis of this general model, a sensitivity analysis was performed for various parameters that are used in this model.

4.2.1 General Analysis - Export to Import Terminal

First a general analysis has been done for the supply chain from the export terminal to the import terminal. A model time period of 10 years is assumed with 2020 as starting year. The country dependent parameters are all equal to the global average of that parameter, given in Appendix D. The composition of the costs per carrier is given in Figure 4.7. This is based on an example where the end-use demand is equal to 2 Mt H_2 and the overseas distance is equal to 10,000 km (5555 nm). The hydrogen retrieval plants are located at the import terminal.

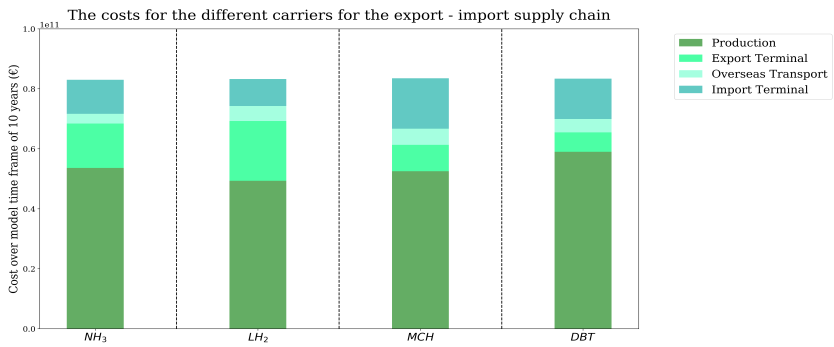


Figure 4.7: Breakdown of the costs for the various carriers for the supply chain from the export terminal to the import terminal

From this graph it can be observed that the production costs are the highest for every carrier. These production costs are the procurement costs for the hydrogen and the material that is required to make the hydrogen carrier. The production costs are particularly high for DBT, this is due to its high procurement costs. The expenses for the export terminal are higher for LH_2 and NH_3 compared to MCH and DBT. This is because the hydrogen conversion plants for LH_2 and NH_3 are more expensive than the ones for MCH and DBT. In particular, the LH_2 export terminal is the more expensive option for the export terminal, this is because LH_2-storage is expensive and because the hydrogen conversion plant for LH_2 consumes a lot of energy. The overseas transport costs lie relatively close to each other for all the carriers, where shipping of NH_3 is the cheapest option. The costs of the import terminal are considerably higher for DBT and MCH, the reason being that the reconversion plants of DBT and MCH are more expensive and also require a lot of energy.

In addition to this cost analysis, the overseas distance and end-user demand have been made variable. When the end-user demand is made variable the supply chain volume changes. The cost price (€/kg

H_2) for all the different carriers over a varying distance and supply chain volume is shown in Figures 4.8 and 4.9.

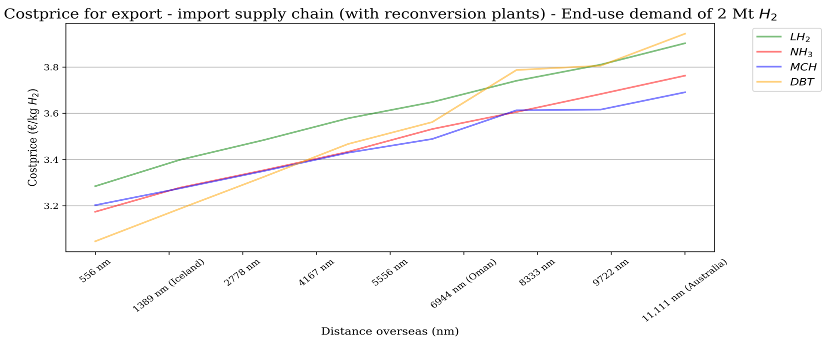


Figure 4.8: Cost price for the supply chain for variable distance

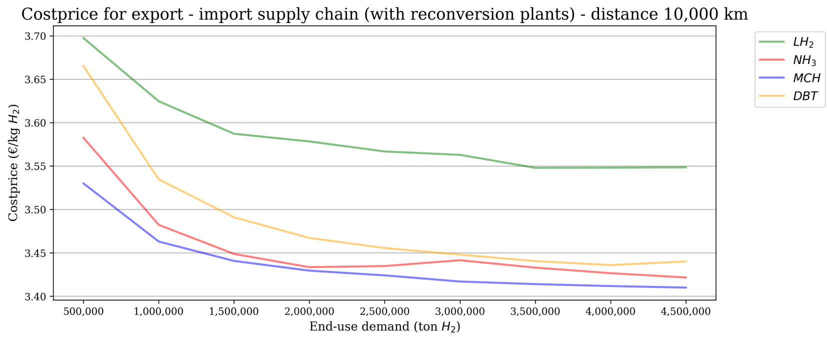


Figure 4.9: Cost price for the supply chain for variable demand

When the overseas distance is made variable (Figure 4.8), a fixed end-user demand of 2 Mt H_2 is assumed. For shorter overseas distances, DBT is the cheapest option. However, due to the high procurement costs of DBT, the cost price grows faster over the distance compared to the other carriers. Around 4000 nm, MCH and NH_3 become more economical than DBT.

When the end-user demand is variable (Figure 4.9) a fixed distance of 10,000 km is assumed (5555 nm). It can also be observed from Figure 4.8 that for 10,000 km, MCH is the cheapest option, followed by ammonia, DBT and LH_2, respectively. Figure 4.9 also illustrates this and reveals that this order remains the same for a varying volume. From the general analysis of the export-import supply chain it can be concluded that for distances up to 4000 nm DBT is the most cost-effective. When the distance becomes greater, NH_3 and MCH become more economical. For a varying volume, the order remains the same.

In addition, the lines of MCH and DBT show kinks over a variable overseas distance, while the lines of NH_3 and LH_2 do not. This is because in the case of NH_3 and LH_2 the material is not re-used; all the N_2 and H_2 that is required to make NH_3 and LH_2 is shipped to the importing country and not returned to the export country for recycling. As a result, all the N_2 and H_2 needed to meet the demand has to be procured in the exporting country. The H_2 is attached to the LOHC in the country of export, transported to the country of import where the H_2 is removed and after which the LOHC is transported back to the country of export to be reused. This means that not all of the LOHC has to be procured to meet the demand, but only a quantity of the LOHC needs to be purchased. This amount is equal to the volume of LOHC that can be used to fill all boats once, as this amount will be transported back to the exporting country and be re-used again. When the overseas distance increases, more and more boats are needed to transport the volume. Every time an extra boat is required, additional LOHC has to be purchased, which causes a sudden increase in costs, but not in throughput, and therefore kinks in the LOHC lines occur.

It should be noted, however, that the cost price of MCH and DBT is very sensitive to the purchase price and selling price. Subsequently, the LOHC vessels use an oil with a low sulphur content as fuel, which means that these ships have CO_2 emissions. If it is assumed that the ships are not allowed to emit CO_2 (such as LH_2 and NH_3), the cost price of the LOHC will be higher, as this is a more expensive option.

4.2.2 General Analysis - Entire Supply Chain

Having looked at the supply chain from the import terminal to the end-user and the supply chain from the export terminal to the import terminal, the entire supply chain from export terminal to import terminal to end-user must be examined. Again a model is made with a time period of 10 years and a starting year in 2020. The country dependent parameters are all equal to the global average of that parameter, given in Appendix D. In this supply chain, the choice can be made to locate the reconversion plants at the import terminal or at the end-user. The supply chain configuration referred to as 'centralized' is the configuration where the hydrogen retrieval plant is located at the import terminal and transport is done by CGH_2-pipelines. The supply chain configuration referred to as 'decentralized' represents the configuration where the plant is located at the end-user and carrier transport is done via barges and trains.

First, the cost composition is examined again. An end-user demand of 2 Mt H_2 is assumed, the whole supply chain is dimensioned to this demand. The distance between the export terminal and import terminal is 10,000 km and the distance between the import terminal and end-user is 500 km. When the decentralized option is considered, barge transport is assumed, for the centralized option the transport is done with CGH_2-pipelines. Figure 4.10 shows the costs for this example for all carriers and the two supply chain configurations (centralized (cen) and decentralized (dec)).

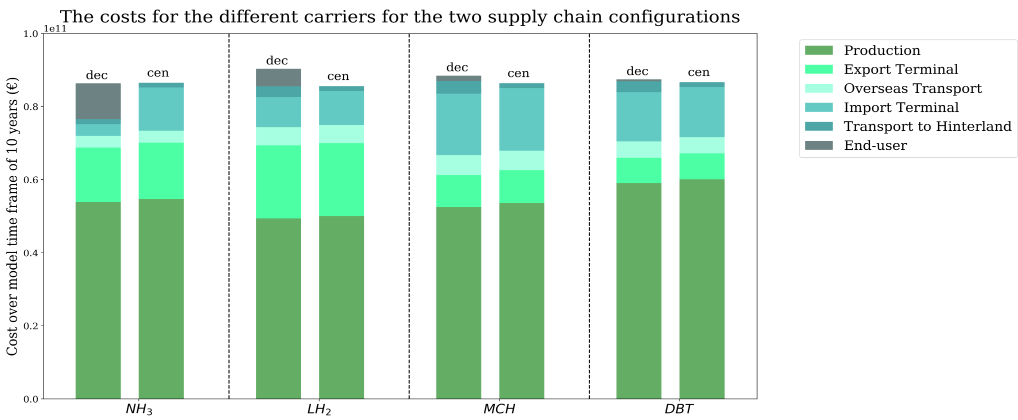


Figure 4.10: Breakdown of the costs for the various carriers for the two supply chain configuration for the entire supply chain

From this figure it can be seen that the production costs (purchase of the hydrogen and the material) account for the largest part of the costs for all four carriers. The difference in production costs for the carriers between the centralized and decentralized options is because more losses occur in a centralized option, requiring more production at the beginning of the supply chain. As discussed in Section 4.2.1, the costs for the export terminal are high for NH_3 and LH_2 compared to MCH and DBT. The overseas transport costs lie relatively close to each other for all the carriers, where shipping of NH_3 is the cheapest option.

When the reconversion plants are at the end-user (decentralized), transport will take place by means of barges and storage tanks will also be required at the end-user. There are no reconversion plants at the import terminal so the costs of the elements there are relatively low. The import terminal is most expensive for LH_2, due to high investment costs for LH_2-storage tanks. However, the number of storage tanks of LH_2 may be reduced in the future if hydrogen pipeline networks connect to salt caverns where the hydrogen can be stored at low cost. The costs of transport to the hinterland are close to each other for all the carriers, where NH_3-barge transport is the cheapest option. The costs for the elements needed at the end-user location are especially high for DBT and MCH because these reconversion plants are expensive and consume a lot of energy.

When the reconversion plants are located at the import terminal (centralized), the CGH_2 will be transported directly by pipeline to the hinterland and no storage tanks will be necessary at the end-user location. Therefore, there are no elements present at the end-user's. This is also the reason for LH_2 to be cheap for the centralized configuration, because there are no additional storage tank required at the end-use location. Again, the costs for the import terminal are high for MCH and DBT due to the reconversion plants with high investment costs and the high energy consumption of those plants. The costs for the transportation to the hinterland is the same for each carrier because the same amount of CGH_2 goes into the pipeline for each carrier.

For ammonia, the centralized supply chain is more expensive as more losses (approximately 2% more) occur in this supply chain and therefore more production is required at the export terminal to meet the demand at the end-user. For LH_2, the centralized option is cheaper because it does not require storage tanks at the end-user's site. The investment costs for CGH_2storage is very high. For the LOHCs the costs for both supply chain configurations are approximately the same. The decentralized option is somewhat cheaper for both LOHCs, which is due to more losses and hence more production costs.

4.2.2.1 Centralized

As explained above, in this supply chain configuration, the hydrogen retrieval plant is located at the import terminal. Transportation to the end-user is done via CGH_2-pipelines and no storage tanks are needed at the end-user. In Figures 4.11, 4.12 and 4.13 the cost price of hydrogen is plotted against a varying overseas distance, hinterland distance and end-user demand.

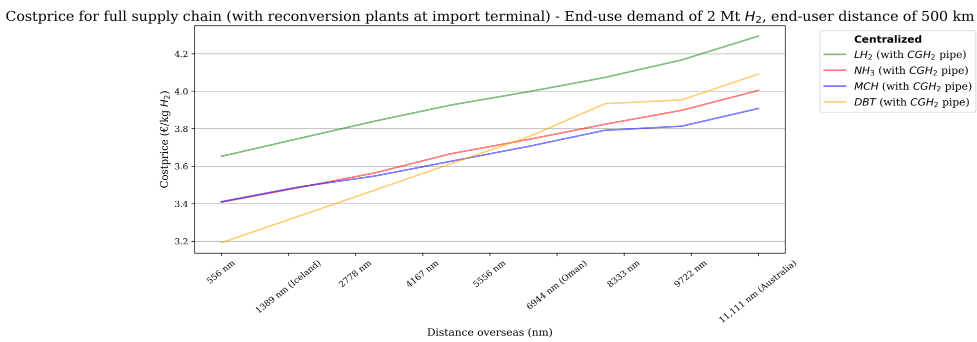


Figure 4.11: Cost price for the supply chain for variable overseas distance

In graph 4.11 the overseas distance is made variable, a fixed demand of 2 Mt LH_2 is assumed and a fixed distance to the end-user of 500 km is assumed. From this graph it can be seen that for smaller distances DBT is the cheapest option, however for larger distances (>10,000 km), MCH and NH_3 become more cost effective.

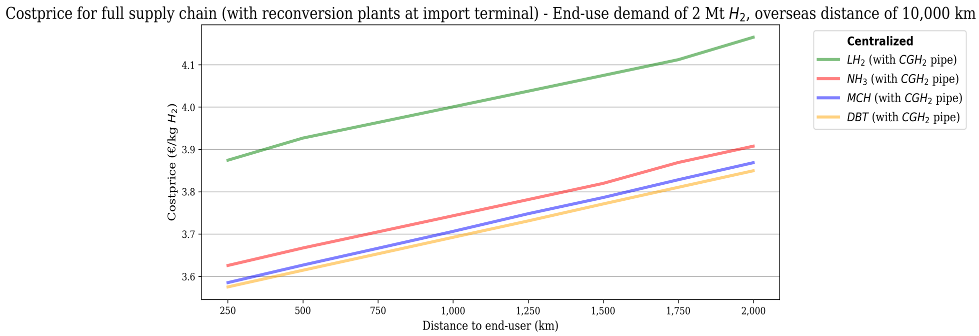


Figure 4.12: Cost price for the supply chain for variable distance to hinterland

When the distance to the hinterland is made variable (Figure 4.12), a fixed overseas distance of 10,000 km is assumed and a fixed demand of 2 Mt LH_2. From Figure 4.11 it can be observed that around 10,000 km, MCH and NH_3 become more cost effective compared to DBT. From Figure 4.12 it can be concluded that for exactly 10,000 km this is not yet the case and that DBT is still slightly cheaper than MCH and NH_3 at this point. This will not change for a varying distance to the hinterland and the cost price of all carriers will increase equally over the distance. This is because this analysis concerns the centralized option, so for all carriers the transport to the hinterland is done as CGH_2, and hence all the costs to the hinterland are the same. In Figure 4.13 the supply chain volume is made variable, from this figure it can be concluded that over a varying volume the cost price is approaching a somewhat constant value. For 10,000 km, the cost prices of MCH, DBT and NH_3 are very similar, LH_2 is the most expensive option.

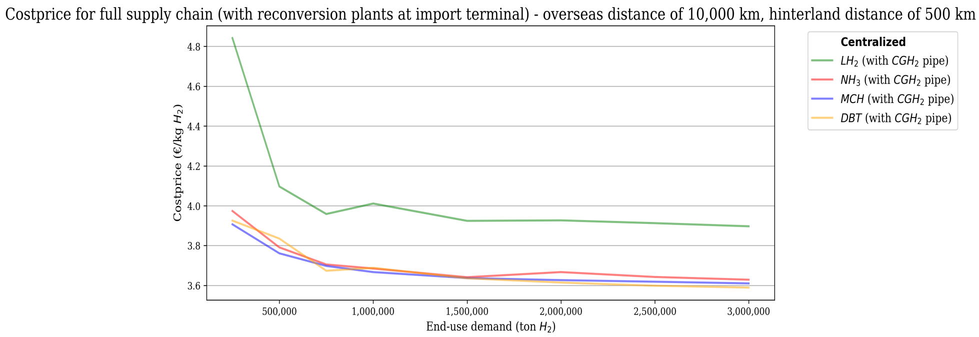


Figure 4.13: Cost price for the supply chain for variable demand

4.2.2.2 Decentralized

As described earlier, the decentralized supply chain configuration considers a hydrogen retrieval plant that is located at the end-use location. This section compares transport to the hinterland by barge and rail. Storage tanks are needed at the end-use location to store the hydrogen carriers. In Figures 4.14, 4.15 and 4.16 the cost price of hydrogen is plotted against a varying overseas distance, hinterland distance and end-user demand, rail and barge are compared in these figures.

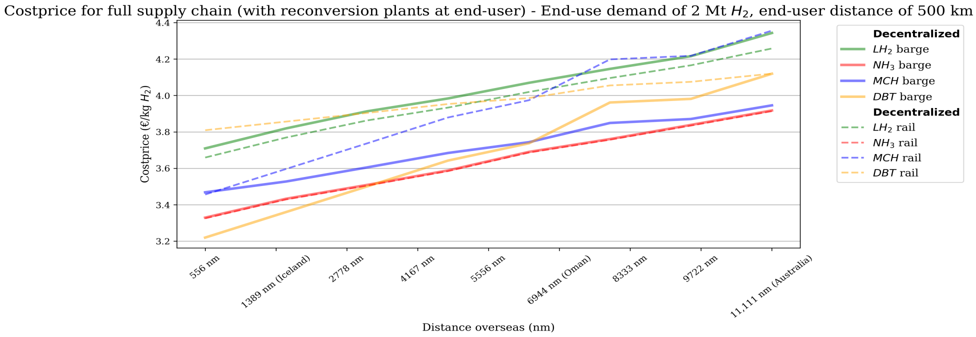


Figure 4.14: Cost price for the supply chain for variable overseas distance

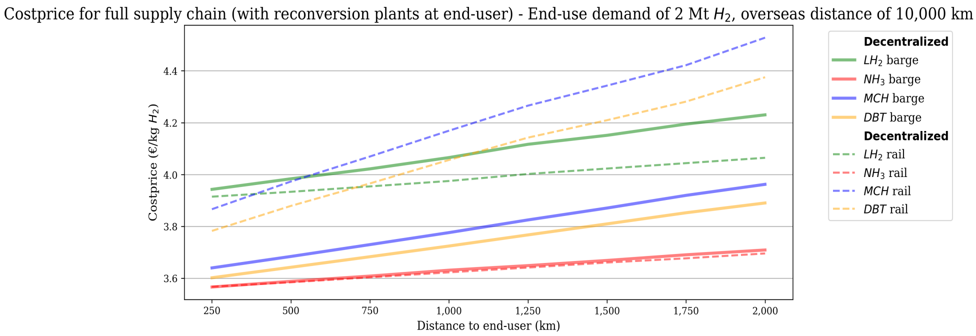


Figure 4.15: Cost price for the supply chain for variable distance to hinterland

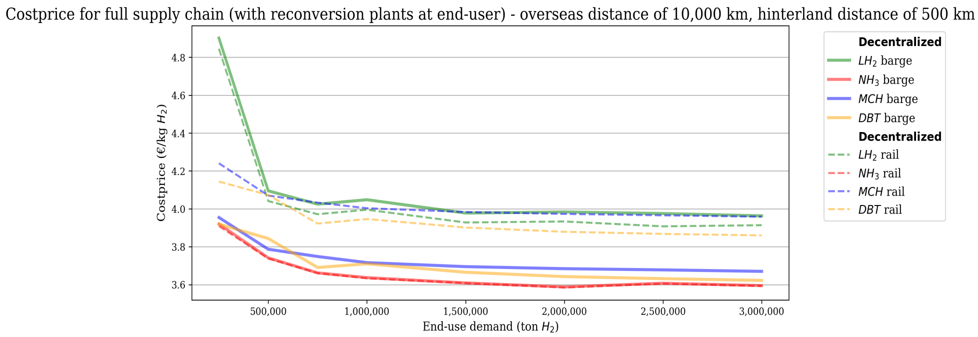


Figure 4.16: Cost price for the supply chain for variable demand

In graph 4.14, the overseas distance is variable. In this example a demand of 2 Mt LH_2 and a distance to the hinterland of 500 km is assumed. From this figure it can be concluded that for distances up to 2800 nm DBT is the cheapest option, when the distance increases NH_3 becomes most economical and around 7000 nm, MCH becomes competitive with NH_3. LH_2 is one of the most expensive options because the investment costs of barge and rail transport a lot higher for LH_2 compared to NH_3 and the LOHCs and because additional storage at the end-user's is accounted for. Rail transport is equally expensive for NH_3, more expensive for LOHCs and cheaper for LH_2 than barge transport. When the distance to the hinterland is made variable, a fixed demand of 2 Mt LH_2 and a overseas distance of 10,000 km is assumed. Figure 4.14 shows that for 10,000 km, ammonia is indeed the cheapest option. Over an increasing hinterland distance, the cost of NH_3-barge and rail transport will increase at the lowest rate, due to the smaller investment costs to transport a ton of NH_3 compared to those of the LOHCs. When the end-user demand is made variable, a fixed overseas distance of 10,000 km and a hinterland distance of 500 km is assumed. From Figure 4.13, it can be seen it can be seen that each carrier approaches an approximately constant cost price when the volume increases. The supply chain volume will not make much difference in the order of the costprices of the carriers.

4.2.2.3 Centralized vs. Decentralized

Now that it has been investigated how the cost price for the various carriers and supply chain configurations changes over the distances and over the volumes, the supply chain configurations can be compared. For the decentralized option, barge transport was considered.

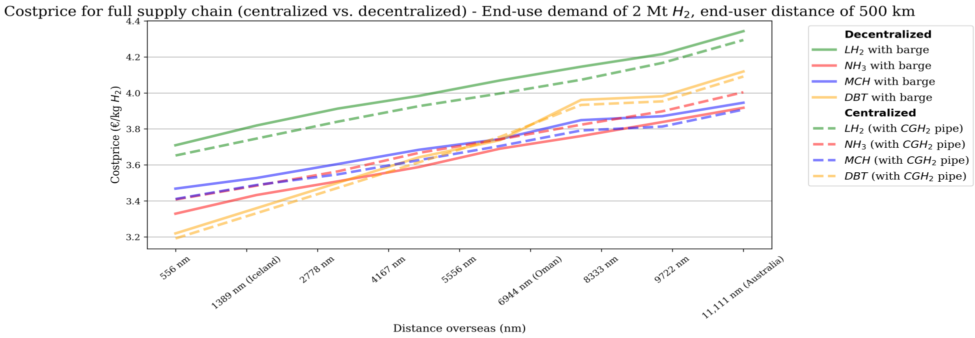


Figure 4.17: Cost price for the supply chain for variable overseas distance

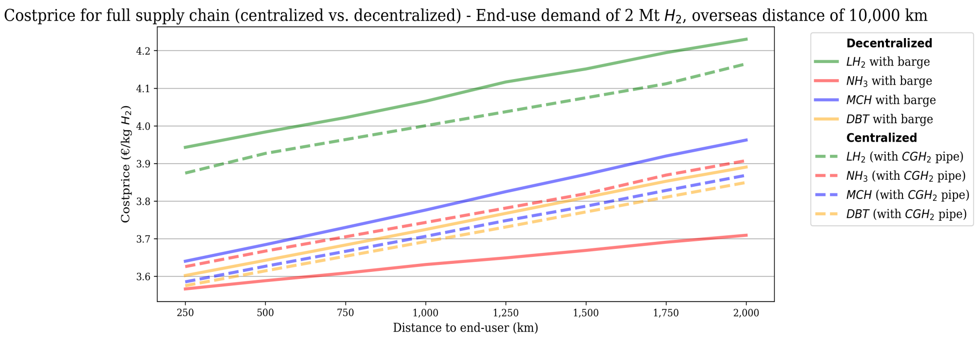


Figure 4.18: Cost price for the supply chain for variable distance to hinterland

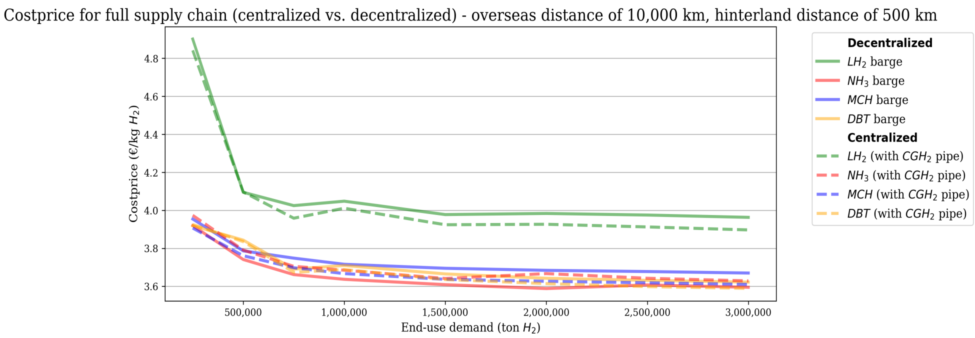


Figure 4.19: Cost price for the supply chain for variable demand

In graph 4.17, the overseas distance is variable, again a fixed demand of 2 Mt H_2 and hinterland distance of 500 km is assumed. From this figure it can be concluded that for distances up to 3500 nm, the centralized an decentralized options for DBT are the most economical. When the distance increases NH_3 and MCH become more cost effective. The centralized option is more economical for all carriers, except NH_3. However, it should be noted that NH_3-barge transport of large volumes is not very likely, given the environmental and social problems it entails. As a result, NH_3-barge transport may not be possible or the costs could be considerably higher.

In Figure 4.18 the hinterland distance is variable and a overseas distance of 10,000 km is assumed with a demand of 2 Mt H_2. When the distance to the hinterland is made variable decentralized reconversion of NH_3 with barge transport is the most cost-effective option. After this option, centralized reconversion of the LOHCs is the most economical.

In Figure 4.19 the end-user demand is variable, again the overseas distance is 10,000 km and the hinterland distance is 500 km. From this graph it can be seen that all options approach an approximate constant cost price for large volumes. All options for NH_3, DBT and MCH lay relatively close to each other and $LH_2$is the most expensive option.

4.2.2.4 Various supply chain volumes

In the sections above, the entire supply chain (from export - import - end-user) is designed on the demand of the end-user (above 2 Mt H_2). However, it is reasonable to assume that an import terminal will have a higher demand and that the end-user's demand will be taken from that terminal. This section therefore looks at the effect on the cost price of a different supply chain volume in the export and import supply chain than the supply chain volume in the import and end-user supply chain.

From the future hydrogen vision of the Port of Rotterdam (Port of Rotterdam, 2020), it can be concluded that an import demand of 18 Mt H_2 can be expected in 2050. In this section a demand of 6 Mt H_2 is assumed as fixed demand of the import terminal. For the demand of the end-user a fixed demand of 1 Mt H_2 is assumed, as the scope of this study is about large supply chain volumes to the hinterland. The overseas distance is again assumed to be 10,000 km and the hinterland distance is again assumed to be 500 km.

Because of the larger demand of the import terminal the volume of the supply chain from the export terminal to the import terminal is much larger than that of supply chain to the hinterland. As a result, more elements will be present at this first supply chain. Therefore, the final cost price will mainly be determined by what happens between the export and import terminal while the supply chain to the hinterland will contribute only slightly to the final cost price.

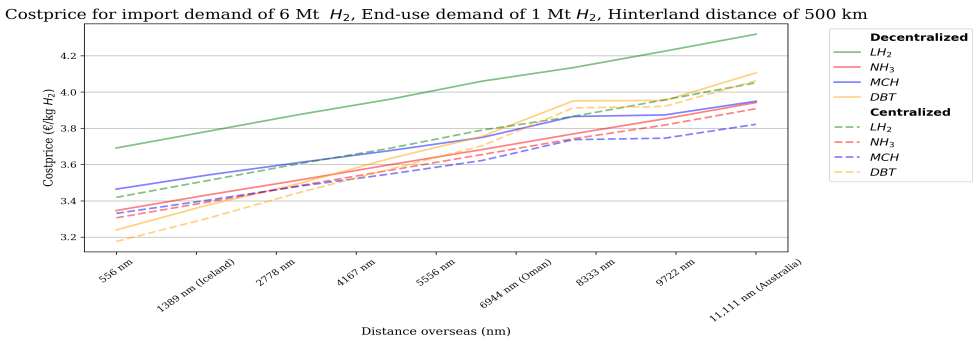


Figure 4.20: Cost price for the supply chain for a variable overseas distance

In Figure 4.20, the overseas distance is made variable and the centralized and decentralized (with barge transport) supply chain configurations are plotted against each other. As the supply chain from export to import terminal determines the cost price for the largest part, one can have a closer look at the figures from Section 4.2.1. Figure 4.9 shows that for smaller overseas volumes the cost price will first decrease for all carriers and remain fairly constant for larger volumes. When the overseas distance is made variable, a large demand of 6 Mt H_2 is imported to the import terminal and a demand of 1 Mt H_2 is transmitted to the end-user that is at a distance of 500 km. Again, it can be seen that DBT is the most cost effective for distances up to 4000 nm, after which MCH and NH_3 become more economical. The centralized option is cheaper than the decentralized option for all carriers.

However, in Figure 4.21 the hinterland distance is made variable and the overseas distance is 10,000 km. From this graph it can be stated that that for NH_3 the centralized option becomes more economical when the hinterland distance is larger than approximately 800 km. A note needs to be made about barge transport of NH_3, as it is not likely, socially and environmentally speaking, that large volumes of NH_3 will be transported to the hinterland by barge in the future. This is because NH_3 is a hazardous substance to handle and barge transport may pass through and past towns, making it a social issue.

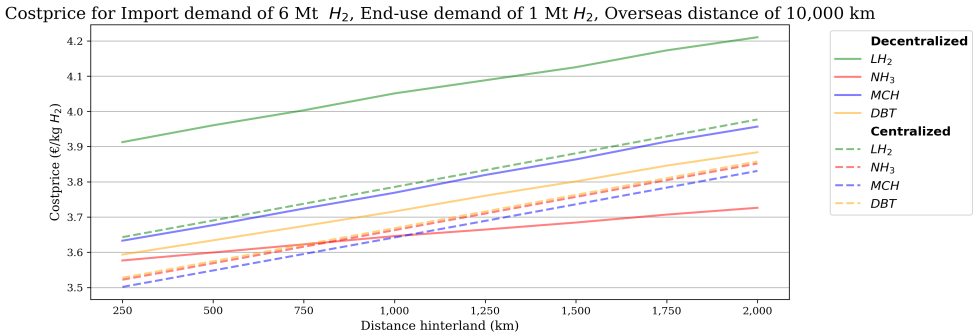


Figure 4.21: Cost price for the supply chain for a variable hinterland distance

In addition to the overseas distance, the overseas volume can also be made variable, see Figure 4.21. This is the volume transported from the export terminal to the import terminal. The overseas distance is 10,000 km, the hinterland distance is 500 km and the demand of the end-user is 1 Mt H_2. Again, one can look at Section 4.2.1. From Figure 4.9 it can be observed that the cost price will decline for small volumes until it remains fairly constant for larger volumes. Figure 4.22 shows the cost price for larger volumes, in which the cost price of all carriers indeed stays at a constant value. Centralized reconversion of MCH with CGH_2-pipe transport to the hinterland is for this example the most economical option. When the overseas distance is smaller than 4000 nm, DBT will be the most cost-effective option, see Figure 4.20.

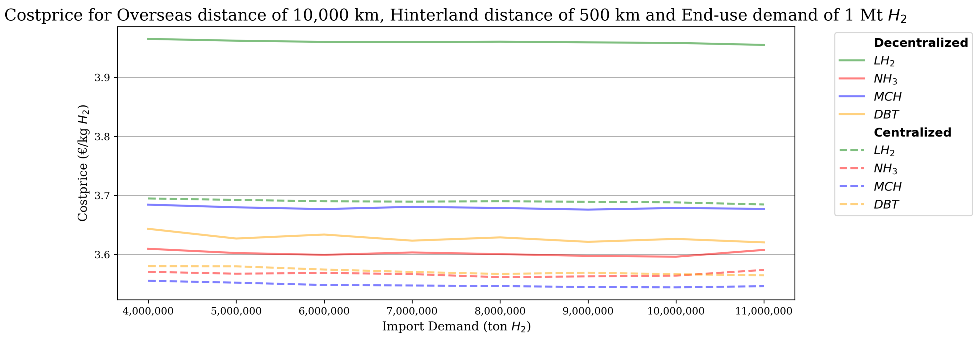


Figure 4.22: Cost price for the supply chain for a variable import demand

In Figure 4.23, the demand of the end-user is made variable, i.e. the volume that passes through the supply chain from the import terminal to the hinterland. Smaller volumes will be transported to the hinterland in comparison to the export and import terminal. As already discussed, the cost price for very small volumes will first decrease and eventually reach a roughly constant value, as is also shown in Figure 4.23. From this figure it can again be concluded that centralized reconversion of MCH with CGH_2-pipeline transport to the hinterland is the cheapest option for this example.

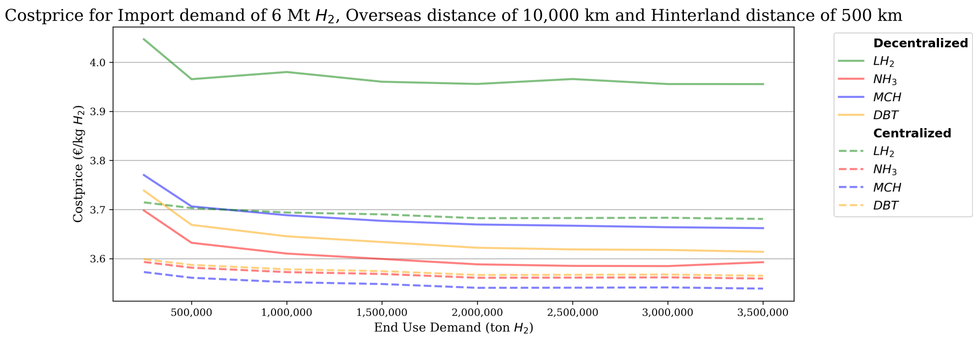


Figure 4.23: Cost price for the supply chain for a variable end-user demand

4.2.3 Sensitivity Analysis

For this model a sensitivity analysis has also been performed to examine for which parameters the final cost price is dependent. This was done for all carriers and two different supply chain configurations; decentralized reconversion with barge transport and centralized reconversion with CGH_2-pipeline transport. The sensitivity is calculated the same way as in Section 4.1.2, that is, by looking at what happens to the cost when the average value of a parameter (the value used in the analysis in this chapter (Appendix D)) increases by 50% and decreases by 50%.

The sensitivity of a parameter is indicated in percentages, this percentage indicates by how much the cost price changes when the parameter is adjusted. The parameters that the model is very sensitive to are shown in red and orange in Table 4.2. It shows that the cost price is very sensitive to the WACC and to the price at which the hydrogen is purchased in the export country. In addition, the cost price of LH_2 is highly sensitive to the number of storage tanks. All hydrogen carrier options are also relatively sensitive to the energy price.

	Parameter	**Decentralized with barge**				**Centralized with CGH_2-pipelines**			
		LH_2	NH_3	MCH	DBT	LH_2	NH_3	MCH	DBT
Country Dependent Parameters	WACC	>15%	>15%	>15%	>15%	>15%	>15%	>15%	>15%
	Fuel barge	<2.5%	<2.5%	<2.5%	<2.5%	-	-	-	-
	Fuel vessel	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
	Energy price	>2.5%	>2.5%	>2.5%	>2.5%	>2.5%	>2.5%	>2.5%	>2.5%
	Labour price	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
Conversion Plant	Purchase H_2	>15%	>15%	>15%	>15%	>15%	>15%	>15%	>15%
	Purchase material	-	<2.5%	>2.5%	>2.5%	-	<2.5%	>2.5%	>2.5%
	Selling material	-	-	<2.5%	>2.5%	-	-	<2.5%	>2.5%
	Recycle rate	-	-	>2.5%	<2.5%	-	-	>2.5%	<2.5%
	CAPEX	>2.5%	>2.5%	<2.5%	<2.5%	>2.5%	>2.5%	<2.5%	<2.5%
	Losses	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
Storage tanks	Dwelltime	>7.5%	>2.5%	>2.5%	<2.5%	>7.5%	>2.5%	>2.5%	<2.5%
	CAPEX	>7.5%	>2.5%	>2.5%	<2.5%	>7.5%	>2.5%	>2.5%	<2.5%
	Losses	<2.5%	<2.5%	-	-	<2.5%	<2.5%	-	-
Jetty	Waiting Factor	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
	CAPEX	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
Vessel	CAPEX	>2.5%	<2.5%	<2.5%	<2.5%	>2.5%	<2.5%	<2.5%	<2.5%
	Losses	<2.5%	<2.5%	-	-	<2.5%	>2.5%	-	-
Reconversion plant	CAPEX	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%	<2.5%
	Losses	-	<2.5%	>2.5%	>2.5%	-	<2.5%	>2.5%	>2.5%
Barges	CAPEX	<2.5%	<2.5%	<2.5%	<2.5%	-	-	-	-
	Losses	<2.5%	<2.5%	-	-	-	-	-	-
Existing pipeline	CAPEX	-	-	-	-	<2.5%	<2.5%	<2.5%	<2.5%
New pipeline	CAPEX	-	-	-	-	<2.5%	<2.5%	<2.5%	<2.5%
Ratio existing and new pipeline	Ratio	-	-	-	-	<2.5%	<2.5%	<2.5%	<2.5%

Table 4.2: Sensitivity of various parameters in the Supply Chain Model

4.2.4 Conclusion

In the general analysis of the Supply Chain Model, it needs to become clear what the effect of supply chain configurations along the entire supply chain from export terminal to end-user are on the final cost price of hydrogen. This has been investigated for four hydrogen carries; LH_2, NH_3, MCH and DBT.

First, only the supply chain from the export terminal to the import terminal was investigated, which showed that DBT is the cheapest option up to 4000 nm, after which MCH and NH_3 become more economical. For a demand at the import terminal of 2 Mt H_2 this is at about 10,000 km. If the volume is made variable, it can be concluded that for smaller volumes the cost price will decrease until it approaches a more or less constant cost price for larger volumes. The order of the carriers' cost prices remains the same.

Second, the entire supply chain from export terminal to end-user is considered. First, both supply chains are dimensioned according to the demand of the end-user. Three supply chain configurations are considered: centralized reconversion with CGH_2-pipeline transport, decentralized reconversion with carrier barge transport and decentralized reconversion with carrier rail transport. It can be concluded that for all carriers except LH_2, rail transport is more expensive than barge transport. If the decentralized option is compared to the centralized option, it can be observed that for a demand at the import terminal of 2 Mt H_2, the centralized and decentralized options for DBT are the most economical for distances up to 3500 nm. When this distance increases NH_3 and MCH become more cost effective. The centralized option is more economical for all carriers except for NH_3. However, it should be noted that NH_3-barge transport of large supply chain volumes is not a realistic future scenario due to social and environmental issues. In addition, the centralized option does not take into account that already existing pipeline networks (of natural gas, for example) are likely to be used in the future for the transport of CGH_2, which will significantly reduce the costs of the hinterland transport.

It is reasonable to assume that an import terminal will have a higher demand and that the end-user's demand will be taken from that terminal. Therefore it is examined what the effect is on the cost price of different supply chain volumes in the export and import supply chain compared to the import to end-use supply chain. Because of the larger demand of the import terminal the volume of the supply chain from the export terminal to the import terminal is much larger than that of supply chain to the hinterland. Therefore, the final cost price will mainly be determined by what happens between the export and import terminal while the supply chain to the hinterland will contribute only slightly to the final cost price.

The model has been analyzed for an import demand of 6 Mt H_2, an end-use demand of 1 Mt H_2, an overseas distance of 10,000 km and a hinterland distance of 500 km. When the overseas distance is variable, it can again be concluded that the centralized and decentralized option for DBT is the most economical for smaller distances (up to approximately 4000 nm), after which MCH and NH_3 become most cost effective. The centralized option is in this example, for an variable overseas distance, more economical for every carrier than the decentralized option. However when the hinterland distance is made variable, it can be observed that after 800 km, the decentralized option becomes more favourable for NH_3.

From the sensitivity analysis, it can be concluded that the eventual cost price is very sensitive to the WACC and to the price at which the hydrogen is purchased in the export country. In addition, the cost price of LH_2 is highly sensitive to the number of storage tanks. All hydrogen carrier options are also relatively sensitive to the energy price.

4.3 Conclusion

In this chapter, a general analysis was first carried out for the supply chain from the import terminal to the hinterland and secondly for the entire supply chain from the export terminal to the import terminal to the hinterland.

If only the supply chain from the import terminal to the end-user is considered, it can be concluded that LH_2 is the most economical option. When comparing distribution modes to the hinterland, barge transport is the most cost-efficient in comparison with rail and truck transport for all the carriers except for LH_2, where rail transport is cheaper than barge. When centralized reconversion with CGH_2-pipeline transport is compared to decentralized reconversion with barge transport, it becomes clear that for large volumes the centralized option is the cheapest. When an end-user has a demand of 500 kton H_2, decentralized reconversion with barge transport becomes attractive for larger distances ($>$1100 km). If the demand and thus the supply chain volume increases, this tipping point will shift to even larger distances as the centralized option is the most attractive for large volumes.

The analysis of the entire supply chain first looks at the supply chain from the export terminal to the import terminal where the hydrogen retrieval plants are located at the import terminal. When the overseas distance is made variable and the import demand is equal to 2 Mt H_2, DBT will be the most economical option for distances up to 4000 nm, after which MCH and NH_3 become more cost effective, LH_2 is always the most expensive option.

When the entire supply chain is examined, both supply chains are first dimensioned to the demand of the end-user. The end-use demand is equal to 2 Mt H_2, the overseas distance is 10,000 km and the hinterland distance is equal to 500 km. When the overseas distance is made variable it can again be seen that DBT is the most economical for smaller distances (up to 3500 nm), after which MCH and NH_3 again become the most cost effective, LH_2 remains the most expensive option. From the analysis it can be concluded that barge transport is cheaper than rail transport for every carrier, except LH_2. The centralized option is always more cost effective than the decentralized option, except for NH_3. For NH_3, the decentralized reconversion with barge transport to the hinterland is the cheapest option, however, it should be noted that NH_3-barge transport of large supply chain volumes is not a realistic future scenario due to social and environmental issues.

Secondly, it is reasonable to assume that an import terminal will have a higher demand and that the end-user's demand will be taken from that terminal. Therefore it is examined what the effect is on the cost price of different supply chain volumes in the export and import supply chain compared to the import to end-use supply chain. In the analysis in this chapter the import demand is 6 Mt H_2, the end-user demand is 1 Mt H_2, the overseas distance is 10,000 km and the distance to the end-user is 500 km. Again DBT is the cheapest for distances up to 4000 nm, after which MCH and NH_3 become most cost effective again. In this example the centralized option is more economical than the decentralized option for every carrier, even for NH_3. However, when the hinterland distance becomes greater than 800 km, the decentralized option becomes more favourable for NH_3.

From the sensitivity analysis, it can be concluded that the eventual cost price is very sensitive to the WACC and to the price at which the hydrogen is purchased in the export country. In addition, the cost price of LH_2 is highly sensitive to the number of storage tanks. All hydrogen carrier options are also relatively sensitive to the energy price

5 | Case Study

In this chapter, the Supply Chain Model discussed in chapter 3 and analysed in Chapter 4 is applied to a case study. In this case study, different supply chains between various countries will be examined. First, the scope of the case study will be explained. Secondly, the hydrogen markets of each country involved in the case study will be examined to determine which demand scenarios will be investigated. Finally these scenarios will be examined by applying them to the model. Appendix D states that the values of the WACC for all the countries used in this case study are very close to each other, therefore an average value of 8% has been used for the WACC of every country in this chapter.

5.1 Case Study Scope

As discussed above, this chapter applies the Supply Chain Model to a case study. In the case study, Rotterdam, the Netherlands is chosen as the import terminal. This is because this report is made in cooperation with the port of Rotterdam authority and because the port of Rotterdam is the largest port in Europe that is known as an international energy hub which has developed an ambitious hydrogen master plan (Notermans et al., 2020).

For the export countries, two countries were selected; one near Rotterdam and one at a greater distance from Rotterdam. By choosing two export countries that are situated both close to and far from Rotterdam, the effect of distance on the cost price should become even more clear. Australia has been chosen for this case study because a Memorandum of Understanding (MoU) has been signed between the government of South Australia and the Port of Rotterdam Authority to study the feasibility of a green hydrogen supply chain between South Australia and Rotterdam (Statista, 2021a). For the export location in Australia the study considers the largest port in South Australia, the Port of Adelaide. Iceland has been selected for this case study because also between Iceland and Rotterdam a MoU has been signed to investigate the feasibility of a green hydrogen chain between the two countries. The green hydrogen in Iceland is produced by energy generated from a hydroelectric power station about 70 km outside Reykjavik, hence the port of Reykjavik is being considered as the export terminal (Port of Rotterdam, 2021a).

Figure 5.1: The vessel routes for Australia to Rotterdam and Iceland to Rotterdam

For the transit to the hinterland, two locations are considered in this case study; Geleen (The Netherlands) and Duisburg (Germany). The Chemelot industrial park is located in Geleen, and Duisburg is situated in the Ruhr area in the province North Rhine Westphalia (NRW), which is also known for its industry. These locations have been chosen because the port of Rotterdam is planning to construct a hydrogen backbone through the port of Rotterdam, which will in turn be connected to the national infrastructure of Gasunie across the Netherlands and corridors to industrial areas in Chemelot in Limburg and North Rhine-Westphalia. In addition, the industrial site of Chemelot has a high demand for hydrogen (van Soest & Warmenhoven, 2019), taking into account the climate accords or the Paris Agreements, Chemelot needs to ensure that they will be a climate-neutral chemical site by 2050 (Chemelot, 2018). It is therefore likely that this industrial site will become a cooperation partner for the hydrogen from Rotterdam (H-Vision, 2019). In addition to Geleen, Duisburg is also included in this case study. Duisburg is a place in Germany located in the industrial Ruhr area in the province of North Rhine-Westphalia (NRW). The hydrogen import demand in the Ruhr area is even more significant than that of Chemelot. NRW has also published a vision for achieving the Paris climate action targets in which the import of hydrogen also plays a role (NRW, 2020).

Transport overseas is done by vessels. The routes from Australia and Iceland to Rotterdam are shown in Figure 5.1 and retrieved from (Shortsea Schedules, 2021) and (Searates, 2021). In this case study, barges, rail and pipelines are compared for transport to the hinterland. Figure 5.2 shows the transport routes to Geleen (number 1 on the map) and Duisburg (number 2 on the map). The blue lines on Figure 5.2 are the barge connections and are taken from (The Blue Road, 2021). The purple lines on Figure 5.2 represent the rail connections and obtained from (European Commission, 2021) and (van der Loos, M., 2021). The orange lines in Figure 5.2 indicate the pipeline routes. Over the past year, Chemelot, in collaboration with the Ministry of infrastructure and water and the Port of Rotterdam, has conducted a feasibility study into a pipeline corridor between Rotterdam, Chemelot and NRW (towards the Ruhr Area). This pipeline corridor consists of gas pipelines and a hydrogen gas pipeline. In the future, the gas pipelines could also be converted to transport hydrogen (Chemelot, 2018). The orientation of the pipeline corridor is partly taken from the database of the port of Rotterdam and partly based on (Port of Rotterdam, 2021b).

Figure 5.2: The routes to Geleen (1) and Duisburg (2) from Rotterdam for pipeline, barge and rail transport

5.2 Future Scenario's

For all the locations included in this case study, this section examines what possible future scenarios could arise. In the export countries hydrogen and material to compute the hydrogen carriers is purchased, this section examines how the market in those countries will influence the prices in the future. For the import terminals and the hinterland locations, it is necessary to find out which hydrogen demand will be a realistic option for these locations in the future. For each site, scenarios are outlined for 2030, 2040 and 2050. These scenarios will be applied in the Supply Chain Model and discussed in paragraph 5.3. First the export locations will be discussed, then the import terminal and finally the hinterland locations.

5.2.1 The Export Locations

In order to compare the situations in 2030, 2040 and 2050, it is necessary to investigate the hydrogen market in the export countries. This should clarify what a realistic price for the hydrogen and the energy could be in these future scenarios. The export terminals in this case study are located in South Australia (Adelaide) and Iceland (Reykjavik). South Australia has abundant wind and solar resources that can provide renewable energy. The government of South Australia is already working with investors to realise the first series of pilot and demonstration projects for the production of renewable hydrogen. It is therefore a mission of the South Australian government to become a world leading producer, exporter and user of green hydrogen (Government of South Australia, 2019). In Iceland, there is also great potential for low-cost green hydrogen given the abundant hydroelectric and geothermal energy (Salameh, 2009).

In Australia, several studies have already been carried out into how green hydrogen can become competitive with grey hydrogen and with other countries that will be exporting hydrogen. From (IRENA, 2019) and (Bruce S et al., 2018) the following data has been retrieved; The cost of green hydrogen in Australia is currently around 4 - 5 €/kg H_2. To become competitive with fossil fuels and with other countries that will export hydrogen, it was concluded from (IRENA, 2019) that the price of green hydrogen must be in the range of 1.50 - 2.50 €/kg H_2 in 2030. In 2040 this should even drop to 1.20 - 1.70 €/kg H_2 and in 2050 to 1.00 - 1.50 €/kg H_2. In comparison, grey hydrogen (without CCS) currently costs around 1.20 - 2.20 €/kg H_2, with the expectation that this price will increase over the years due to CO_2 pricing. The price of blue hydrogen (with CCS) will be around 1.20 - 2.20 €/kg H_2 from 2020 to 2050. PWC (PWC, 2020) states that the green energy price has to drop to 20 $/MWh (0.02 $/kWh) to get to a green hydrogen price of 1.50 $/kg H_2 in 2040. It is thus assumed that in 2030 the energy price must be in the range of 0.02 - 0.04 €/kWh, in 2040 of 0.015 - 0.03 €/kWh and in 2050 of 0.01 - 0.02 €/kWh.

Besides hydrogen, nitrogen must also be purchased if ammonia is the hydrogen carrier. As this technology is already well developed, it is assumed that there will be no price reduction over time and the price will remain equal to 27 €/ton N_2 as indicated in Appendix D. If the hydrogen carrier is an LOHC, DBT or Toluene must also be purchased. The market for Toluene is already more advanced than the market for DBT because Toluene is already used today in several industrial processes (IEA, 2019). Therefore, it is assumed that the price of Toluene will not change over time. It is assumed that the price of DBT will decrease over time. Table 5.1 shows the values that will be used in the future in scenario's.

	Australia and Iceland			
	2030	2040	2050	Unit
Hydrogen price	2.00	1.50	1.25	€/kg H_2
Energy price	0.030	0.023	0.015	€/kWh
Nitrogen price	27	27	27	€/ton N_2
DBT price	3500	3300	3100	€/ton DBT
Tol price	600	600	600	€/ton Tol

Table 5.1: Data future scenario's export locations

5.2.2 The Import Location

The import terminal in this report is, as discussed above, located in the port of Rotterdam, the Netherlands. The port of Rotterdam is known as an international energy hub. Currently, 8800 PJ/year is imported and exported overseas in the port of Rotterdam, this energy originates mainly from fossil fuels. If a climate neutral world is to be achieved by 2050, the port of Rotterdam must become a hydrogen hub for Northwest Europe. The demand for hydrogen in Rotterdam is currently 0.4 Mt H_2/year, throughout the Netherlands it is 0.8 Mt H_2/year and in Germany it is 1.6 Mt H_2/year (Port of Rotterdam, 2020).

In the coming years, this demand for hydrogen will increase considerably. According to (Gigler et al., 2020) and (Knoors et al., 2019), the demand for hydrogen in the Netherlands could be as much as 14 Mt H_2/year in 2050 and in Germany this could even increase to 24 Mt H_2/year. The energy demand in the port of Rotterdam is more than the Dutch energy demand, which is due to the fact that Rotterdam not only supplies the Netherlands with energy but also exports energy to the hinterland. Currently, one third of Germany's demand for oil and coal is supplied via the port of Rotterdam (Port of Rotterdam, 2020). In order to maintain this position, one third of the total German import demand for hydrogen in 2050 must be supplied by Rotterdam, which is roughly equivalent to 8 Mt H_2/year. In addition, the hydrogen demand in the Netherlands will partly be met by Dutch offshore wind, but most of it will be imported by sea-going vessels from areas where the renewable electricity is more affordable. In (Port of Rotterdam, 2020) it is stated that the port of Rotterdam could have a hydrogen demand of 20 Mt H_2/year (2400 PJ) in 2050. This includes 8 Mt H_2 for Germany, 7 Mt H_2 for the Netherlands and 5 Mt H_2 for other demand within North-Western Europe. Furthermore, it is approximated in (Port of Rotterdam, 2020) that in 2050 about 0.8 - 2.4 Mt green hydrogen and 3.5 Mt blue hydrogen will be produced in the port of Rotterdam, this makes the import demand of the Port of Rotterdam equal to 14.1 - 14.7 Mt H_2 in 2050. In 2030, the import demand in the Port of Rotterdam is expected to be approximately equal to 1 Mt H_2 (Wijk et al., 2019). For the 2040 values a linear growth is assumed.

Also in the Netherlands the (green) energy price must decrease to make green hydrogen competitive with fossil fuels and grey hydrogen. From (Bhimji, 2021) it is concluded that in 2030 the energy price must be between 0.33 and 0.4 €/kWh in the Netherlands. It is assumed that this will have to decrease even more to make green hydrogen competitive in 2050. The future scenario data that is used for Rotterdam is shown in Table 5.2.

	Rotterdam			
	2030	2040	2050	Unit
Hydrogen demand	1.0	7.8	14.5	Mton H_2
Energy price	0.035	0.030	0.025	€/kWh

Table 5.2: Data future scenario's import location

5.2.3 The Hinterland Locations

In addition, the future demand of end-users has yet to be determined. The locations Geleen and Duisburg are examined in this paragraph.

The Chemelot industrial site in Geleen has a vision of becoming an energy-neutral chemical area by 2050. The site has a potential hydrogen demand of 25 to 40 PJ (0.2 - 0.28 Mt H_2). In 2030, this will increase slightly to 0.24 - 0.32 Mt H_2 and in 2050 to 0.25 - 0.34 Mt H_2 (van Soest & Warmenhoven, 2019) (Chemelot, 2018). A pipeline corridor from Rotterdam to Geleen to NRW is being planned since 2021, where it concerns a hydrogen pipeline with an annual capacity of 2 Mt H_2. From (Chemelot, 2018) it is also taken that 50% of the hydrogen demand in Chemelot can be supplied from green, local production, and the other 50% will be imported. It is assumed that all of this imported hydrogen is supplied by Rotterdam.

The German region of NRW, in which the Ruhr area is located, also has the vision to meet the Paris agreement targets (NRW, 2020). NRW has a high import quota of about 90%, which implies that a large part of its hydrogen demand will be covered by imports. From (NRW, 2020) it can be concluded that the hydrogen import demand of NRW in 2050 will approximately equal 86 TWh (2.2 Mt H_2). In this study it is assumed that the entire demand will be imported from Rotterdam and will pass through Duisburg. All the data required for the 2030, 2040 and 2050 scenarios for Geleen and Duisburg is presented in Table 5.3.

	Geleen			**Duisburg**			
	2030	2040	2050	2030	2040	2050	Unit
Hydrogen demand	0.24	0.28	0.3	0.5	1.35	2.2	Mton H_2
Energy price	0.035	0.030	0.025	0.035	0.030	0.025	€/kWh

Table 5.3: Data future scenario's hinterland locations

5.3 Scenario Analysis

In this section, the case study described in Section 5.1 is applied to the Supply Chain Model described in chapter 3. Four supply chains are examined, these being:

- Australia – Rotterdam – Geleen
- Australia – Rotterdam – Duisburg
- Iceland – Rotterdam – Geleen
- Iceland – Rotterdam – Duisburg

For all four supply chains, three different supply chain configurations are investigated:

- Centralized reconversion with CGH_2-pipeline transport
- Centralized reconversion with barge transport
- Centralized reconversion with rail transport

Below, all of the options are compared and it is examined which supply chain configuration is the most cost-effective. In this section the cost price for the years 2030, 2040 and 2050 is compared. The data used for this analysis is presented in the paragraph above (paragraph 5.2). The main difference between these scenarios is that the import demand in Rotterdam increases significantly over the years. Since it is unrealistic that the entire import demand is supplied by one country, this chapter assumes that half of the demand of Rotterdam is imported from the country that is being analysed in the case study (Iceland or Australia). For the demand of the hinterland (Geleen or Duisburg), it is assumed that everything is imported from Rotterdam.

As the overseas distance between Rotterdam and Iceland is considerably smaller than the distance between Australia and Rotterdam, the effect of this difference on the cost price should become more clear in this analysis. In addition, Duisburg has a much higher hydrogen demand than Geleen, so the effect of this larger supply chain volume on the cost price should become more explicit.

5.3.1 Iceland - Rotterdam - Geleen

First, the supply chain from Iceland to Rotterdam to Geleen is examined. The data for the years 2030, 2040 and 2050 is taken from Section 5.2. For the import demand from Rotterdam it is assumed that 50% is imported from Iceland. For Geleen's import demand, it is assumed that 100% is imported from Rotterdam. In paragraph 5.2 it was discussed that the pipeline to Geleen is part of a new pipeline corridor to NRW, containing a hydrogen pipeline with a capacity of 2 Mt H_2 per year. The hinterland demand for the pipeline design is therefore equal to 2 Mt H_2 for all scenario's, rather than the demand of Geleen from Section 5.2.

The distance between Iceland and Rotterdam is 2275 km. The distance to Geleen for barge transport is 260 km, for rail transport it is 230 km and for the hydrogen pipeline it is 235 km. Figure 5.3 shows the cost price over the years for all carriers and all supply chain configurations. It can be seen from this figure that DBT with centralized reconversion and CGH_2 transport is the cheapest option for all scenario's.

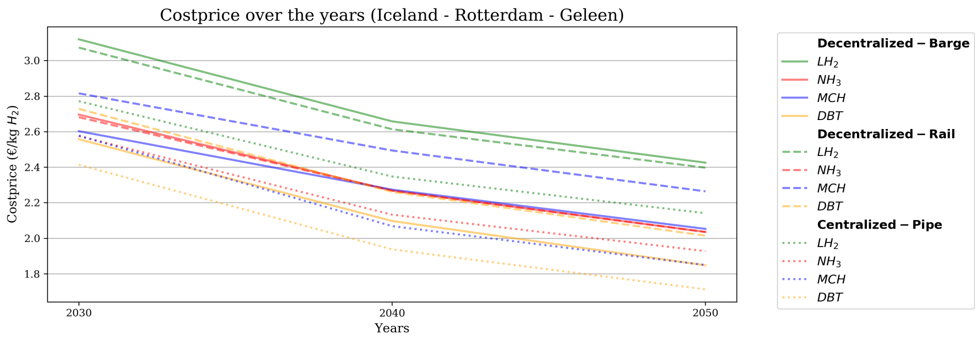


Figure 5.3: Cost price for the future scenario's for the supply chain from Iceland to Rotterdam to Geleen

5.3.2 Australia - Rotterdam - Geleen

Now the supply chain from Australia to Rotterdam to Geleen is being examined. The big difference with the previous supply chain is that Australia is a lot further from the Netherlands than Iceland. Again, the years 2030, 2040 and 2050 are compared. It is assumed that 50% of Rotterdam's import demand is supplied by Australia and that 100% of Geleen's demand is supplied by Rotterdam. The distance between Australia and Rotterdam is 20,400 km. The distance to Geleen for barge transport is 260 km, for rail transport it is 230 km and for the hydrogen pipeline it is 235 km.

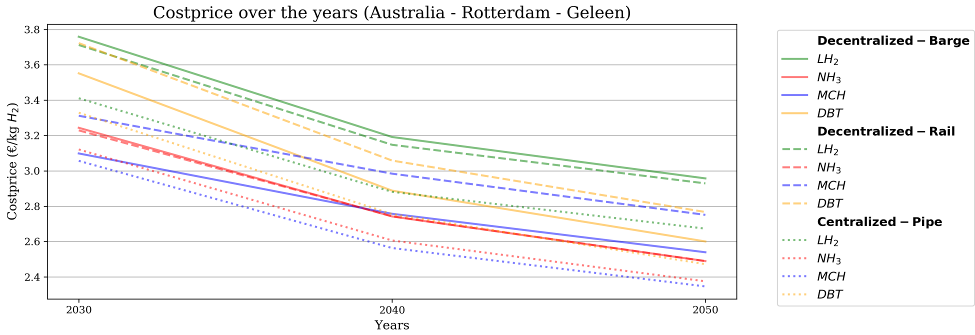


Figure 5.4: Cost price for the future scenario's for the supply chain from Australia to Rotterdam to Geleen

Figure 5.4 shows the cost price over the years for this supply chain. From Figure 5.4 it can be concluded that MCH with centralized reconversion and CGH_2 transport is the cheapest option for all scenario's. The cost price of NH_3 with centralized reconversion and and CGH_2 transport is the second most cost effective option, with a cost price that is very close to that of the centralized MCH option. However, it should be noted that the cost price of LOHCs is highly dependent on the selling price of the LOHCs at the end of the project. If they cannot be sold for the indicated selling price (see Appendix D) but only for a lower price, these options will become more expensive and there is a chance that ammonia will become the most cost effective option.

5.3.3 Iceland - Rotterdam - Duisburg

Now the supply chain from Iceland to Rotterdam to Duisburg is being investigated. The difference between Duisburg and Geleen is that Duisburg's demand is much higher than Geleen's demand. The data for the scenarios in 2030, 2040 and 2050 is taken from Section 5.2. For the import demand of Rotterdam it is again assumed that 50% of it is imported from Iceland. For the import demand of Duisburg it is assumed that 100% is imported from Rotterdam. In paragraph 5.2, it was discussed that the pipeline to Geleen is part of a corridor to NRW (Duisburg), containing a hydrogen pipeline with a capacity of 2 Mt H_2 per year. So also for Duisburg, it is assumed that for all scenario's the hinterland demand is 2 Mt H_2 when analysing the supply chain configuration with a pipeline.

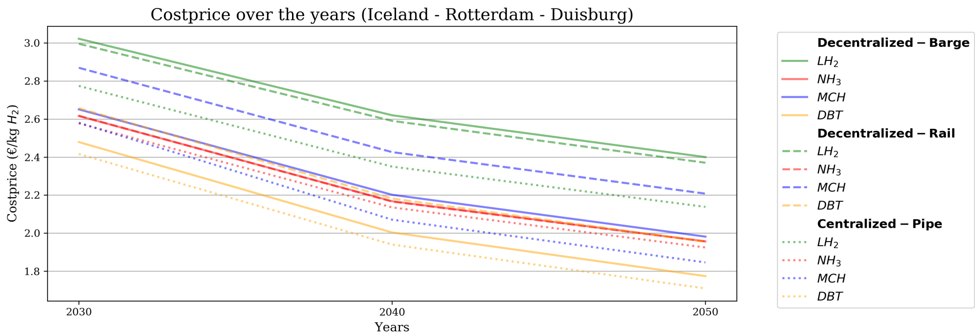


Figure 5.5: Cost price for the future scenario's for the supply chain from Iceland to Rotterdam to Duisburg

The distance between Iceland and Rotterdam is 2275 km. The distance to Duisburg for barge transport is 235 km, for rail transport it is 240 km and for the hydrogen pipeline it is 245 km. Figure 5.5 shows the cost price over the years for all carriers and all supply chain configurations. It can be observed from this figure that for a small overseas distance, MCH with centralized reconversion and CGH_2 transport is again the cheapest option for all years. The cost price of the centralized supply chain configuration with CGH_2-pipeline transport to the hinterland remains the same compared to the case study to Geleen as both supply chain configurations are designed with a hinterland demand of 2 Mt H_2. This option is again followed closely by the centralized and decentralized supply chain configuration of NH_3. However, it must be said that the option of ammonia barge transport is probably not realistic in the future due to social and environmental issues related to shipping large volumes of ammonia.

5.3.4 Australia - Rotterdam - Duisburg

Now the supply chain from Australia to Rotterdam to Duisburg is being examined. The difference between Duisburg and Geleen is that Duisburg's demand is much higher than Geleen's demand. The data for the years 2030, 2040 and 2050 is taken from paragraph 5.2. For the import demand of Rotterdam it is again assumed that 50% of this is imported from Australia. For the import demand from Duisburg it is assumed that 100% is imported from Rotterdam. The distance between Australia and Rotterdam is 20,400 km. The distance to Duisburg for barge transport is 235 km, for rail transport it is 240 km and for the hydrogen pipeline it is 245 km.

Figure 5.6 shows the cost over the years for all carriers and all supply chain configurations. From this figure it can be concluded that for a large overseas distance, DBT with centralized reconversion and CGH_2 transport is again the cheapest option for all years.

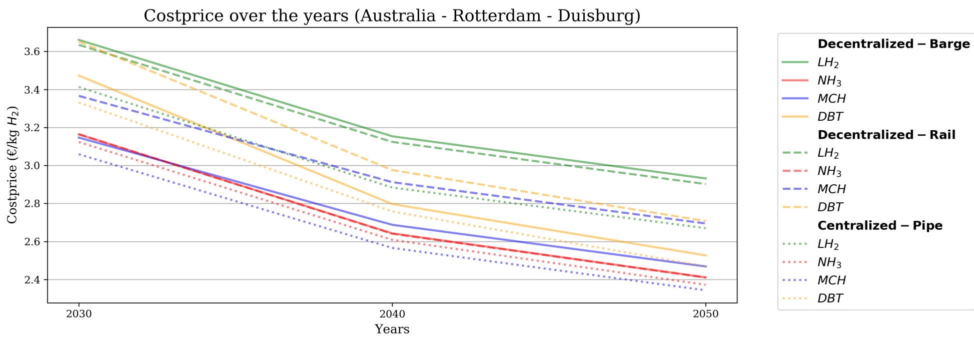


Figure 5.6: Cost price for the future scenario's for the supply chain from Australia to Rotterdam to Duisburg

5.3.4.1 Conclusion

From the analysis of these supply chains, it can be concluded that for shorter overseas distances, MCH with centralized reconversion and CGH_2-pipeline transport the most cost effective option is. If the overseas distance is large, DBT with centralized reconversion and CGH_2-pipeline transport is the most economical option. However, it must be stated that the cost price of LOHCs is highly dependent on the purchase and selling price of the LOHCs. In addition, the hinterland volume of Geleen and Duisburg is different. By comparing these options, it can be concluded that when the hinterland volume is larger (Duisburg), the cost price of the centralized and decentralized options will move closer to each other. Nevertheless, the centralized option will still be the most economical option for all carriers. Especially for NH_3, the centralized and decentralized options will lie very close to each other. However, it must be said that the option of NH_3-barge transport is probably not realistic in the future due to social and environmental issues related to shipping large volumes of NH_3. Liquid hydrogen is generally the most expensive option.

5.4 Conclusion

In this chapter, a case study is applied to the Supply Chain Model. The export countries are Australia and Iceland, the import terminal is located in Rotterdam in the Netherlands and the hinterland locations are Geleen in the Netherlands and Duisburg in Germany. A literature study was carried out to outline future scenarios for these supply chains. For 2030, 2040 and 2050 the import demand of Rotterdam, Geleen and Duisburg has been examined. In addition, the energy price and hydrogen purchase price were examined for the future scenario's in order to make green hydrogen competitive with grey hydrogen and fossil fuels. These future scenarios and supply chains have then been applied to the Supply Chain Model. It can be concluded that for shorter distances overseas (Iceland), DBT with centralized reconversion and CGH_2-pipeline transport is the most cost-effective option. For large overseas distances (Australia), MCH and NH_3 will be the most cost effective. Liquid hydrogen is generally the most expensive option.

6 | Discussion

In this chapter, the most important results obtained in this research are discussed. New insights that can be gained with this model and research are briefly explained. Followed by a brief external validation in which the results are compared to the findings of other studies. In addition, the limitations of this research are highlighted, addressing the quality and reliability of this research.

6.1 Discussion of Results

To achieve a fossil fuel free future, hydrogen supply chains will have to emerge in the coming years. However, the influence of different end-uses, distances and supply chain volumes on the structure and cost of the supply chains and on the form of hydrogen transport is still inconclusive at present. In this study the first steps have been made to investigate in what way the cost price may change for different hydrogen carriers when considering different supply chain configurations of the entire supply chain from export terminal to import terminal to end-user. To investigate this, a model was created that is able to identify the influence of different supply chain configurations on the final cost price.

When looking only at the hinterland supply chain, it is clear that the LH_2 supply chain configurations are the cheapest options. However, when the supply chain of the export terminal and the import terminal is linked to the hinterland supply chain, all supply chain configurations of LH_2 become the most expensive options. This is due to the fact that for LH_2 the conversion plants, storage tanks and overseas transport contribute the most to the total cost. Considering only the supply chain from the export terminal to the import terminal with reconversion plants situated at the import terminal, it can be concluded that for smaller overseas distances, DBT is the most economical option and that from approximately 4000 nm, NH_3 and MCH become the cheapest options. When the supply chain from the export terminal to the import terminal is coupled with the supply chain to the hinterland, it can again be concluded that for short oversea distances, DBT is the most economical option and that for longer oversea distances MCH and NH_3 will be the most cost effective. This turning point will be around 3500 - 4500 nm (6500 – 8400 km), depending on the supply chain volume, the distance to the end-user and if the supply chain configuration is centralized or decentralized. However, it is important to mention that the cost price of MCH and DBT is very dependent on the purchase and selling price of the LOHCs. The cost price will only be equal to the price in the report if the LOHCs can also be purchased and sold for the corresponding prices. The cost price of the LOHCs can therefore be considered as a business case in which many different scenarios are possible.

For each carrier, the centralized option is more cost-effective than the decentralized option. Only in the case of NH_3 the decentralized option with barge transport for large hinterland distances can become more economical than the centralized option. However, it must be stressed that the transport of large quantities of NH_3 by barge to the hinterland raises social and environmental concerns as NH_3 is a highly flammable and toxic substance. As a result, transporting large quantities of NH_3 to the hinterland may not be a realistic future scenario in some countries, or it may entail many additional costs that will increase the cost price significantly. If the entire supply chain is considered, always emerges as the most expensive option. However, it should be noted that the type of end-use is not included in this model. If the LH_2 is to be used as an end product (LH_2 for direct use), LH_2 may in fact become one of the more cost effective options. This applies not only to LH_2 but to all the other carriers as well. If the model were to be extended to include specific user cases and the possibility of direct use of a carrier, different conclusions will probably be drawn compared to the conclusions of this research

A sensitivity analysis has also been carried out as the model takes many different parameters into account and only a limited number of scenarios can be investigated. The main findings of this analysis were that the cost price for each hydrogen carrier is always very sensitive to the WACC, the purchase price of hydrogen in the exporting country and the energy price. However, it is debatable whether including the hydrogen production provides a reliable comparison of the supply chain costs. This is because the cost of producing hydrogen can still vary greatly from one area to another, even between areas where renewable energy sources are abundant. In addition, it can also be deduced from the sensitivity analysis that the cost price of LH_2 is very sensitive to the number of required storage tanks. However, the model does not take into account the low-cost storage of H2 in salt caverns. A realistic future scenario is that the import terminal will be connected to pipelines leading to these salt caverns. As a result, the LH_2 could be reconverted immediately when it reaches the import terminal and the H_2 can immediately be transported via the pipelines to the salt caverns for storage. As a result, there will be a considerable reduction in the number of storage tanks needed for LH_2 at the import terminal and the cost price of LH_2 will therefore also decrease.

It should also be pointed out that the study did not compare fairly in terms of transportation. In the case of NH_3 and LH_2, it is assumed that both vessels use their own carriers as fuel, as a result there will be no emission of CO_2. This has not been assumed for the LOHCs, because this is not yet a developed technology. In contrast, the LOHCs use a fuel with a low sulphur content, which will produce CO_2-emissions. Hence, in terms of CO_2-emissions, this is a not a fair comparison. In addition, the hinterland supply chain is dimensioned according to the demand of the end user. For transport such as barge, rail and truck this is correct, however for pipelines this is not correct. In the future, gaseous hydrogen transport by pipeline will use already existing pipeline networks of, for example, natural gas. These existing networks will be converted to enable the transport of gaseous hydrogen and will be connected to salt caverns where hydrogen can be stored at low cost. As a result, the pipeline network is not dimensioned according to the demand of an end user, which means that the two systems are not comparable. The analysis of the model in this study also did not include technological developments in the long run. At present, the supply chain of NH_3 is already highly developed, whereas the supply chains of the LH_2 and the LOHCs are still in their initial phase. Within these supply chains, there is still a lot of potential for technological developments that can significantly reduce the cost price.

6.2 External Validation

The model has been validated using manual calculations (Appendix H and G). A more thorough validation and calibration of the model is needed to increase its reliability. However, this is a challenge as some supply chain configurations are still in the development phase, meaning that the results from the model cannot be compared to already existing supply chains. In order to enhance the trustworthiness of the model that is developed in this study, a quantitative validation has been carried out by comparing it to an alternative model created in another research, as well as a qualitative evaluation of the results.

The model developed in this study is compared quantitatively with the model from (Lanphen, 2019). The supply chain from the export terminal to the import terminal is compared. The model from this research is compared with the model from (Lanphen, 2019) because the model from this research includes the same elements in the supply chain from export terminal to import terminal as the research from (Lanphen, 2019). In addition, (Lanphen, 2019) used the model of the company Kalavasta (HyChain)(Terwel & Kerkhoven, 2019) as the initial set up of her model, as a result this model is also indirectly compared. results from (Lanphen, 2019), where the overseas distance is made variable. In the figure the carriers LH_2, NH_3, MCH and CGH_2 have been compared and the demand is equal to 700,000 t H_2/year.

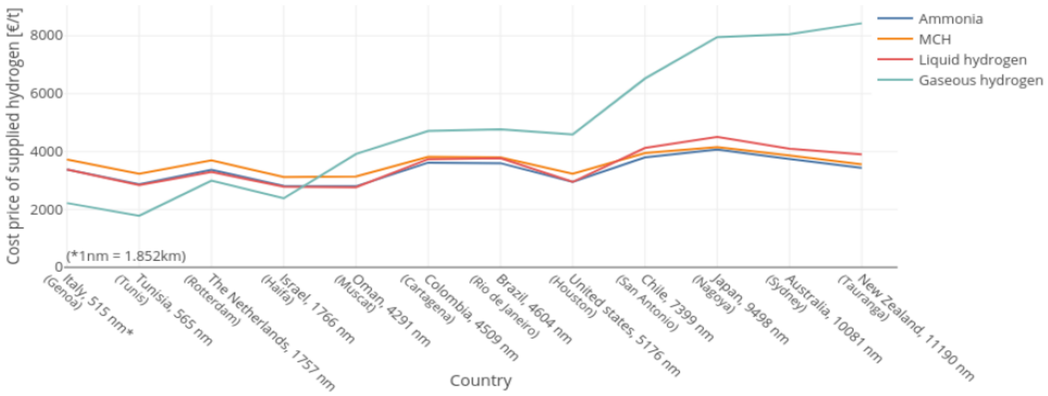


Figure 6.1: Cost price for the supply chain for a variable hinterland distance from (Lanphen, 2019)

The models are compared by applying the data used by (Lanphen, 2019) in the model of this study. When the overseas distance is varied and the demand is set to 700,000 t H_2/year in the model of this research, the graph from Figure 6.2 arises.

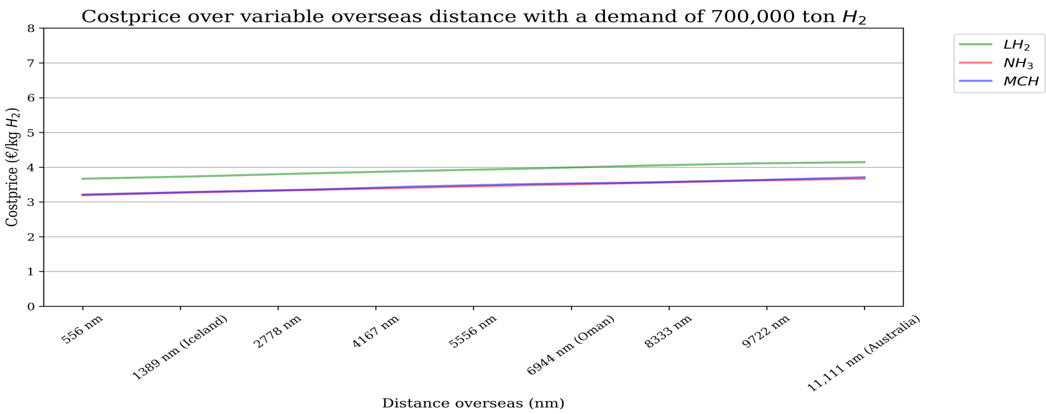


Figure 6.2: Cost price for the supply chain for a variable hinterland distance

As can be seen, the cost prices of the carriers are more or less in the same range, however, the lines do not follow the exact same path due to some fundamental differences in the assumptions and calculations. The main difference that can be observed between the two graphs is that the lines from (Lanphen, 2019) contain many kinks. The lines of the graph from (Lanphen, 2019) show kinks because this model uses a different WACC, energy price and fuel price for each country. Therefore, the cost price will never be a linear line since these values are different for each distance. In the model from this study, an average value is assumed for the WACC, energy price and fuel price, making linear lines possible. In addition, (Lanphen, 2019) assumes that LH_2-ships run on the boil-off gasses from the carried LH_2, whereas NH_3- and MCH-ships run on heavy fuel oils. In this study, it was assumed that LH_2- and NH_3-ships both use their carriers as fuel and that MCH-ships use a low sulphur content oil. As a result, the cost price of NH_3 will increase more over the distance due to losses. Other discrepancies can be attributed to differences in calculations and model structure.

Compared to other hydrogen supply chain models made in previous studies, the model created in this study differs in several aspects. Currently, the most developed hydrogen supply chain model in terms of cost is the HyChain model produced by Kalavasta (Terwel & Kerkhoven, 2019). A similarity with this model is that it also presents a cost implication model for the import of green hydrogen and includes similar elements such as conversion and reconversion plants, storage tanks and shipping. The main difference with the HyChain model is that the model developed in this study evaluates the associated costs for different supply chains. In this research, the model has been applied to an issue concerning liquid bulk (LH_2, NH_3, LOHCs), however, the model is constructed in such a way that it can also be applied to supply chains of other commodities such as agribulk or containers. In addition, the HyChain model focuses only on the supply chain from the export terminal to the import terminal, whereas the model in this study is designed to connect multiple supply chains. Therefore, this research can examine the interaction between the overseas supply chain and the hinterland supply chain, which was identified in the research gap as an important issue that has not yet been sufficiently researched. Furthermore, the HyChain model calculates the costs based on one year in which the model assumes a fixed demand. The model from this research uses a certain model period in which a fluctuating demand can be applied. This makes it possible to include certain expansions of the terminal or transport elements to be included in the eventual cost price. The model in this study is also set up in such a way that the throughput over the entire supply chain is parametrically linked to the losses of elements in the supply chain. As a result, it is included that due to losses, more elements may be required in the supply chain to meet the final demand. In this way, the model in this study provides a good insight into the effect of losses in different supply chain configurations.

The results of this study can also be qualitatively compared with the results of previous studies. For instance, the IEA study (IEA, 2019) shows that for hydrogen supply chains with overseas transport, ammonia is the most economic option. However, this study only covers distances up to 5000 km and is based on a fixed demand. The research of (Lanphen, 2019) results in the conclusion that over a varying overseas distance, the cost prices of all commodities will be very close to each other. The difference between this conclusion and the one found in this study is mainly due to the difference in the values of the input parameters. In this research, low, medium and high scenario's were made to increase the reliability of the input parameters. Another big difference is that the model in this study is constructed in such a way that the throughput over the entire supply chain is influenced by the losses over the supply chain. Also, (Lanphen, 2019) does not include the influence of the supply chain to the hinterland.

6.3 Limitations

In this section, the limitations of the research are presented. By pointing out the limitations of this research it should become clear where the shortcomings are in this research. This allows the findings explained in this research to be qualified and helps in understanding applications to any future research.

Model values constant over time

An assumption that has been made in the model is that some values do not fluctuate over time, however this is not a realistic expectation. For example, it is assumed that the energy price, fuel price, employment cost and the WACC will remain constant over time, although these values will vary from year to year. In addition, a constant value is used for the investment costs of elements. However, due to technological developments it is likely that certain costs will decline over time. In addition, the capacity of elements has also been taken as a fixed value, whereas this can also be altered by technological developments.

Model values not country dependent

Only the values of the energy price, fuel price and WACC are made country-dependent in the model. However, the values of all other parameters may also depend on the respective countries. For example, a constant value is assumed for the investment costs of all elements whereas these can of course differ per country. Lower investment costs in certain countries can make certain supply chains more economically attractive. In addition, the production price of hydrogen on the export side is also very dependent on the country.

Costs not ownership dependent

The costs that are incurred in the model for certain elements are not attributed to a particular company that has ownership over those elements. In addition, each element is assumed to use the WACC of the country in which it is located. However, the WACC of a country is different from the WACC of a particular company in a particular sector. Realistically, the elements in the model will be owned by certain companies. Applying this would change the WACC for each element and the costs within the supply chain can be allocated to certain companies.

Elements have a residual value of zero

When calculating the cost price, it is assumed that the residual value of each element at the end of the project is zero. In reality, this will not be the situation and certain elements can be sold again for a certain price. This will reduce the value of the final cost price.

For the LOHCs it is assumed that they will be sold again at the end of the project as it is possible to recycle these materials. However, this assumption results in a business case for the LOHC options; With the assumptions made in this study for the purchase and selling price of the LOHCs, the cost price of the LOHCs will vary as indicated in this report. However, if the LOHCs cannot be sold at this selling price at the end of the project but at a lower price, the cost price of this option increases. The same can happen for ammonia with released nitrogen; in this study it is assumed that the nitrogen is not sold at the reconversion plant but released into the air. However, if reconversion takes place in industrial areas, the released nitrogen can be sold, thus reducing the cost price of the ammonia option.

Model results strongly depend on the quality of parameters

The final cost from the model for a certain supply chain configuration strongly depends on the input parameters. The input parameters used in this report have a high unreliability. As can be seen in Appendix C and D, low, medium and high cost scenarios have been made for all parameters to increase the reliability. However, the difference between the low, medium and high scenarios is still very significant for some parameters. The unreliability of the parameters is due to the fact that the exact values of some technologies are not yet known because they are still in the development phase. Increasing the reliability of these parameters will increase the accuracy of the cost price.

Model triggers

As discussed in Chapter 3, the expansions of elements are based on the reactive trigger, this trigger ensures that investment are made based on the current demand. This trigger does not take into account any investments based on future demand. In addition, the triggers of the elements in the model are set up in such a way that if there is even a tiny bit of capacity shortage at the terminal, investments are immediately made for new elements in order to meet the demand. In reality, however, trade-offs will be made as to whether such an investment is necessary to meet a slightly higher demand, or whether a choice is made not to meet the demand. The triggers are also structured in such a way that they do not take into account delays in construction time or transport time caused by, for example, weather conditions.

Not taking into account safety, social and environmental challenges

For all the examined supply chain options, this report does not take into account any challenges that may arise related to safety, social or environmental issues. For example, ammonia and hydrogen are much more difficult products to handle than LOHCs as they are toxic and highly flammable. In addition, it is already known that transporting large volumes of ammonia to the hinterland by ships or trains is probably not a feasible option due to social issues. For instance, inland navigation and train traffic will pass through inhabited areas where people would prefer not to have transport of large volumes of toxic and highly flammable products due to safety and the environment. Ammonia is a product for which the supply chains are already well developed, therefore it is likely that these problems will also play a role in the transport of hydrogen. Furthermore, the construction of a pipeline can take much longer than the indicated construction time. This is because the construction of a pipeline can be associated with social problems, for instance, that people do not want a pipeline with (highly flammable) products near their homes or even cultural issues if the pipeline has to be constructed near religious grounds or through a nature reserve.

Not taking into account multimodal transportation options

This study does not take into account multimodal transport. However, in reality, multimodal transport is a realistic scenario for supply chains. For example, a pipeline may be built up to a certain distance in the supply chain and thereafter the transport will be done by ships, trains or trucks. Especially last mile transport by trucks is very common.

Not taking into account the specific end-use

The model does not yet include the intended use of the hydrogen as end product. If a carrier is to be used for direct consumption, this will probably reduce the cost price of the carrier considerably. In addition, the analysis in this research considers very large supply chain volumes, however, if smaller supply chain volumes are required, for example at refuelling stations, a very different approach than used in this analysis will be needed.

7 | Conclusion and Recommendations

This chapter presents the conclusion of this research by addressing all research questions discussed in Chapter 1. Subsequently, recommendations for future research are given.

7.1 Conclusion

The aim of this research is to gain more insight into how certain supply chain configurations affect the final cost price of hydrogen at the end-user. In this chapter, all sub-research questions will be answered one by one with the results of this study in order to eventually answer the main research question. The first sub-question relates to the required information and data, the next sub-questions concern the applied methodology and the last sub-questions focus on the costs of different supply chain configurations. In the last section, the main research question will be answered.

7.1.1 Information and Data

The first sub-question has to do with the information and data that is needed to carry out this research:

"What information about the components of the hydrogen supply chain is needed to determine the influence of supply chain configurations on the eventual cost price?"

To answer this question, it was first of all important to determine which supply chain configurations are being investigated in this study in order to identify which elements need to be included. This research looks at the supply chain from the export terminal to the import terminal and at the supply chain from the import terminal to the end-user. The hydrogen carriers included in this study are LH_2, NH_3, MCH and DBT. The transport between the export terminal and the import terminal is limited to vessels and for the transport between the import terminal and the hinterland a choice can be made between pipelines, trucks, rail and barges. The supply chain configuration can be set up in such a way that the hydrogen reconversion takes place at the import terminal (centralized) resulting in transport to the hinterland in the form of gaseous hydrogen. Alternatively, the hydrogen reconversion can be situated at the end-user (decentralized) in which case there is transport to the hinterland in the form of the chosen carrier. In order to increase the reliability of the applied data, low, medium and high scenarios have been made for the investment costs regarding the elements.

7.1.2 The Method

The following sub-questions are related to the method used to answer the main research question, the first one being:

"How can a method be developed that can not only analyse a single supply chain but can also connect multiple supply chains and what is the added value of this approach?"

The aim of the study is to investigate the influence of different supply chain configurations on the final cost price. This must not only be done for a single supply chain, but supply chains also need to be linked in order to clarify the influence of the interaction between supply chains. This is of great value as the literature review (Section 1.3) has shown that this is an important topic that has not been sufficiently researched yet. A model has been developed to investigate this issue. The model is structured in such a way that it uses a terminal investment simulation program (OpenTISim) to determine how many elements should be present at the terminal each year. The model uses a complex logistics simulation program (OpenCLSim) to simulate the transport between the terminals in order to find out how many transport elements are needed each year. By coupling OpenTISim to OpenCLSim, it thus becomes possible to determine how many elements are needed throughout the entire supply chain. This allows the investigation of a individual supply chain, but it also enables the interconnection of several supply chains.

In addition to being able to link supply chains, the model must also be capable of examining different supply chain configurations, the corresponding research question for this problem reads:

"What requirements are imposed on the fundamental structure of the used software by the possibility of making the distance, volumes, commodities and structure of the supply chain variable?"

By simulating the transport with OpenCLSim, the distance of both supply chains can easily be made variable. For the supply volume it is a somewhat more challenging task as the throughput of the entire supply chain under consideration depends on the losses of each element that is present in the supply chain. This ensures that all elements within the model must be parametrically aligned in order to include the loss of each element within the final throughput. In this way, the model takes into account that for more losses, more elements may be needed in a supply chain to meet a certain demand. In addition, it is also possible to choose for which commodity the supply chain configuration is investigated. For each commodity which can be selected in the model (LH_2, NH_3, MCH and DBT), an associated database is available that contains the data of the specific elements which belong to the specified commodity. Furthermore, the structure of the supply chain (the order of the elements in the supply chain) also needs to be made flexible. This is possible in the model by allowing a choice to be made as to which elements are present at each terminal. This makes it possible to define the structure of the supply chain configuration under investigation before the model simulation begins.

The aim of the study is to determine how the supply chain configurations affect the cost price, the sub-question for the calculation of the cost price is:

"How can the calculation of the final cost price best be incorporated into the resulting model?"

As mentioned above, this research is about the influence of various supply chain configurations on the final cost price. The cost price is calculated by dividing the total cost over the model period by the entire throughput over the model period. The throughput follows from the parametric coupling of all supply chain elements. The cost is calculated by storing the capital and operational costs of each element whenever it is added to the investigated supply chain. Thus, at the end of the model period, it is possible to easily sum up all costs of all the elements and divide it by the total throughput to determine the final cost price.

7.1.3 Supply Chain Costs

The last sub questions are related to the cost of various supply chain configurations. First, the supply chain to the hinterland is discussed:

"How does the cost price of hydrogen evolve for different supply chain configurations for the supply chain from the import terminal to the hinterland?"

If only the supply chain to the hinterland is analysed, it can be concluded that truck and rail transport is always more expensive than barge transport for all carriers. With the exception of LH_2, where rail transport is slightly more cost-effective than barge transport. When centralized reconversion with CGH_2-pipeline transport is compared to decentralized reconversion with carrier barge transport, it is shown that for small supply chain volumes the decentralized option is cheaper and that for large supply chain volumes the centralized option becomes more cost-effective. If the distance is made variable, the centralized option will be the cheapest up to a certain distance, after which decentralized reconversion with barge transport will become more economical again. This tipping point depends on the supply chain volume, for a larger volume this tipping point will be for larger distances, in this study the tipping point is at 1100 km for a supply chain volume of 500 kton H_2.

$LH_2$is always the cheapest option in terms of the supply chain to the hinterland. After LH_2, NH_3 is often the most cost-effective and MCH is usually the most costly option. This is due to the fact that the reconversion plant for LH_2 is a lot less expensive than the reconversion plants for NH_3 and MCH. However, a hydrogen conversion plant for LH_2 is a lot more expensive than the conversion plants for NH_3 and MCH. It is therefore interesting to look at the entire supply chain from the export terminal to the import terminal to the end-user. First, the supply chain configurations from the export terminal to the import terminal were examined:

"How does the cost price of hydrogen evolve for different supply chain configurations for the supply chain from the export terminal to the import terminal?"

The supply chain from the export terminal to the import terminal that is investigated is centralized; the reconversion plants are located at the import terminal. From the analysis of this supply chain, it can first be concluded that the largest part of the cost price derives from the procurement of hydrogen and raw material in the exporting country. Besides, the costs for the export terminal are high for NH_3 and LH_2 and the costs for the import terminal are high for the LOHCs (MCH and DBT). When the overseas distance is made variable it can be concluded that for distances up to about 4000 nm, DBT is the most cost-effective option, for larger distances MCH and NH_3 become the most economical options. When the supply chain volume is made variable it can be stated that the cost price approaches an approximately constant value for large volumes, the order of the cost price of the carriers does not change.

Now that the supply chains from the export terminal to the import terminal and from the import terminal to the end-user have been examined, it is important to assess the entire supply chain from export to import to end-user:

"How does the cost price of hydrogen evolve over for different supply chain configurations for the entire supply chain?"

To answer this question, the supply chain from the export terminal to the import terminal and the supply chain from the import terminal to the end user are connected. It is reasonable to assume that an import terminal will have a higher demand and that the end-user's demand will be taken from the volume supplied at the import terminal. The supply chain volumes and distances have been made variable in order to understand their effect on the cost price; graphs such as Figure 7.1 have been produced to illustrate this effect.

In Figure 7.1, the overseas distance is made variable; from this figure it can be concluded that DBT is the most economical option for distances up to approximately 4000 nm, and that MCH and NH_3 become more cost effective for larger distances. This conclusion is consistent with the findings of the export-import supply chain analysis. It can also be observed from Figure 7.1 that the centralized option is cheaper than the decentralized option for all carriers when the oversea distance increases. In Figure 7.2 the hinterland distance is made variable.

From this figure it can be concluded that for a larger hinterland distance, the centralized option for NH_3 may become more cost-effective than the decentralized option for NH_3. However, it must be stressed that the transport of large quantities of NH_3 by barge to the hinterland raises social and environmental concerns as NH_3 is a highly flammable and toxic substance. As a result, transporting large quantities of NH_3 to the hinterland may not be a realistic future scenario in some countries, or it may entail many additional costs that will increase the cost price significantly. In addition to the distances, the supply chain volumes have also been made variable, which leads to the conclusion that for large volumes the cost price becomes more or less constant and that the order of the carriers' cost prices does not change with varying volume.

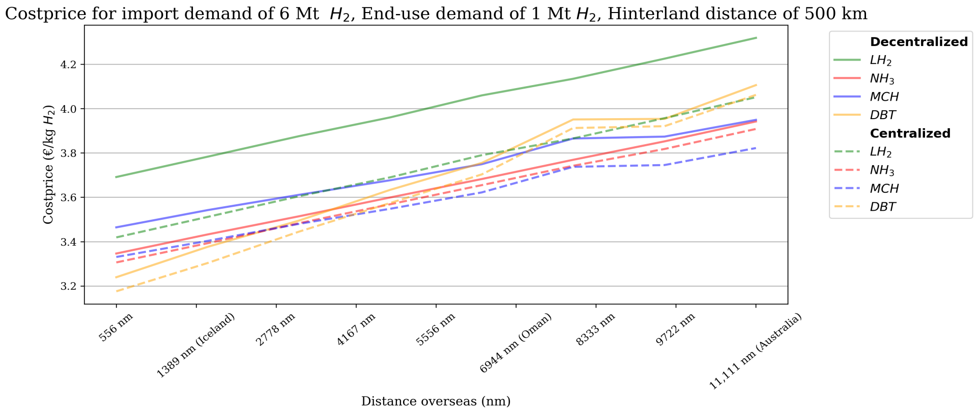


Figure 7.1: Cost price for the supply chain for a variable overseas distance

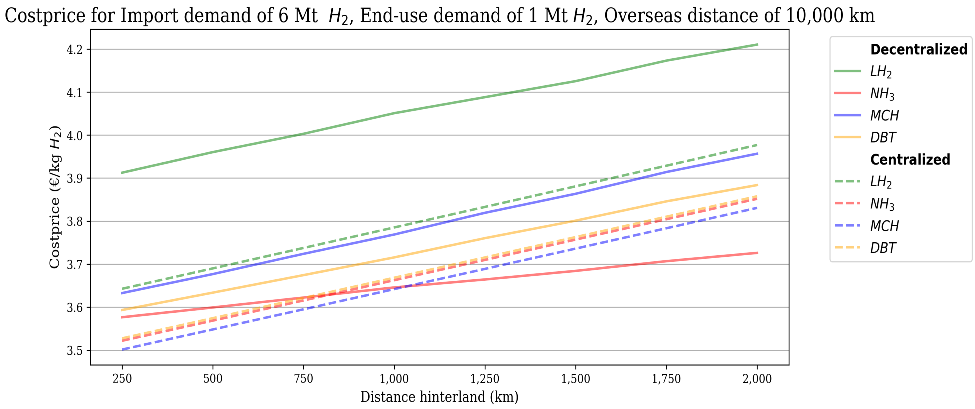


Figure 7.2: Cost price for the supply chain for a variable hinterland distance

7.1.4 Main Research Question

Having addressed all the sub-questions, the main research question can now be answered:

"What is the influence of the required volumes, transport distances, the type of hydrogen carrier and the structure of the entire hydrogen transport supply chain on the cost price of hydrogen at the end-use location and what will be the most cost-effective supply chains?"

When the supply chain from the export terminal to the import terminal is linked to the supply chain to the hinterland, it can be concluded that for short oversea distances, DBT is the most economic option and that for longer oversea distances MCH and NH_3 will be the most cost-effective options. This tipping point is around 3500 - 4500 nm (6500 - 8400 km), depending on the volume of the supply chain, the distance to the end user and whether the supply chain configuration is centralized or decentralized. However, it is important to note that the cost price of MCH and DBT is highly dependent on the procurement and selling price of the LOHCs. The centralized option will be more cost effective than the decentralized option for all the carriers. However, this may change for NH_3 in case of a large distance to the hinterland. It should be stressed, however, that the transport of large quantities of NH_3 by barge to the hinterland raises social and environmental concerns as NH_3 is a highly flammable and toxic substance. As a result, transporting large quantities of NH_3 to the hinterland may not be a realistic future scenario in some countries, or it may entail many additional costs that will increase the cost price significantly. It can also be concluded that the cost price of each carrier will approach a some what constant value at large supply chain volumes.

From the sensitivity analysis, it can be concluded that the eventual cost price is very sensitive to the WACC and to the price at which the hydrogen is purchased in the export country. In addition, the cost price of LH_2 is highly sensitive to the number of storage tanks. All hydrogen carrier options are also relatively sensitive to the energy price.

7.2 Recommendations

This research has established a model in which the influences of supply chain configurations on the final cost price can be examined. It not only focuses on a single supply chain, but can connect multiple supply chains in order to clarify the influence of the interaction between supply chains. In the future, the model can be further improved and applications of the model can be explored. In addition, improving the accuracy of the values of parameters and validation can increase the overall reliability. This section discusses the recommendations for possible future research:

- In order to increase the reliability of the model's results, further research must be done into the applied data. In addition, the degree of accuracy of the model will also increase if all parameters can be made variable over time and place (country dependent).
- Validate the research by comparing the results with actual findings from already operational supply chains (i.e. LNG) to increase the reliability of the model.
- Enhance the model in such a way that it can be applied to brownfield scenarios as well. This will be of great value as it is likely that for some hydrogen carriers no new terminals will be created but rather terminals will be created by adapting existing ones.
- By assigning elements to certain ownerships, it can become clear what the cost implication of a certain supply chain configuration is for a certain company and the WACC can be applied in more detail.
- By developing the cost model to include the residual value of elements, a more reliable cost price can be achieved. Furthermore, revenues can be included in the future in order to create possible business cases.
- The model should be adapted in such a way that situations with multimodal transport can also be investigated. This will be of added value since it is likely that these situations will occur in the future. Especially at the beginning of the transition, during which supply chains have not yet been developed, there is a big chance that the first supply chains will consist of multimodal transport because, for example, (parts of) pipelines have not yet been constructed.
- More research is needed into the implications of safety, social and environmental aspects on hydrogen carrier costs to increase cost reliability and the possibility of supply chain configurations. This would give a more realistic picture of the possible alternative supply chain configurations.
- Future research should also investigate the surface requirements for the various supply chain configurations. The potential of a particular supply chain configuration will depend not only on the implied costs but also on the required surface area.
- The model should be extended to include the specific end-use of hydrogen in a supply chain. If a carrier can be utilised directly at the end-user, this can significantly reduce the cost price of that carrier.
- More research needs to be done into possible technical developments within the supply chain components of the carriers. For NH_3, a relatively well-developed supply chain is already in place, however, the supply chains of LH_2 and the LOHCs are still in the development phase, therefore, there is a high potential for technical developments in these supply chains that could significantly reduce the cost price.

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A | Literature

- Giacomazzi & Gretz (1993) states that the Euro-Quebec Hydro-Hydrogen Pilot Project (EQHHPP) considers a supply chain from Quebec to Germany (Hamburg). The carriers that this report focuses on are LH_2 and MCH. The supply chain considers production by electrolysis in Quebec, liquefaction, overseas transport and storage. The LH_2 demand is 14600 ton/year. This study describes the processes in the examined supply chain.

- Andreassen et al. (1993) performed a study where Norwegian hydro-energy is exported to Germany as hydrogen or electricity. The study focuses on LH_2 that is produced in North Norway and shipped to German ports and distributed to specific cities.A ship with fixed cryogenic tanks is used for the transport of LH_2 over water and cryogenic 40 ft containers are applied for the distribution to the users. This study evaluates the technical and economical feasibility of the examined supply chain.

- The WE-NET project consists of two phases. The first phase studies the large-scale utilization of hydrogen energy and focuses on renewable hydrogen production with electrolysis in Canada which is transported to Japan. The research considers LH_2, NH_3, and MCH as hydrogen carriers. The sea-borne transportation is done by a cryogenic tanker for LH_2. The first phase ends at the storage. The second phase of the study focuses on the distributed utilization; transportation fuel, fuel cells,hydrogen combustion turbines, chemical feed stocks and households. In the first phase the conceptual design, the energy balance and the cost of electricity were verified. In the second phase the distributed technologies are being prepared for field demonstrations (Hijikata, 2002) (Mitsugi et al., 1998).

- In Specht et al. (1998) supply chains for LH_2 and methanol are examined. The supply chain for LH_2 consists of; hydrogen production in Canada from hydroelectric power,liquefaction, intercontinental transport with ship to Germany, storage, LH_2 distribution with trucks to filling tank at 200 km, a car using LH_2 as fuel is filled here. The supply chain for methanol consists of: hydrogen production in Canada from hydro electric power, conversion to methanol plant, inter-continental transport with ship to Germany,storage where gasoline blending takes place and this blending creates M85-fuel, M85-fuel distribution to a filling station where a car is filled that uses M85-fuel. In this study methanol and LH_2 are compared with crude-oil gasoline by looking at the costs and the energy efficiency.

- Wietschel & Hasenauer (2007) looks at potential hydrogen transport corridors between European countries.First the study identifies which countries in Europe are the most promising to produce renewable hydrogen for export. After identifying these countries, the study looked at whether transport by ship (LH_2), pipeline (H_2), truck (LH_2) is best. After this the study focuses on 12 different transport routes within Europe. The study does not look at storage. The potential hydrogen transport corridors are compared by examining both the economic aspects and the aspects which enable a sustainable hydrogen supply.

- Stiller et al. (2008) considers various hydrogen supply chains from Norway to Germany. The first supply chain is that of natural gas (NG); (1) transported via a pipeline or (2) first reformed to H_2 and then transported via a pipeline. Second, a offshore wind supply chain is studied;(1) electricity via HVDC sea cable or (2) hydrogen produced by electrolysis with the offshore wind and transported via pipeline. The third supply chain is again that of NG but this time it is liquefied; (1) NG liquefied to LNG and transported via ship or (2) NG is reformed to LH_2 and transported via ship. The last supply chain takes into account onshore wind that is transported as LH_2 via shipping. The supply chains are evaluated with respect to efficiency, GHG emissions and costs.

- Kim et al. (2008) takes into account a supply chain with hydrogen production facilities, transportation modes and storage facilities. A model is made that investigates what strategic decisions need to be made to fulfill the demand of each regions. Next to these strategic decisions the model also minimizes both the capital and operating costs of the hydrogen supply chain. Seven different case studies have been studied with this model in this research. The carriers are LH_2 or compressed hydrogen gas (CGH_2) and the delivery is via tank trucks, tube trailers or pipelines. The various case studies have been evaluated in terms of the total cost of the network.

- Kawasaki Industries made in 2010 public that they were researching a CO_2-free hydrogen supply chain. The supply chain under consideration started in Australia, where the hydrogen is produced from brown coal with CCUS and the hydrogen is converted to LH_2. The LH_2 is transported with ships to Japan and the hydrogen end-uses that are examined consist of: use in processes, use in power plants, use in energy equipment and use in transportation equipment. A feasibility study has been carried out on this supply chain, assessing the cost of imported hydrogen and its cost competitiveness compared to conventional fossil fuels (Kamiya et al., 2015).

- Babarit et al. (2018) examines the supply chains that start with hydrogen production by fleets of far offshore (1000 km) wind energy converters. In the first option the fleets of far offshore wind energy converters sail to the shore-based terminal and unload the hydrogen at the hydrogen terminal. This first option looks at distribution of hydrogen as LH_2 or as compressed gaseous hydrogen (CGH_2). The hydrogen needs to be distributed to the end-use location which is 600 km form the terminal. The local distribution methods are; LH_2 trailers, Hydrogen pipelines and CGH_2-tube trailers. In the second option the fleets of far off shore wind energy converters are situated further than 1000 km offshore. In this option there are offshore terminals and the transport of hydrogen between the offshore terminal and the import terminal is done by hydrogen carriers (either LH_2 carriers or a CGH_2 carriers). The distribution to the end-use is the same as the first option. The supply chains are compared by examining the short and long term costs of the supplied hydrogen.

- The supply chain that is considered in Heuser et al. (2019) starts with the production of hydrogen with wind energy in Patagonia. The hydrogen is compressed and transported locally to the port of Comodoro Rivadavia via pipelines over a distance of 4500 km. Here the hydrogen is liquefied and stored in LH_2-tanks. The LH_2 is transported to Japan with hydrogen carriers based on the concept of Kawasaki Heavy Industries. The end of the supply chain is the storage of LH_2 in Japan. The costs and cost competitiveness in Japan of the supplied LH_2 has been examined.

- Al-Breiki & Bicer (2020) focuses on three energy carriers; LNG, NH_3 and methanol. The supply chain consists of: production of LNG, conversion of LNG into one of the three carriers, storage at the port in the export country, transport via ship and storage at the port in the import country.The energy consumption and the energy losses due to boil off gasses are examined in this study.

B | Supply Chain Elements

B.1 Characteristics Hydrogen Forms of Transport

Table B.1 presents the properties of the different types of hydrogen transport considered in this report. The values are based on (Lanphen, 2019),(IEA, 2019), (Aziz et al., 2019), (Aakko-Saksa et al., 2018) and (Reuß et al., 2017).

	$\mathbf{CGH_2}$	$\mathbf{CGH_2}$	$\mathbf{LH_2}$	$\mathbf{NH_3}$	**MCH**	**DBT**
Chemical formula	H_2	H_2	H_2	NH_3	C_7H_{14}	$C_{21}H_{32}$
Pressure [bar]	700	100	Ambient	Ambient	Ambient	Ambient
Density [kg/m^3]	3.9	5.7	71	682.6	770	1057
State of matter	Gas	Gas	Liquid	Liquid	Liquid	Liquid
Temperature [°C]	Ambient	Ambient	-253	-33	Ambient	Ambient
Melting point [°C]	-259	-259	-259	-78	-127	-34
Boiling point [°C]	-253	-253	-253	-33	101	395
Hydrogen content [%]	100	100	100	17.65	6.2	6
Energy density [MJ/L]	5.6	0.9	9.1	15.6	5.7	7.4

Table B.1: The properties of different forms of hydrogen transport considered in this report

B.2 LOHCs

Liquid Organic Hydrogen Carriers (LOHCs) are liquids or (low melting) solids that can be reversibly hydrogenated and dehydrogenated at elevated temperatures in the presence of a catalyst. After the release of the rechargeable hydrogen, the initial structure of the LOHC remains the same, so no new production of carriers is required (Markiewicz et al., 2015). However, the carrier must be transported back to a location where it can be reloaded with hydrogen. A big advantage of LOHCs is that the structure is very similar to that of oil products, which makes them very compatible with the fuel infrastructure that already exists (Aakko-Saksa et al., 2018). In addition, there are hardly any losses during transport and storage, and the purity level of the released hydrogen from LOHCs is high. A disadvantage of LOHCs is that hydrogenation and dehydrogenation take place at high temperatures and therefore these processes require a lot of energy, which results in high costs.

There are currently a few LOHCs that have been commercially introduced and are in an advanced stage of research; LOHCs debenzyl and benzyl toluene (DBT, BT) (Hydrogenious, 2021) (Schneider, 2015) are being investigated by the German company Hydrogenious and the LOHC methylcyclohexane (MCH) is being investigated by the Japanese company Chiyoda Corporation (Chiyoda Corporation, 2021). The advantages, disadvantages and differences between these LOHCs are briefly explained below.

B.2.1 DBT

The initial structure (not loaded with hydrogen) of DBT is H0-DBT, when loaded with hydrogen it is called H18-DBT, the process is shown in Figure B.1. The hydrogenation is an exothermic process, the dehydrogenation is an endothermic process, for both processes catalysts are needed. Hydrogenation takes place under a pressure of about 50 bar and a temperature of about 150°C. The dehydrogenation takes place under atmospheric pressure with a temperature of about 300°C. For the hydrogenation about 4.7 GJ/t H_2 is needed, for the dehydrogenation approximatley 34.2 GJ/t H_2 is needed (Tijdgat, 2020). The storage and transport of H0-DBT and H18-DBT is easy because it can use the existing infrastructure for oil products.

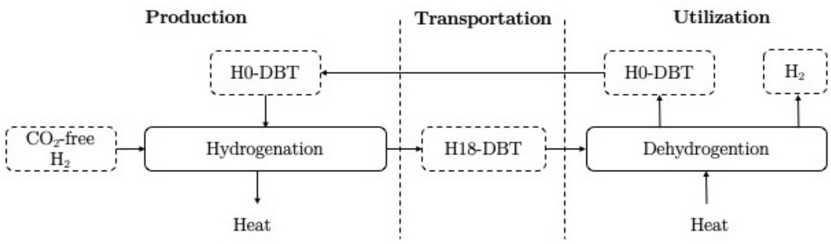

Figure B.1: DBT as a carrier (based on (Aziz et al., 2019))

B.2.2 MCH

The initial structure of MCH is toluene $C_6H_5CH_3$, the cyclic process is presented in Figure B.2. In hydrogenation and dehydrogenation, a catalyst is used, e.g. a platinum (Pt) based catalyst (Wijayanta et al., 2019). Hydrogenation is carried out at temperatures of between 180-300°C and at a pressure of about 200 kPa. The dehydrogenation takes place at high temperatures ranging from 230-400°C at a relatively low pressure. Especially the dehydrogenation often forms a bottle neck in the supply chain of LOHCs, as this process is very energy intensive. Toluene and MCH can both be easily transported and stored using existing regulations and infrastructure such as gasoline tanker trucks and ships (Crolius, S, 2021). Hydrogenation requires about 4.7 GJ/t H_2 and dehydrogenation requires about 36 GJ/t H_2 (Tijdgat, 2020).

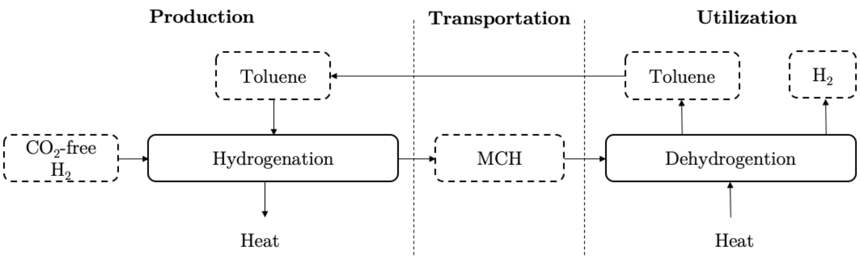

Figure B.2: MCH as a carrier (based on (Aziz et al., 2019))

B.2.3 DBT vs. MCH

The energy requirements for hydrogenation and dehydrogenation are approximately the same for both LOHCs. In addition, the H_2 content is almost the same for MCH and DBT (Wijayanta et al., 2019). A major advantage of MCH is that toluene is already widely produced, as it is used in many industrial applications as a feedstock. DBT is also used in industry (as a heat transfer fluid), but its production is on a smaller scale compared to toluene. A disadvantage of toluene is that it is a toxic and flammable product, whereas DBT is not, which makes it easier to meet the requirements of storage and transport than with toluene. Another advantage of DBT is that the purity of the released hydrogen is higher than that of toluene, which means that DBT does not require an extra purification process if the hydrogen has to be used in PEM fuel cells. However, a disadvantage of DBT is that the hydrogenation and dehydrogenation process is more complicated because multiple different catalysts are needed, this is not the case with MCH.

C | Model Data: The End-Use Model

In this Appendix it will be explained what data is used in the End-Use Model and how was arrived at these values. All the elements of the End-Use Model are described in Chapter 2. For all costs, a conversion factor of 0.82 was used to convert dollars to euros (Macrotrends, 2020). For the data, several interviews have been conducted with experts and employees of the Port of Rotterdam, literature has also been consulted. Because many elements in this hydrogen supply chain are still under development, the values found for the various elements have a large variance. In order to increase the reliability of these values, low, medium and high scenarios have been created for the investment costs of the elements. The values of the medium scenario are used in the model.

The values that are found for the various elements in literature and from interviews are often linked to elements with different capacities than the elements in this model. To convert the costs of a certain element with a capacity to the costs for an element with another capacity which is used in this report, no linear relationship is assumed, but economies of scale are considered; as the size of an element grows, there will be a reduction in average costs. The formula used in this report to take account for this is given below (formula C.1). C_B is the CAPEX of the new element with capacity S_B. C_A is the CAPEX of the element found in the literature with capacity S_A. The scaling factor is indicated in the formula by n, in this report a value of 0.7 is used (Sekkesaeter, 2019).

$$C_B = C_A * (\frac{S_B}{S_A})^n \tag{C.1}$$

As already discussed in Chapter 2, the End-Use Model consists of two elements; the reconversion plant and the transport to the end-user. Furthermore some general parameters are used in the model. The general parameters are country dependent. In this Appendix the general data that is used in the model that is analyzed in Chapter 4 is explained.

C.1 General Data

In the model, some general parameters that are country dependent are used as input values; Fuel costs, energy costs and the WACC. This section briefly explains the assumptions and values behind this data. The generic model analysed in Chapter 4 examines a supply chain that is situated in the Netherlands. Therefore, the general data will be determined for the Netherlands.

C.1.1 Fuel

The distribution options are trucks, barges, rail and pipelines. For trucks, barges and rail, it is necessary to decide on what kind of fuel these transport modes run. Below is explained what has been assumed for the fuel for each transport mode in this report.

Trucks

Trucks can work on different fuels, such as diesel, hydrogen, or electricity. First, a small literature study was done on these three options to choose which one will be used in this report. The fuel consumption of trucks depends on the size, weight, and whether the journey is through urban or non-urban areas. Due to the density differences of the carriers, the same volume of ammonia and LOHCs will be much heavier than that same volume in LH_2 and CGH_2. However, the steel tubes that hold the CGH_2 are very heavy (Office of Energy Efficiency & Renewable Energy, 2021a). In addition, the LH_2 has to be cooled down to -253°C, which requires a lot of heavy equipment and causes more fuel consumption (Office of Energy Efficiency & Renewable Energy, 2021b). Therefore, it is assumed that the fuel consumption is the same for all trucks.

- **Diesel trucks**: At the moment, diesel fuel is popular for freight transport because a lot of power is needed for trucks to cover long distances. Diesel is currently the cheapest fuel that can provide this power (Webfleet Solutions , 2021). The Spanish Observatory of road freight transport costs report (October 2019) states that a truck with a payload of 25000 kg has a consumption of about 35 L/100 km and a truck with a payload of 16000 kg uses about 25 L/100 km (Webfleet Solutions , 2021). In (Amos, 1998) it is assumed that the fuel consumption of a truck is 38 L/100 km. Taking both estimations into account, this report assumes that the consumption of a diesel truck is equal to 40 L/100 km. In addition, an average diesel price in The Netherlands of 1.20 €/Liter is assumed (ANWB, 2021). The investment costs for the diesel trucks are taken from (IEA, 2019) and are approximately equal to 123000€.

- **Hydrogen trucks**: Hydrogen trucks are currently still in the early development phase. (Oostdam, 2019) has calculated that at this moment the investment cost of a hydrogen truck is 400000€, in 2040 these costs could drop to 200000€. In this same literature, it is concluded that at the moment the hydrogen price in Europe is approximately 10 €/kg H_2, in 2040 this cost could decrease 50 to 63% to about 5 - 3.7 €/kg H_2. In (Oostdam, 2019) it is also stated that a loaded truck uses 15 kgH_2/100 km and an unloaded truck about 7 kgH_2/100 km. In (Unterlohner, 2020), the investment cost of a hydrogen truck is currently estimated at 437000€ and concludes that the cost could decrease to 319000€ by 2030. It also assumes that the price of hydrogen is currently around 6.40 €/kgH_2 and that it could fall to 5.40 €/kgH_2 by 2030. The assumed costs in this report are shown in Table C.1. We assume here that a truck drives on average 0.1 kgH_2/km per trip with a price of 4 €/kg H_2 in the Netherlands.

- **Electric trucks**: More and more electric trucks are now coming onto the market. (Unterlohner, 2020) finds that the investment costs for an electric truck are currently lower than those of a hydrogen truck. The estimated cost in (Unterlohner, 2020) is 353000€ in 2020 and this may decrease to 256000€ in 2030. (Unterlohner, 2020) finds that electric trucks are becoming cost-competitive with diesel trucks earlier than hydrogen trucks. However, a major disadvantage of electric trucks is that the refueling process takes much longer than with diesel and hydrogen (2-8 h vs. 3-8 min). In (Unterlohner, 2020) an estimation was also made for the price of recharging in Europe, which is 0.17 €/kWh in 2020 and 0.15 €/kWh in 2030. With a consumption of about 720 kWh/400 km, this equals a low cost per km of 0.31 €/km.

	CAPEX (€)		**Fuel Price (€/km)**	
	2020	2040	2020	2040
Diesel	123000	123000	0.48	0.48
Hydrogen	400000	200000	1.50	0.40
Electric	350000	250000	0.31	0.27

Table C.1: Data for the fuel of trucks

The investment costs and fuel price for the three trucks are compared in Table C.1. An important conclusion is that the biggest price reduction will take place for hydrogen. For diesel, a constant price has now been assumed as in (Oostdam, 2019), but these costs might even increase in the future given the climate agreements. Besides, the major disadvantage of electric cars compared to hydrogen cars is that they take much longer to charge. With a view to the future and because a supply chain of hydrogen to the end-user will most likely be realized sometime in the future, the report is modeled with hydrogen trucks at future prices. The values used in the model are truck investment costs of 200000€ and a fuel price of 0.40 €/km in the Netherlands.

Barges

In this report, it is assumed that the barges run on gasoline (Backer van Ommeren, 2012). This is because electric and hydrogen-fuelled ships are still in the development phase. However, it is assumed that LH_2-ships use the boil-off of the hydrogen as fuel (Lanphen, 2019). This is therefore included in the LH_2-losses during transport. For the consumption of the boil-off, a comparison is made for LH_2 with LNG. An LNG ship consumes approximately 100 tonnes/day. By comparing the energy content of LNG (53.6 MJ/kg) and LH_2 (130 MJ/kg) it can be assumed that a liquid hydrogen ship consumes 33 tons/day (Lanphen, 2019).

From (Kruse et al., 2017) it is concluded that an average barge uses about 1 liter to transport 1 tonne over 275 km. To determine the ultimate consumption of a barge in L/km, it is thus necessary to look at the weight of the ship. The weight of the ship is given in the tables of the data of the barges (Table C.5) and the calculations is shown in Appendix E. In addition, it is assumed that the diesel price for barges in the Netherlands is equal to 66 €/100 liter (Backer van Ommeren, 2012).

Trains

Passenger trains often run on electricity, but due to the heavyweight of freight trains and the fact that they often have to travel long distances, these freight trains often run on diesel. Hydrogen trains are currently still in the development phase, therefore it is assumed in this report that all trains run on diesel. It is also determined from (Kruse et al., 2017) that a train can transport 1 tonne over 203 km with 1 liter of fuel. So again, the consumption depends on the weight of the train. The weight of the train is given in the tables of the data of the trains (Table C.4) and the fuel calculations are given in Appendix E. The same diesel price as for trucks is assumed here, being 1.20 €/liter in the Netherlands.

C.1.2 Energy

The model takes an energy price in €/kWh. However, this price differs per country and over time. The general model assumes a plant located in the Netherlands and a model time frame starting in 2020 and ending in 2040. The energy price is based on the report by (Lanphen, 2019) in which it is assumed that the energy price increases linearly over time. In addition, it is also assumed in this report that the hydrogen conversion plants and reconversion plants are located in countries with low energy prices. This is due to the fact that both processes consume a lot of energy, so it is reasonable to assume that, looking at the energy costs, these plants will be located in countries with a low energy price. By taking into account the findings of (Lanphen, 2019) and including the assumption of a low energy price, this model is based on an energy price equal to 0.06 €/kWh.

C.1.3 WACC

Whenever money can earn interest, as with investments in ports and terminals, the current money is worth more in the future because of its potential earning capacity. In other words, money that is received at an earlier stage is worth more than money that is received in the future. To take this into account in the model, cash has to be discounted; cash flows in the future have to be converted to their respective present value, this is also called a discounted cash flow analysis and is used to assess the feasibility of a project (IJzermans, 2019). This conversion is done by using a discount rate. In this model the costs are calculated for each year, therefore a yearly discount rate is applied here. The discount rate used in this model is based on the cost of capital and is called the WACC. The cost of capital is the required rate of return that is necessary to ensure that investments will be made in a certain project. This return is defined by the risk premium; the higher the project risk, the higher the cost of capital (C. Lee & Lee, 2013).

The WACC is calculated with formula C.2 (IJzermans, 2019). The WACC is country and project dependent, since the values used in the formulas are country and project dependent, all parameters used in the formula are described below. Formula C.2 calculates the nominal WACC and formulaC.3 shows how the nominal WACC is converted to the real WACC. In this report the nominal WACC is used. The WACC is used in the End-Use Model and the Supply Chain Model. The values of the WACC described below are for the case study of an import terminal in Rotterdam (The Netherlands). For an import terminal in Rotterdam the $WACC_{nom}$ is equal to 8.3% and the $WACC_{real}$ is equal to 5.5%.

$$WACC_{nom} = D_{\%} * (1 - T_c) * D_c + E_{\%} * E_c \quad \text{(C.2)}$$

$$WACC_{real} = \frac{WACC_{nom} + 1}{inf + 1} - 1 \quad \text{(C.3)}$$

- $D_{\%}$: Percentage of the project that is provided through a loan, also called Gearing. This report assumes that 60% of the required funds are provided through a loan from the World Bank (IJzermans, 2019).
- T_c: Corporate tax rate, which is country dependent. In the Netherlands, the rate is 25% when the taxable amount is 200,000€ or more (Government of the Netherlands, 2021).
- D_c: The costs of debt, calculated with: $D_c = r_p + r_{f,local}$
  - r_p: The risk premium, this premium is a payment to investors for tolerating the extra risk of a certain investment compared to a risk-free investment. This premium depends on the risk of the project and on the investors in the project. For a company with a reputation for handling large-scale projects, and in the case of infrastructure projects, the risk premium is somewhere around 3.1% for projects in Western Europe and 9% for projects in Africa. So in this case for the Netherlands an average risk premium of 3.5% is assumed (IJzermans, 2019).
  - $r_{f,local}$: the risk-free rate, this is the return of an investment without risk. The average risk-free rate in the Netherlands is around 1.6% based on (Statista, 2021b).
- $E_{\%}$: Percentage of the project that is provided from equity. Looking at the Gearing, in this project 40% of the funds are provided from equity. This percentage carries more risk than the percentage provided by a loan from the bank. For instance, if the project goes bankrupt, the bank's investors have more claim on the project's assets than the equity investors (Brealey et al., 2011).
- E_c: The cost of equity, calculated with: $E_c = r_{f,local} + \beta * r_{m,local}$
  - $r_{f,local}$: the risk free rate, see above
  - β: This is a sector-specific risk factor. When the sector contains high risks, the value of beta is high and vice versa. For example, a brownfield project has a lower risk than a greenfield project. From (IJzermans, 2019) it can be concluded that a greenfield project for a port has a beta value of 2.
  - $r_{m,local}$: The market risk premium, this is the difference between the expected return and the risk-free rate. This is country-specific and in the Netherlands an average value of 6.2% is assumed based on (KPMG, 2021b).
- inf: Inflation, this is an increase in the general level of prices, expressed in percentages, resulting from the rate at which the value of a currency decreases. In the Netherlands, the average value of inflation is 2.7% (Inflation.eu, 2021).

C.2 The Reconversion Plant

The data for the reconversion plants is presented in Table C.2. The values found in literature are converted using economies of scale. Low, medium and high scenarios are made for the different carriers with the different collected data. The investment costs and the other data come from (Lanphen, 2019), (Sekkesaeter, 2019), (Ishimoto et al., 2020), (IEA, 2019), (Terwel & Kerkhoven, 2019), (Vos et al., 2020) and Chiyoda Corporation.

For these reconversion plants it is assumed that no additional purification step is added to the reconversion plant. The purity of the hydrogen for the LOHC and NH_3 power plants is therefore only suitable for hydrogen that is intended for combustion and not for hydrogen used in fuel cells.

	LH_2	**NH_3**	**MCH**	**DBT**	**Unit**
Investment (low)	18	100	100	150	M€/plant
Investment (med)	30	225	200	250	M€/plant
Investment (high)	42	350	300	350	M€/plant
Lifespan	20	20	20	20	Years
Construction time	2	2	2	2	Years
Crew	3	3	3	3	#
Energy consumption	600	5890	9360	7360	kWh/ton H_2
Capacity	137	221	742	742	Ton carrier/ h
Losses	0	1	10	10	%

Table C.2: Data for the reconversion plants

C.3 The Transport to End-use

As already discussed in Chapter 2, there are four transport options to choose from in this model: truck, rail, barge, and pipelines. Besides, one can choose between three different forms of hydrogen; LH_2, NH_3, and LOHCs. In addition, the transport of CGH_2 is also considered if the reconversion is centralized. Transport of CGH_2 is only considered for trucks and pipelines, because no literature on CGH_2 transport by barge and rail was found. Furthermore, CGH_2 transport is expensive and the energy density of CGH_2 is much lower than that of LH_2. Therefore it is assumed that this transport is very inefficient considering barge and rail, hence this type of transport will probably not take place in the future and is not included in this report. Below the data adopted in this report for each form of transport is discussed.

C.3.1 Trucks

For liquid tanker trucks, large tankers have a maximum capacity of 11600 gallons (43.5 m^3) and a maximum weight of 80000 lbs (36290 kg) (Trailer of Texas, INC, 2021). In order to be able to compare the transport of the carriers properly, it was assumed that each truck has a capacity of 43.5 m^3 (if not too heavy). In Table C.3 this volume has been converted into tonnes of H_2 for each carrier. For CGH_2, the largest possible tanker volume is equal to 26 m^3. The hydrogen is compressed in this tank to 500 bar, the density is then equal to 33 kg H_2/m^3, so about 860 kg of hydrogen fits in a tanker (Hydrogen Europe, 2021).

It is assumed that all trucks are hydrogen trucks, hence one truck costs 200000€ (paragraph C.1.1). The costs of the trailers differ, for instance LH_2 must be cooled to -253°C, which makes the costs of this trailer high compared to NH_3 and LOHCs. The cost of CGH_2 transport is also high as it has to be compressed to 500 bar. In (Amos, 1998), (IEA, 2019) and (Simbeck & Chang, 2002) prices have been mentioned for the trailer costs of LH_2 and tube trailers used for CGH_2. By comparing all costs, low, medium and high scenarios have been made for the investment costs for the trailers, based on (Amos, 1998), (IEA, 2019), (Simbeck & Chang, 2002), (Kim et al., 2008), (Barckholtz et al., 2013), (Reuß et al., 2017) and (Schneider, 2015), presented in Table C.3.

	CGH_2	LH_2	NH_3	MCH	DBT	Unit
Investment trailer (low)	300	320	140	100	100	k€/trailer
Investment trailer (med)	525	548	250	218	218	k€/trailer
Investment trailer (high)	750	775	360	335	335	k€/trailer
Investment truck	200	200	200	200	200	k€/truck
Lifespan	12	12	12	12	12	Years
Construction time	0	0	0	0	0	Years
Crew	1	1	1	1	1	#
(un)loading time	1.5	3	1.5	1.5	1.5	Hours
Average speed	50	50	50	50	50	km/h
Capacity	0.9	3.1	16.7	34	46	Ton carrier
Losses	0	1	0.2	0	0	%/d

Table C.3: Data for the trucks

C.3.2 Rail

In order to be able to compare train transport, it is assumed that all tanks of each carrier on a train also have an equal volume. A tank on a train has a larger capacity than a tank on a truck (Amos, 1998). In this report, a capacity of 130 m^3 is assumed, because this is already an existing rail tanker for NH_3 (GBX, 2021). In addition, it has been taken from (Amos, 1998) that the capacity of a rail tanker for LH_2 ranges from 2300 to 9100 kg. Thus 130 m^3 is a realistic capacity. In addition, the weight of a train is needed to calculate its fuel consumption C.1.1. The weight is taken from (Amos, 1998) and also represented in Table C.4.

For the costs, literature is considered as well as the costs for a tank used for the trucks. A tank on a train usually has a larger capacity than a tank on a truck. An undercarriage is also required for each tanker and the investment for this equals 83000 €/tank (Amos, 1998). It is assumed that the cost of the undercarriage is the same for each carrier. Again low, medium and high scenario's are made for the investment costs of the rail tankers, based on values found in (Amos, 1998) and based on the truck trailer values found in (IEA, 2019), (Kim et al., 2008), (Barckholtz et al., 2013), (Simbeck & Chang, 2002), (Schneider, 2015) and (Reuß et al., 2017). The values are presented in Table C.4.

The number of wagons that a freight train can carry depends, among other things, on the train's length. In the Netherlands, the maximum length of a train is 750 meters (Drenth, 2019). The existing tanker for NH_3 is approximately 18.8 meters long (GBX, 2021), this results in about 38 wagons. van der Meulen et al. (2020) has assumed 35 wagons for it's freight trains, therefore in this report 35 wagons have been assumed.

	LH_2	NH_3	MCH	DBT	Unit
Investment 35 tanks (low)	14	9.8	8	8	M€/tank
Investment 35 tanks (med)	24.5	15.4	12.2	12.2	M€/tank
Investment 35 tanks (high)	35	21	16.5	16.5	M€/tank
Investment undercarriages	2.8	2.8	2.8	2.8	M€/unit
Lifespan	15	15	15	15	Years
Construction time	2	2	2	2	Years
Crew	2	2	2	2	#
(un)loading time	24	24	24	24	Hours
Average speed	45	45	45	45	km/h
Capacity train	325	3105	3505	4810	Ton carrier
Weight of empty train	2100	2100	3000	3000	Ton
Losses	0.3	0.02	0	0	%/d

Table C.4: Data for the trains

C.3.3 Barge

For the barges, too, a similar transport volume is assumed in order to be able to easily compare the carriers. In this report, a volume of 10000 m^3 is assumed, this volume belongs to a large liquid barge (B. Jha, 2020). With the different properties of the carriers from Table B.1, the number of tonnes H_2 per barge was calculated, see Table C.5. The investment cost scenarios for the barges are based on (IEA, 2019), (Lanphen, 2019), (Ishimoto et al., 2020) and (Terwel & Kerkhoven, 2019). The boil-off rates for the barges are based on (Al-Breiki & Bicer, 2020), (Reuß et al., 2017), (Schneider, 2015), (Amos, 1998) and (Sekkesaeter, 2019). All data used in this report is presented in Table C.5. In addition, for the fuel it is assumed that a barge carrying LH_2 uses the boil-off of this LH_2 as fuel. The NH_3 and LOHC barges use diesel as fuel (Appendix C.1.1). The weight of a barge is also needed to calculate the fuel consumption. The weight is taken from (Terwel & Kerkhoven, 2019) and converted with economies of scale.

	LH$_2$	**NH$_3$**	**MCH**	**DBT**	**Unit**
Investment ship (low)	25	15	8	8	M€/ship
Investment ship (med)	40	20	11	11	M€/ship
Investment ship (high)	55	25	14	14	M€/ship
Lifespan	20	20	20	20	Years
Construction time	1	1	1	1	Years
Crew	2	2	2	2	#
(un)loading time	48	48	48	48	Hours
Average speed	7	7	7	7	knots
Capacity barge	710	6826	7700	10570	Ton carrier
Weight of empty barge	1500	4400	2300	2300	Ton
Losses	0.3	0.08	0	0	%/d

Table C.5: Data for the barge

C.3.4 New Pipelines

For the pipeline, a CGH_2-pipeline and an NH_3-pipeline are being considered. A pipeline can also be built for an LOHC, but because an LOHC has to return to its place of origin, two pipelines would have to be built. The cost of this will be so high that the option will always be extremely expensive. Hence, a LOHC pipeline is not considered in this report. In addition, a distinction must be made between an all-new pipeline and a pipeline that is already in existence. This section discusses the data for an entirely new pipeline and Section C.3.5 discusses the data for an already existing pipeline. Below the data is described that is used for new CGH_2 and NH_3-pipelines.

CGH_2-pipeline

In this report a CGH_2-pipeline is considered where the hydrogen is compressed to a pressure of 100 bar. The construction time of a pipe is assumed to be 3 years. From (IEA, 2019) it is taken that the diameter of the pipeline depends on the volume in the supply chain. The cost of the pipeline (€/km) is again dependent on the diameter. The diameter is calculated with formulas C.4, C.5. Where Q is the flow rate in the pipeline in m^3/s, V_{max} is the maximum volume in the pipeline over the model frame in ton H_2, ρ_{ch} is the density of CGH_2 (0.0057 ton/m^3/s), v is the speed of the hydrogen gas in the pipeline in m/s (15 m/s (Lanphen, 2019)) and D is the diameter of the pipeline in m.

$$Q = \frac{V_{max}}{\rho_{ch} * \frac{sec}{year}} \tag{C.4}$$

$$D = \sqrt{\frac{4 * \frac{Q}{v}}{\pi}} \tag{C.5}$$

Because the investment costs of the pipeline depend on the diameter the low, medium and high scenarios are expressed here as formulas, based on (Yang & Ogden, 2007), (IEA, 2019) and (Terwel & Kerkhoven, 2019).

	CGH_2 pipeline	**Unit**
Investment pipe (low)	$((D * 100/2.545454)^2 * 1869/1000/1.21 + 300/1.21)/1000$	M€/km
Investment pipe (med)	$(D^2 * 2200 + D * 860 + 247.5)/1000$	M€/km
Investment pipe (high)	$(D^2 * 3858 + D * 679 + 373)/1000$	M€/km

Table C.6: Investment cost formulas for CGH_2-pipeline

Compressors are needed to keep the hydrogen gas at the right pressure over the distance. It is assumed that a compressor is needed every 250 km (Lanphen, 2019). Low, medium and high scenarios were also made for the investment costs of the compressors. It is assumed that the energy needed to compress the hydrogen (E_c) is equal to 0.2 kWh/kg H_2 (Terwel & Kerkhoven, 2019). The values for the compressors are shown in Table C.7, based on (Wang et al., 2020). The losses for a pipeline are 0.5% and per compressor station the losses are 0.5% (IEA, 2019), (Lanphen, 2019). The costs of the compressors are given in M€/MW, in formula C.6 this is converted to M€/compressor.

	CGH_2	**Unit**
Investment compressor (low)	2.2	M€/MW
Investment compressor (med)	3.4	M€/MW
Investment compressor (high)	6.7	M€/MW

Table C.7: Investment costs for the compressors

$$\frac{EUR}{compressor} = (\frac{(Q * \rho_{ch} * 3600) * E_c}{1000}) * \frac{EUR}{MW} \tag{C.6}$$

NH_3-pipeline

An ammonia pipeline is also considered in this report. The main difference between the ammonia and gaseous hydrogen pipeline is that a liquid moves a lot slower in a pipeline than a gas, the material of the pipelines is more or less the same. Hence the same formulas that are used for the CGH_2-pipeline can be used for the NH_3-pipeline. The only difference in equation C.4 is that the density (ρ_{ch}) is now equal to 0.683 ton$/m^3/s$. The difference in equation C.5 is that the velocity (v) of ammonia in a pipeline is equal to 2 m/s (based on expert interviews with Port of Rotterdam). Furthermore it is taken from (Lanphen, 2019) that 100 kWh/ton is needed to move the liquid.

C.3.5 Existing Pipelines

In this section the data used for already existing pipelines is discussed. The already existing pipelines that can be used depend on the area that is under consideration. The general model from Chapter 4, considers the Netherlands which has a hinterland connection to Europe. From (Wang et al., 2020) it can be taken that there is a European vision that must ensure that hydrogen supply and demand is connected by 2040 throughout Europe with a pipeline network. The vision is a 6800 km pipeline network by 2030, which will expand to about 23,000 km by 2040. It is mainly based on the conversion of already existing pipelines. The pipeline network will consist of approximately 25% of new pipelines and

75% converted pipelines. The cost price for this is estimated with an average scenario at 0.13€/kg/1000 km, see Table C.8.

	Low	Medium	High	Unit
Levelised cost, European Hydrogen Backbone (75% retrofitted, 25% new infrastructure)	0.09	0.13	0.17	€/kg H_2/1000 km

Table C.8: Cost of the European Hydrogen Backbone from (Wang et al., 2020)

D | Model Data: The Supply Chain Model

As already discussed in Chapter 2, the Supply Chain Model consists of the end-use supply chain and the export-import supply chain, all the elements of these supply chains are described in Chapter 2. The data of the end-use supply chain is already presented in Appendix C. In this chapter the additional data used in the Supply Chain Model will be discussed. This additional data consists of the data of the elements that are present at the export and import terminal, the data of the vessels that are used for the transport between those terminals and some general data that is used as input value in the Supply Chain Model. In this Appendix firstly the general data that is used is described, than the data for the terminal elements and lastly the data for the seaborne transport.

D.1 General Data

The general data used in this model is country-specific. In Chapter 4, a general analysis is carried out where a global average is taken for the country dependent parameters and in Chapter 5, a case study is done where the countries Iceland, the Netherlands, Germany and Australia are used. The general data is thus determined for these four countries and for the global average for the reference year 2030.

D.1.1 Fuel

Fuel is needed for the transport to the hinterland and the transport between the import terminal and the export terminal. Ships are used for the transport between the export terminal and the import terminal. It is assumed that LH_2-ships sail on the boil-off of the carried LH_2. For ammonia, it is assumed that the ship sails on the carried NH_3. It is assumed that an LOHC vessel sails on oil with a low sulphur content (BW0.1%S). For transport to the hinterland the same assumptions are made as in Appendix C, Section C.1.1. It can be chosen whether these modes run on diesel or hydrogen. The fuel prices for diesel, hydrogen and BW0.1%S for the reference year 2030 are shown in Table D.1. All fuel prices are assumed to be the same for all countries considered and the world average.

D.1.2 Energy

It is assumed that all countries have a low energy price. Supply chains will only be developed if the energy price is low in the respective countries, making it attractive to locate the conversion and reconversion plants there. Again, the energy price is based on the report by (Lanphen, 2019) in which it is assumed that the energy price increases linearly over time. In addition, it is also assumed in this report that the hydrogen conversion plants and reconversion plants are located in countries with low energy prices. This is due to the fact that both processes consume a lot of energy, so it is reasonable to assume that, looking at the energy costs, these plants will be located in countries with a low energy price. By taking into account the findings of (Lanphen, 2019) and including the assumption of a low energy price, this model is based on an energy price equal to 0.06 €/kWh.

D.1.3 WACC

How the WACC is calculated has already been described in Appendix C, Section C.1.3, in this section, the WACC for the Netherlands has been calculated. For Germany, Iceland and Australia, an average risk premium of 3.5% an average risk-free rate of 1.6% and an average market risk premium of 6% is assumed. The corporate tax rate however does differ per country; these are 15.8% (PWC, 2021a), 20.0% (PWC, 2021b) and 30.0% (Lanphen, 2019) respectively. The inflation rate also differs per country and is 1.7% (Destatis, 2021), 2.7% (Destatis, 2021) and 1.6% (Statista, 2021a) respectively. The average nominal WACC in the world is 8% (KPMG, 2021a) and the average global inflation rate is 3.2% (Statista, 2020). With the inflation and the nominal WACC, the real WACC can be calculated. The models in this report use the nominal WACC, the values can be found in Table D.1.

D.1.4 Hydrogen and material

At the export terminal there is a conversion plant that requires hydrogen to make liquid hydrogen, hydrogen and nitrogen to make ammonia, hydrogen and toluene to make MCH and hydrogen and DBT to make perhydro-DBT. Hydrogen, nitrogen, toluene and DBT must therefore be supplied to the export terminal. It has been assumed that nitrogen, toluene and DBT can be purchased for the same price all over the world, these prices are shown in Table D.1 and are based on values found in (Lanphen, 2019) and (Terwel & Kerkhoven, 2019). For the purchased hydrogen, a difference in price is made between grey, blue and green hydrogen. The prices for the Netherlands and Australia are taken from (Lanphen, 2019). For Iceland the same values as Australia were used and for Germany the same values as the Netherlands. The global average prices are also based on the values that were found in (Lanphen, 2019). All values used in this report are shown in Table D.1. Additionally, it is also taken into account that part of the MCH and DBT will be sold again at the end of the plant's lifetime. For DBT, it is assumed that 50% is sold for 2500 €/ton and for MCH it is assumed that 50% is sold for 500 €/ton.

	NL	**DL**	**IC**	**AUS**	**Global Average**	**Unit**
Fuel Price (BW0.1%S)	556	556	556	556	556	€/ton
Fuel Price (Diesel)	1.20	1.20	1.20	1.20	1.20	€/L
Fuel Price (Hydrogen)	4	4	4	4	4	€/kg H_2
Energy Price	0.06	0.06	0.06	0.06	0.06	€/kWh
Hydrogen Price	Green: 3.02 Blue: 2.00 Grey: 1.72	Green: 3.02 Blue: 2.00 Grey: 1.72	Green: 3.10 Blue: 1.64 Grey:1.72	Green: 3.10 Blue: 1.64 Grey: 1.72	Green: 2.86 Blue: 1.64 Grey: 1.64	€/kg H_2
Nitrogen Price	27	27	27	27	27	€/ton
Toluene Price	600	600	600	600	600	€/ton
DBT Price	3500	3500	3500	3500	3500	€/ton
WACC nom	8.3	8.6	8.2	7.2	8.0	%
Inflation	2.7	1.7	2.7	1.6	2.0	%
WACC real	5	6.8	5.3	5.5	5.6	%

Table D.1: All country dependent values used in this report

D.2 Terminal Elements

The terminal elements used in the model are described in Chapter 2 and shown in Figures 2.2 and 2.6. It is assumed that the data used for the jetty, pipeline and storage's is the same for the export and import terminal. At the export terminal, there can be conversion plants that convert the supplied CGH_2 into one of the carriers. At the import terminal there in turn can be conversion plants that can convert the supplied carriers back into CGH_2. Below all the data that is used for the terminal elements is briefly discussed.

D.2.1 Jetty

As described in Section 2.2.1.1 an L-shaped jetty is used in the model. In addition, this section also describes that the vessels will have ship based pumps that can unload the liquid bulk at the import terminal. Therefore, no equipment is needed at the import terminal for the unloading of the liquid bulk (Lanphen, 2019). However, the export terminal does require equipment to load the liquid bulk on to the vessels.

The data used to compute the jetty is described in Table D.2. The costs of the mooring dolphins is based on (Lanphen, 2019), where it is assumed that a mooring dolphin requires a steel pole with concrete.

The number of mooring dolphins is calculated with the maximum length of the arriving vessels (see Appendix D). An L-shaped jetty with catwalk is applied of which the dimensions and price per m^2 are given in Table D.2, obtained from (Lanphen, 2019). Finally, the capacity of a jetty is calculated by looking at the pumping capacity of the ship based pumping systems on the vessels. It is assumed that the equipment at the export terminal loads with the same rate as the ship-based pumping systems, therefore the capacity of a jetty at the export terminal will be the same as that at the import terminal. For detailed calculations, see Appendix F.

	Import Terminal	**Export Terminal**	**Unit**
Loading Equipment investment	-	1,000,000	€/Jetty
Mooring Dolphins investment	250,000	250,000	€/Dolphin
Construction period	1	1	years
Lifespan	30	30	years
Jetty width x length	16 x 30	16 x 30	m x m
Jetty investment	2000	2000	€/m^2
Catwalk width x length	5 x 100	5 x 100	m x m
Catwalk investment	1000	1000	€/m^2

Table D.2: Data for the jetty

D.2.2 Pipeline Jetty to Terminal

From the jetty there will be a pipeline to the storage's that are situated at the terminal. At the export terminal this pipeline will bring the liquid bulk to the jetty to be loaded on to the vessels and at the import terminal this pipeline will bring the unloaded liquid bulk to the storage's. It is assumed that the same pipeline will suffice for all the carriers, so only one type of pipeline is considered. The pipeline of the jetty is designed in such a way that there is one dedicated pipeline per jetty, meaning that the jetty and the pipeline have the same capacity. The data used for this pipeline is shown in Table D.3 and obtained from (Lanphen, 2019).

	LH_2/NH_3/LOHC	**Unit**
Investment	13000	€/m
Construction period	3	years
Lifetime	26	years
Energy Consumption	100	kWh/ton

Table D.3: Data for the pipeline from jetty to terminal

D.2.3 Storage

At the export and import terminal, there are storage facilities that are suitable for the carriers. All storage's have a volume of 50000 m^3, however, the storage of LH_2 and NH_3 is much more difficult because these have to be cooled to -253°C and 196°C respectively, the associated costs will therefore be higher. The data for the storage's used in this model is presented in Table D.4, the values are based on the data found in (Lanphen, 2019), (Terwel & Kerkhoven, 2019), (IEA, 2019) and (Ishimoto et al., 2020). As with the End-Use Model, low, medium and high scenarios were created in order to make the price more reliable. At the export terminal and the import terminal an average dwell time of 30 days per year is assumed. At the end-user an average dwell time of 15 days per year is assumed because the product will be used faster at this location. Furthermore, for an LOHC extra storage is needed because the product also has to be brought back to its place of origin. For LH_2 a smaller dwell time is assumed because the boil-off of this product is higher (Reuß et al., 2017).

	LH_2	NH_3	MCH	DBT	Unit
Investment storage (low)	175	50	18	10	M€/unit
Investment storage (med)	250	55	28	15	M€/unit
Investment storage (high)	325	60	38	20	M€/unit
Lifespan	30	30	30	30	Years
Construction time	2	2	2	2	Years
Crew	1	1	1	1	#
Capacity	3550	34130	38500	52850	ton carrier
Energy use	610	100	10	1	kWh/ ton carrier
Losses	0.06	0.03	0	0	%/d

Table D.4: Data for the storage's

D.2.4 Conversion Plant

At the export terminal, conversion plants are present which convert the supplied CGH_2 into one of the carriers (NH_3, MCH, DBT or LH_2). In the case of LH_2, the H_2 is cooled down to -253 °C and no additional materials are needed. With NH_3 MCH and DBT however, additional materials are needed to make the carrier. NH_3 requires hydrogen and nitrogenm MCH requires hydrogen and toluene and DBT requires DBT and hydrogen. The price of these additional materials is presented in Section D.1.4. The data for the conversion plants is shown in Table D.5 and based on (Lanphen, 2019),(Terwel & Kerkhoven, 2019), (IEA, 2019), (Ishimoto et al., 2020) and (Reuß et al., 2017).

	LH_2	NH_3	MCH	DBT	Unit
Investment (low)	180	273	10	10	M€/unit
Investment (med)	300	362	25	18	M€/unit
Investment (high)	420	450	40	26	M€/unit
Lifespan	20	20	20	20	Years
Construction time	2	2	2	2	Years
Crew	3	3	3	3	#
Capacity	30	130	45	45	ton carrier / h
Energy use	6100	640	20	20	kWh/ ton carrier
Losses	0	1	1	1	%/d

Table D.5: Data for the conversion plants

D.2.5 Reconversion Plant

At the import terminal a reconversion plant can be present that converts the supplied carrier back to CGH_2. The data that is used for this element is shown in Appendix C, Section C.2.

D.3 Seaborne Transport

For the transport of the carriers by sea, several ships are included in the model. The LH_2 ships are still in the development phase, hence LNG ships that are already in use at the moment are considered for the transport of LH_2. However, the costs of an LH_2ship will be higher than an LNG ship because the LH_2has to be further cooled. For NH_3 the research looks at LPG vessels and for the LOHCs it looks at oil tankers. The ship values are taken from (Terwel & Kerkhoven, 2019), (Lanphen, 2019), (IEA, 2019) and (Ishimoto et al., 2020). As the transport in this model is related to large volumes and long distances, it is assumed that all the transport is done with the largest possible vessels. Therefore, this model includes only one ship for each carrier. As stated in Section D.1.1, it is assumed that the LH_2

and NH_3-ships use their carrier as their fuel, hence the losses for these ships is higher.

In addition, the ships are equipped with ship-based pumps. Ships with a capacity of less than 250000 tonnes can unload 10% of their carry mass per hour (Ligteringen & Velsink, 2012). Therefore, it is assumed in this report that each ship is equipped with ship-based pumps that have an unloading rate equal to 10% of their carry mass per hour (Lanphen, 2019). All values are shown in Table D.6.

	LH_2	**NH_3**	**MCH**	**DBT**	**Unit**
Investment ship (low)	219	64	78	78	M€/ship
Investment ship (med)	334	82	127	127	M€/ship
Investment ship (high)	450	100	175	175	M€/ship
Lifespan	20	20	20	20	Years
Construction time	2	2	2	2	Years
Crew	20	20	20	20	#
Capacity	266,000	82,200	260,000	260,000	m3
Capacity	18,886	56,110	200,000	275,000	ton carrier
Pump capacity	1888.6	5611	20,000	27,500	ton carrier / h
Ship weight	7261	19,128	37,432	37,432	ton
Average speed	13.5	13.5	13.5	13.5	knots
Mooring time	3	3	3	3	hours
LOA	300	230	300	300	kWh/ ton carrier
Losses	0.3	0.5	0	0	%/d

Table D.6: Data for the vessels

E | Calculations: The End-Use Model

This Appendix explains how the End-Use Model arrives at its final results. The End-Use Model computes the number of supply chain elements that are needed each year, based on a certain end-user demand. All elements in the supply chain are sized for H_2; the retrieval plant has a certain production capacity of tonnes H_2 per hour and the transport mode can transport a certain amount of H_2.

For all elements, the costs are calculated in order to arrive at a certain cost price. The end-use supply chain consists of two elements that are linked; the reconversion plant and the transport mode to the hinterland (see Chapter 2, Figure 2.2). In the paragraphs below, it is described how the model calculates the number of elements that are needed each year and how this is translated into costs.

The final cost price (€/kg H_2) over the model time frame is calculated with Formula E.1. Each year the number of plants that are online are multiplied with the total costs for one plant. After this the total number of transport modes that are online need to be multiplied with the total transport costs for one transport mode. These costs are added up over the model time frame and divided by the total throughput over the model time frame.

$$Costprice = \frac{\sum_{n=modelframe} (Total\ costs_{Plant} * \#Plants) + (Total\ costs_{Transport} * \#Transport)}{\sum_{n=modelframe} Throughput_{year}} \tag{E.1}$$

E.1 Reconversion Plant

An element of the end-use supply chain is the reconversion plant. The plant can be located at the import terminal, at the end-use location or it can be not present in the supply chain at all. The different possible locations of the plant affect the number of plants that are needed and the associated costs. Below it is described how the model calculates the number of plants needed and their costs for the different supply chain configurations.

E.1.1 Number of Plants

Each year, the number of retrieval plants needed is calculated by calculating the plant occupancy. The plant occupancy of a year is calculated with the demand of that year and the capacity of the plants that are already online in that year. If the plant occupancy becomes greater than 1 (which means that the demand is greater than the online capacity), new plants must be built until the occupancy becomes smaller than 1. The plant occupancy is therefore the trigger that determines when and if new retrieval plants must be built. If the plant occupancy is smaller than 1, there are enough retrieval plants to meet the demand. This plant occupancy calculation is given in Formula E.2.

$$Plant\ occupancy = Demand_{Plant\ Out} / \ Reconversion\ plant_{Capacity\ online} \tag{E.2}$$

The $Demand_{PlantOut}$ represents the amount of H_2 that must be produced by the plant to meet the demand. This demand differs for the different supply chain configurations, i.e. the place of the reconversion plant:

- **Centralized plant:** the $Demand_{PlantOut}$ equals the end-user demand plus the transport losses
- **Decentralized plant:** the $Demand_{PlantOut}$ equals the demand of the end-user

The transport losses are given as a loss of load of a certain percentage per day (%/d) (see Appendix C). In the model, this loss is calculated by first calculating how many days it takes the transportation mode to arrive at the end-user location. The number of days of a trip are calculated by looking at the distance that needs to be travelled and the average speed of the transport mode. With the number of days it takes to transport the cargo, the loss of load is calculated.

E.1.2 Costs of Plant

The total cost of a power plant is the sum of its capital (CAPEX) and operational (OPEX) costs. In addition, costs can also be deducted if the retrieval plant is located at the import terminal, as capacity that is not used can then be sold to other supply chains (SOLD), see Formula E.3. How all the costs are calculated is explained below.

$$Total\ costs_{Plant} = CAPEX + OPEX - SOLD \tag{E.3}$$

E.1.2.1 CAPEX

The capital costs of the reconversion plants are equal to the investment costs given in Appendix C. The timing of payment of these costs depends on the construction time of the element. The retrieval plant is constructed within two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40%.

E.1.2.2 OPEX

The total operational cost is the sum of the costs of insurance, maintenance, energy, labour and fuel (Formula E.4. How all costs are calculated is described below.

$$Plant_{OPEX} = Plant_{Insurance} + Plant_{Maintenance} + Plant_{Energy} + Plant_{Labour} + Plant_{fuel} \tag{E.4}$$

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula E.5). In this case, it is 1% of the capital costs (Lanphen, 2019).

$$Plant_{Insurance} = Ins_{\%} * CAPEX \tag{E.5}$$

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$) (Formula E.6). In this case, it is 1.5% of the capital costs (Lanphen, 2019).

$$Plant_{Maintenance} = Main_{\%} * CAPEX \tag{E.6}$$

Energy

The energy costs are the expenses for the energy that an element in the model needs to consume each year to function. The energy consumption (E_c) for the reconversion plant is given in Appendix C and given in kWh/ton H_2. The energy price (E_p) that is used for the calculations is also given in Appendix C and is equal to 0.09 €/kWh in the Netherlands. The total energy costs per year can be calculated with the annual capacity of a plant (ton H_2/year) and the plant occupancy that is online. The calculation for the energy costs is given in Formula E.7.

$$Plant_{Energy} = Plant_{Capacity} * Operational\ hours * Plant\ occupancy * E_c * E_p \tag{E.7}$$

Labour

Appendix C shows how many crew members are required per plant. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a plant and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas E.8 and E.9.

$$Crew_{year} = (\#crew * Operational\ hours)/(Shift\ length * Annual\ shifts) \tag{E.8}$$

$$Plant_{Labour} = Crew_{year} * Annual\ operational\ salary \tag{E.9}$$

Fuel

There are no fuel costs for the reconversion plant.

E.1.2.3 SOLD

When the plant is at the import terminal, the hydrogen produced in the reconversion plant and not used in the supply chain is sold to other supply chains. This income is calculated by looking at the percentage of each year's remaining capacity and the throughput of the plant. This remaining capacity is sold to other supply chains for a certain price. This price is equal to the cost price of one kg of hydrogen when only looking at costs of the plant, see Formula E.10.

$$Selling\ price = (Plant_{CAPEX} + Plant_{OPEX})/Plant_{Throughput} \tag{E.10}$$

E.2 Distribution Mode

In the End-Use Model, the carrier or the CGH_2 is transported to the hinterland with a certain transport mode. In the model, a choice can be made between trucks, trains, barges or pipelines. First, it is explained how the model calculates how many transport means are needed each year and then how the costs are calculated.

E.2.1 Number of Transport Modes

For the transport modes trucks, trains and barges, the number of required transport modalities is calculated in the same way as for the plants; with an occupation factor. If the transport occupancy factor is larger than 1, the online transport capacity is not enough to meet the demand. New transport modes need to be added until the transport occupancy is smaller than 1. The occupancy calculation is shown in Formula E.11.

$$Transport\ occupancy = Demand_{Transport\ In}/Transport_{Capacity\ online} \tag{E.11}$$

The $Demand_{TransportIn}$ is equal to the amount of H_2 as input of the transport mode which is needed to meet the demand of the end-user. Again, the $Demand_{TransportIn}$ depends on the specific supply chain configuration, i.e. the place of the reconversion plant:

- **Centralized plant:** the $Demand_{TransportIn}$ equals the demand of the end-user plus the transport losses.
- **Decentralized plant:** the $Demand_{TransportIn}$ equals the demand of the end-user plus the losses of the plant and the losses of the transport
- **No plant:** the $Demand_{TransportIn}$ equals the end-user demand plus the transport losses

The transport losses are given as a percentage per day (see Appendix C). This is calculated in the same way as described in Section E.1.1. The losses of the plant are given in Appendix C.

For the pipeline to the hinterland, it is assumed that one pipeline is constructed that can handle the maximum volume in the model life time. The size of the pipeline therefore depends on this assumed maximum volume, the calculation for the diameter of the pipeline can be found in C.

E.2.2 Costs of Transport Modes

The total cost of a transport mode is the sum of its capital (CAPEX) and operational (OPEX) costs. For transport, only dedicated transport for the supply chain is considered, which means that there is no additional income as in the case of the reconversion plant (Formula E.12).

$$Total\ costs_{Transport} = CAPEX + OPEX \tag{E.12}$$

E.2.2.1 CAPEX

The capital costs of the trucks, barges and trains are equal to the investment costs that can be found in Appendix C. The timing of payment of these costs depends on the construction time of the element. When the delivery time is one year, all costs are paid off in one year. If the delivery time is longer than 2 years, 40% of the costs are paid off in the year before the element comes online and 60% in the year before that.

The capital cost of the pipeline depends on the diameter and the distance, the Formula for this can be found in Appendix C. The delivery time of the pipeline is 3 years, so the costs will be paid off in the 2 years before the pipeline comes online, in the ratio 60/40.

E.2.2.2 OPEX

The total operational costs is the sum of the costs of insurance, maintenance, energy, labour and fuel (Formula E.13). How all costs are calculated is described below.

$$\begin{aligned} Transport_{OPEX} = Transport_{Insurance} + Transport_{Maintenance} + Transport_{Energy} + \\ Transport_{Labour} + Transport_{Fuel} \end{aligned} \tag{E.13}$$

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$)(Formula E.14). In this case, it is 1% of the capital costs (Lanphen, 2019).

$$Transport_{Insurance} = Ins_{\%} * CAPEX \tag{E.14}$$

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$)(Formula E.15). In this case, it is 1.5% of the capital costs (Lanphen, 2019).

$$Transport_{Maintenance} = Main_{\%} * CAPEX \tag{E.15}$$

Energy

The energy costs are the expenses for the energy than an element in the model needs to consume each year to function. For trucks, barges and trains, there is no energy consumption as these modes of transport run on fuels. For the pipeline however, energy is needed to ensure that the commodity in the pipeline remains at the right pressure over the distance. The energy needed to compress gaseous hydrogen (E_c) is equal to 0.2 kWh/kg H_2 and the energy price (E_p) is given in Appendix C (€/kWh). The energy costs can now be calculated with Formula E.16.

$$Transport_{energy} = E_c * Throughput\, pipe * 1000 * E_p \tag{E.16}$$

Fuel

In Appendix C the fuel consumption and fuel price for each transport mode is given, a pipeline does not require fuel. The fuel consumption for the trucks is given in €/km and the fuel price for the barges and trains depends on the weight. The fuel costs are thus calculated in two different ways.

Trucks

For the trucks it first needs to be calculated how much distance is travelled by a truck each year. This is calculated by looking at how many trips are made per year, so the duration of one trip needs to be calculated first.

and to know this, the duration of 1 trip needs to be calculated first. All calculations are shown in Formulas E.17, E.18 and E.19. An uncertainty factor of 1.5 is applied, which takes into account traffic jams, refuelling times, etc.

$$\begin{aligned} Trip\, duration = &((distance/average\, speed) * 2 \\ &+ (loading\, time + unloading\, time) * uncertainty\, factor \end{aligned} \tag{E.17}$$

With the duration of one trip, it can be calculated how many trips are made per year and how much distance is covered by these trips. With this travelled distance the annual fuel costs can be calculated (Formula E.19).

$$travelled\, distance = (operational\, hours/Trip\, duration) * distance * 2 \tag{E.18}$$

$$Transport_{fuel} = travelled\, distance * fuel\, price \tag{E.19}$$

Barge and Rail

For the barges and the trains, the annual consumed litres of fuel are considered to calculate the fuel costs. In order to calculate the number of litres consumed per year, it is necessary to know the weight of the transport mode. The weight of an unloaded and loaded transport mode is of course different, which is why a distinction is also made between them. In this way, the loaded and unloaded consumption is calculated in l/km. The loaded and unloaded consumption in l/km is calculated with the loaded and unloaded weight (W_{load}, W_{unload}) and the consumption in km/ton/l (C_u), given in Appendix C.

$$C_l = W/C_u \tag{E.20}$$

The unloaded weight (W_{unload}) is given in Appendix C and the loaded weight (W_{load}) is the unloaded weight plus the load of the full capacity of the transport mode. The capacity is given in ton H_2, however, one still has to calculate the weight of the full load by taking into account the hydrogen content of the carrier (H_{con}), this is given in Appendix B. Equation E.21 shows how the loaded weight is calculated.

$$W_{load} = (Transport_{Cap} * 100/H_{con}) + W_{unload} \tag{E.21}$$

It is now necessary to calculate how many km are driven unloaded and loaded. It is assumed that each outward journey the transport mode is loaded and each return journey the transport mode is empty. Only for a LOHC is it assumed that the outward and return journeys are both loaded, because the product must be brought back to its place of origin. The distance of the outward and return trips is calculated using the Formulas E.22 and E.23. This time a lower uncertainty factor (1.2) is applied, as there is less need to take traffic jams into account.

$$\begin{aligned} &Trip\,duration = ((distance/average\ speed) * 2 \\ &+ (loading\ time + unloading\ time) * uncertainty\ factor \end{aligned} \tag{E.22}$$

$$travelled\ distance = (operational\ hours/Trip\ duration) \tag{E.23}$$

With the distance travelled it is now possible to calculate how many litres per year are consumed when the transport mode is loaded and when it is unloaded, and thus the annual fuel costs (Formulas E.24 and E.25).

$$liter/year = travelled\ distance * fuel\ consumption \tag{E.24}$$

$$Transport_{fuel} = liter/year * fuel\ price \tag{E.25}$$

Labour

Appendix C shows how many crew members are required per transport mode. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a specific transport mode and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas E.26 and E.27.

$$Crew_{year} = (\#crew * operational\ hours)/(shift\ length * annual\ shifts) \tag{E.26}$$

$$Transport_{Labour} = Crew_{year} * Annual\ operational\ salary \tag{E.27}$$

F | Calculations: The Supply Chain Model

This Appendix explains how the Supply Chain Model arrives at its final results. The Supply Chain Model computes the number of supply chain elements that are needed each year, based on a certain end-user demand. It looks at all the elements at the export terminal, import terminal and end-use location and at the transport that is needed between these locations. All supply chain elements are discussed in Chapter 2. All elements in the supply chain are sized for the chosen carrier; the capacity of all the elements is taken in tonnes carrier.

For all the elements the costs (operational and capital) are calculated in order to arrive at a certain cost price. There are different elements available at each terminal, the seaborne transport is limited to vessels and for the transport to the hinterland one can choose between different transportation modes. Furthermore, it can be chosen if the reconversion plant is situated at the import terminal (centralized) or at the end-user location (decentralized). All the different supply chain configurations that are possible for the carriers LH_2, NH_3, MCH and DBT are shown in Table F.1.

	Export Terminal	**Transport 1**	**Import Terminal**	**Transport 2**	**End-use location**
Decentralized	- Conversion plant - Storage tanks - Jetty	- Transport mode: • Vessels	- Jetty - Storage tanks	- Transport mode: • Barge • Train • Truck • Pipe (NH3)	- Storage tanks - Reconversion plant
Centralized	- Conversion plant - Storage tanks - Jetty	- Transport mode: • Vessels	- Jetty - Storage tanks - Reconversion plant	- Transport mode: • Pipe (CGH_2)	

Table F.1: Possible supply chain configurations in the Supply Chain Model

The final cost price (€/kg H_2) over the model time frame is calculated with Formula F.1. In which CP is the eventual cost price in €/kg H_2, Total $costs_{ET}$ are the total costs of the export terminal, Total $costs_{T1}$ are the total costs of the transport between export and import terminal (transport 1), Total $costs_{IT}$ are the costs for the import terminal, Total $costs_{T2}$ are the costs that are associated with the transport to the end-user (transport 2) and Total $costs_{EU}$ are the costs of the end-user location. The costs of all the elements that are present in the supply chain are added up over the model time frame and divided by the total throughput over the model time frame (kg H_2).

$$CP = \frac{\sum\limits_{n=modelframe} Total\ costs_{ET} + Total\ costs_{T1} + Total\ costs_{IT} + Total\ costs_{T2} + Total\ costs_{EU}}{\sum\limits_{n=modelframe} Throughput_{year}} \tag{F.1}$$

In the paragraphs below, it is described how the model calculates the number of elements that are needed each year and how this is translated into costs. All the elements in the model are dimensioned according to the demand at the end-user. Therefore, the calculations are explained below in the order; the end-use location, the transport from the import terminal to the end-user (transport 2), the import terminal, the transport from the export terminal to the import terminal (transport 1) and the export terminal.

F.1 End-use Location

It can be observed from Table F.1 that there are only elements present at the end-use location in a decentralized model. In this supply chain configuration, reconversion plants and storage tanks are present at the end-use location. The demand that is needed as input of the transport depends on the end-use demand and the losses. this is shown below for both elements ($\text{Demand}_{Plant\,in}$, $\text{Demand}_{Storage\,in}$).

- **Decentralized:**
  - $\text{Demand}_{Plant\,in} = \text{Demand}_{End-user} + \text{Losses}_{Plant}$
  - $\text{Demand}_{Storage\,in} = \text{Demand}_{Plant\,in} + \text{Losses}_{Storage}$

F.1.1 Amount of Elements

How many elements are needed depends on the demand that is needed as input in an element to eventually meet the end-user demand, this is shown above for both elements ($\text{Demand}_{Plant\,in}$, $\text{Demand}_{Storage\,in}$). Ultimately, the trigger of that element will determine whether expansions are needed.

F.1.1.1 Reconversion Plant

The trigger of the reconversion plant is the plant occupancy. The plant occupancy is calculated with Formula F.2. If the plant occupancy becomes greater than 1 (which means that the demand is greater than the online capacity), new plants must be built until the occupancy becomes smaller than 1.

$$Plant\,Occupancy = Demand_{Plant\,in} / (Capacity\ Plants * Operational\ hours * number\ of\ plants\ online) \tag{F.2}$$

F.1.1.2 Storage Tank

The trigger of the storage tanks is the storage capacity that is needed for the given demand while taking into account the dwell time, referred to as $\text{Storage}_{Cap\,dwell}$. If the storage capacity is smaller than this capacity, storage tanks need to be added until the capacity is sufficient. The storage capacity that is needed is calculated with Formula F.3. Where the allowable dwell time is given in days per year (f.e. 30/365) and 1.1 is a storage buffer taken from (Terwel & Kerkhoven, 2019).

$$Storage_{Cap\,dwell} = (Demand_{Storage\,in} * allowable\ dwell\ time) * 1.1 \tag{F.3}$$

F.1.2 Cost of Elements

The total cost of an element is the sum of its capital (CAPEX) and operational (OPEX) costs, see Formula F.4. How all the costs are calculated for each element is explained below.

$$Total\ costs_{element} = CAPEX + OPEX \tag{F.4}$$

F.1.2.1 Retrieval Plant

The capital and operational costs related to a hydrogen retrieval plant are explained below.

<u>CAPEX</u>

The capital costs of the reconversion plants are equal to the investment costs given in Appendix C. The timing of payment of these costs depends on the construction time of the element. The retrieval plant is constructed within two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40%.

OPEX

The total operational cost is the sum of the costs of insurance, maintenance, energy, labour and fuel (Formula F.5). How all the costs are calculated is described below.

$$Element_{OPEX} = Element_{Ins} + Element_{Main} + Element_{Energy} + Element_{Labour} + Element_{Fuel} \quad (F.5)$$

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula F.6). In this case, it is 1% of the capital costs (Lanphen, 2019).

$$Element_{Insurance} = Ins_{\%} * CAPEX \quad (F.6)$$

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$) (Formula F.7). In this case, it is 1.5% of the capital costs (Lanphen, 2019).

$$Element_{Maintenance} = Main_{\%} * CAPEX \quad (F.7)$$

Energy

The energy costs are the expenses for the energy that an element in the model needs to consume each year to function. The energy consumption (E_c) for the reconversion plant is given in Appendix C and given in kWh/ton H_2. The energy price (E_p) that is used for the calculations is also given in Appendix C and is given in €/kWh. The total energy costs per year can be calculated with the annual capacity of a plant (ton H_2/year) and the plant occupancy that is online. The calculation for the energy costs is given in Formula F.8.

$$Plant_{Energy} = Plant_{Capacity} * Operational\ hours * Plant\ Occupancy * E_c * E_p \quad (F.8)$$

Labour

Appendix C shows how many crew members are required per plant. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a plant and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas F.9 and F.10.

$$Crew_{year} = (\#crew * Operational\ hours)/(Shift\ length * Annual\ shifts) \quad (F.9)$$

$$Element_{Labour} = Crew_{year} * Annual\ operational\ salary \quad (F.10)$$

Fuel

There are no fuel costs for the reconversion plant.

F.1.2.2 Storage Tank

The capital and operational costs related to a storage tank are explained below.

CAPEX

The capital costs of a storage tank are equal to the investment costs given in Appendix D. The timing of payment of these costs depends on the construction time of the element. A storage tank is constructed within two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40%.

OPEX

The total operational cost is the sum of the costs of insurance, maintenance, energy, labour and fuel (Formula F.5). How all costs are calculated is described below.

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula F.6). In this case, it is 1% of the capital costs (Lanphen, 2019).

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$) (Formula F.7). In this case, it is 1% of the capital costs (Lanphen, 2019).

Energy

The energy costs are the expenses for the energy that an element in the model needs to consume each year to function. The energy consumption (E_c) for a storage tank is given in Appendix C and given in kWh/ton carrier. The energy price (E_p) that is used for the calculations is given in the Appendix C in €/kWh. The total energy costs per year can be calculated with the yearly capacity of a storage tank (ton carrier) and the storage occupancy that is online (Formula F.11). The calculation for the energy costs is given in Formula F.12.

$$Storage\ Occupancy = Storage_{Cap\ dwell}/(Capacity\ Storage * Number\ of\ storages\ online) \tag{F.11}$$

$$Storage_{Energy} = Storage_{Capacity} * (\frac{365}{allowable\ dwelltime * 1.1}) * Storage\ Occupancy * E_c * E_p \tag{F.12}$$

Labour

Appendix C shows how many crew members are required per storage tank. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a storage tank and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas F.9 and F.10.

Fuel

There are no fuel costs for the storage tanks.

F.2 Transport to Hinterland

It can be observed from Table F.1 that for the distribution to the hinterland one can choose between different transportation modes. The demand that is needed as input of the transport depends on the end-use demand and the losses, which depends on if the reconversion plant is centralized or not. Below it is shown what the demand is that is needed as input for the transport for the different supply chain configurations.

- **Centralized:**:
  - $\text{Demand}_{Transport\,in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\,2}$
- **Decentralized**:
  - $\text{Demand}_{Transport\,in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{End-user}$

F.2.1 Amount of Elements

The calculations in the Supply Chain Model for the transport to the hinterland are done as described in Appendix E.

F.2.2 Cost of Elements

The calculations in the Supply Chain Model for the transport to the hinterland are done as described in Appendix E.

F.3 Import Terminal

It can be observed from Table F.1 that a jetty and storage tanks are always present at the import terminal and depending on if the supply chain configuration is centralized there are also reconversion plants present at the import terminal. The demand that is needed as input of the elements depends on the end-use demand and the losses. This is shown below for all the elements ($\text{Demand}_{Plant\,in}$, $\text{Demand}_{Storage\,in}$, $\text{Demand}_{Jetty\,in}$).

- **Centralized:**:
  - $\text{Demand}_{Plant\,in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{Plant}$
  - $\text{Demand}_{Storage\,in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{Plant} + \text{Losses}_{Storage}$
  - $\text{Demand}_{Jetty\,in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{Plant} + \text{Losses}_{Storage} + \text{Losses}_{Jetty}$
- **Decentralized**:
  - $\text{Demand}_{Storage\,in} = \text{Demand}_{End-user} + \text{Losses}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{Storage}$
  - $\text{Demand}_{Jetty\,in} = \text{Demand}_{End-user} + \text{Losses}_{End-user} + \text{Losses}_{Transport\,2} + \text{Losses}_{Storage} + \text{Losses}_{Plant}$

F.3.1 Amount of Elements

How many elements are needed depends on the demand that is needed as input in an element, this is shown above for all the elements ($\text{Demand}_{Plant\,in}$, $\text{Demand}_{Storage\,in}$, $\text{Demand}_{Jetty\,in}$). Ultimately, the trigger of that element will determine whether expansions are needed.

F.3.1.1 Jetty

The jetty consists of a jetty with a dedicated pipeline. A new jetty and pipeline are build when a new berth is needed. A new berth is needed when the waiting factor exceeds the allowable waiting service time ratio. The allowable waiting service time ratio is 0.3, taken from (Monfort et al., 2011). The waiting factor is calculated with the queuing theory denoted by the Kendall notation. The E2/E2/n queue is used because this is a realistic queue for a dedicated shipping line (Monfort et al., 2011). The waiting factor is a function of the planned berth occupancy ($bo_{planned}$), the chosen queuing theory and the number of berths, see Formula F.13.

$$WF(bo_{planned}, kendall\ theory, number\ of\ berths) \tag{F.13}$$

The planned berth occupancy ($bo_{planned}$) is calculated by looking at the total time that the vessels spends at the berth, the operational hours per year and the numbers of jetties that are planned (Formula F.14).

$$bo_{planned} = \frac{total\ time\ at\ berth_{planned}}{operational\ hours * number\ of\ jetty_{planned}} \tag{F.14}$$

The total time at the berth that is planned is calculated by looking at the vessel mix that arrives at the terminal. The vessel mix can consist of different vessels with different characteristics, denoted in the equations as $vessel_n$. The total time at the berth is calculated by multiplying the number of calls per year of a particular vessel with the time that that particular vessel spends at the berth, see Formula F.15.

$$total\ time\ at\ berth_{planned} = \sum_{n=vessels} (Calls\ planned\ vessel_n) * (Time\ at\ terminal\ vessel_n) \tag{F.15}$$

The time that a vessel spends at the terminal depends on how fast the loading/unloading and the mooring goes, see Formula F.16

$$Time\ at\ terminal\ vessel_n = (call\ size\ vessel_n / pump\ capacity\ vessel_n) + mooring\ time\ vessel_n \tag{F.16}$$

The number of calls per year that are planned for a certain vessel are calculated by dividing the volume that that vessels needs to transport that year with the call size of the vessel, see Formula F.17

$$Calls\ planned\ vessel_n = planned\ volume\ vessel_n / call\ size\ vessel_n \tag{F.17}$$

When the vessel mix is known, it is clear what percentage of the total volume that has to be transported each year is to be carried by a particular type of vessel. With this information, the eventual planned berth occupancy can be calculated in the case of 1 berth and thus 1 jetty. The waiting factor can now be determined with this berth occupancy. If this waiting factor for 1 berth and 1 jetty is greater than 0.3, a new berth occupancy and waiting factor need to be calculated for the case of 2 berths and 2 jetties. This process continues until the waiting factor is smaller than 0.3, at which point it is clear how many berths and jetties are needed.

F.3.1.2 Storage Tank

The trigger of a storage tank is described in Section F.1.1.2.

F.3.1.3 Reconversion Plant

The trigger of a reconversion plant is described in Section F.1.1.1.

F.3.2 Cost of Elements

The total cost of an element is the sum of its capital (CAPEX) and operational (OPEX) costs (Formula F.5). How all the costs are calculated is explained below.

F.3.2.1 Jetty

The capital and operational costs related to a jetty are explained below.

CAPEX

The capital costs of the jetty consists of the capital cost of the jetty and the capital cost of the pipeline that is at the jetty. The capital costs of the jetty are based on (Lanphen, 2019). The total capital costs for a jetty are the sum of costs needed for the catwalk, the jetty head and the dolphins. The costs of the catwalk and the jetty head are calculated by multiplying the area with the price per square metre, see Formulas F.18 and F.19 .

$$Jetty\ head_{CAPEX} = Jetty\ head_{Width} * Jetty\ head_{length} * Jetty\ head_{price} \tag{F.18}$$

$$Catwalk_{CAPEX} = Catwalk_{Width} * Catwalk_{length} * Catwalk_{price} \tag{F.19}$$

The cost of the dolphins depends on the number of the dolphins that are needed. The number of the dolphins that are needed depends on the length of the vessel, see Formula F.20 (Lanphen, 2019).

$$\begin{aligned} LOA &< 200m \rightarrow 6\ dolphins \\ LOA &> 200m \rightarrow 8\ dolphins \end{aligned} \tag{F.20}$$

Now the total capital costs for the jetty can be calculated with Formula F.21.

$$Jetty_{CAPEX} = Jetty\ head_{CAPEX} + Catwalk_{CAPEX} + (\#\ Dolphins * Dolphins_{price}) \tag{F.21}$$

The capital costs for the pipeline are calculated with Formula F.22.

$$Pipe_{CAPEX} = Pipe_{length} + Pipe_{Price} \tag{F.22}$$

The jetty is constructed in two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40% is paid. The jetty pipeline is constructed in one year, hence the capital costs for the pipeline are paid off in one year.

OPEX

The total operational cost is the sum of the cost of the insurance, maintenance, energy, labour and fuel for the jetty and the jetty pipeline. The jetty only has insurance and maintenance and the pipeline has insurance, maintenance, energy and labour, see Formula F.23.

$$Jetty_{OPEX} = Jetty_{Ins} + Pipe_{Ins} + Jetty_{Main} + Pipe_{Main} + Pipe_{Energy} + Pipe_{Labour} \tag{F.23}$$

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula F.6). In this case, it is 1% of the capital costs for both the Jetty and the jetty pipeline.

Maintenance

Each element in the model requires maintenance. The maintenance of that element is a certain percentage of the capital cost of that element ($Main_{\%}$) (Formula F.7). In this case, it is 1% of the capital costs for both the jetty and the jetty pipeline.

Energy

The pipeline that is present at the jetty needs energy to ensure that the liquid can be pumped towards its location. How much energy the pipe needs to do this is given in kWh/ton carrier. The annual cost of the required energy each year is thus calculated using the throughput that goes through the pipeline each year, the energy that the pipe uses per ton carrier (E_c) and the energy price in €/kWh (E_p), see Formula F.24.

$$Jetty\ Pipe_{Energy} = Jetty\ Pipe_{Throughput} * E_c * E_p \tag{F.24}$$

Labour

Appendix C shows how many crew members are required per jetty pipeline. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a jetty pipeline and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas F.9 and F.10.

F.3.2.2 Storage Tank

The costs for the storage are described in Section F.1.2.2.

F.3.2.3 Reconversion Plant

The costs for the retrieval plant are described in Section F.1.2.1.

F.4 Overseas Transport

It can be observed from Table F.1 that the transport between the export terminal and import terminal is limited to transport with vessels. The demand that is needed as input of the vessels depends on the end-use demand and the losses. $\text{Demand}_{Transport\ in}$ is the demand that needs to go into the vessel for different supply chain configurations.

- **Centralized:**
  - $\text{Demand}_{Transport\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2}$
- **Decentralized:**
  - $\text{Demand}_{Transport\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2} + \text{Losses}_{End-user}$

F.4.1 Amount of Elements

How many vessels are needed depends on the demand that is needed as input of the transport; $\text{Demand}_{Transport\ in}$. Ultimately the trigger of the transport will determine whether new transport modes are needed each year.

F.4.1.1 Vessels

The trigger of the vessel is the maximum yearly capacity of a vessel. This is calculated by looking at how many trips a vessel can make each year and what the capacity of a ship is (Formula F.25).

$$Vessel_{Yearly\ cap} = Vessel_{Cap} * Trips\ per\ year \tag{F.25}$$

The capacity of the ship is a constant and is given in Appendix D. How many trips a vessel can make each year depends on the distance, the time at berth and the sailing time (Formula F.26). The time at the berth is the (un)loading time plus the mooring time and the sailing time is the distance divided by the average speed of a vessel.

$$Trips\ per\ year = Operational\ hours/((time\ at\ berth + sailing\ time) * 2) \tag{F.26}$$

By dividing the volume that needs to be transported by the maximum yearly capacity of a vessel it is calculated how many vessels are needed each year.

F.4.2 Cost of Elements

The capital and operational costs related to a vessel are explained below.

CAPEX

The capital costs of a vessel are equal to the investment costs given in Appendix D. The timing of payment of these costs depends on the construction time of the element. A seaborne vessel is constructed within two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40%

OPEX

The total operational cost is the sum of the costs of insurance, maintenance, energy, labour and fuel (Formula F.5). How all the costs are calculated is described below.

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula F.6). In this case, it is 1% of the capital costs (Lanphen, 2019).

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$) (Formula F.7). In this case, it is 1.5% of the capital costs (Lanphen, 2019).

Energy

There are no energy costs for the vessels.

Labour

Appendix C shows how many crew members are required per vessel. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a vessel and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas F.9 and F.10.

Fuel

In Appendix D it is already explained that it is assumed in this report that LH_2-ships sail on the boil-off of the carried LH_2 and NH_3-ships sail on the carried NH_3. the fuel costs for these vessels are included in the boil off losses. The LOHC ships sail on oil with a low sulphur content. The total fuel costs per year are calculated by multiplying the average fuel consumption (F_c) in L/km by the distance in km and the fuel price in €/L (F_p), see Formula F.27.

$$Vessel_{fuel} = F_c * F_p * Travelled\,distance_{year} \tag{F.27}$$

The distance a ship can cover in one year depends on the distance between the export terminal and the import terminal, the time a ship spends at the terminal and the operational hours per year, see Formula F.28. The sailing time is calculated by dividing the distance with the average vessel speed.

$$Travelled\,distance_{year} = \frac{Operational\,hours}{((time\,at\,terminal + sailing\,time) * 2)} * Distance \tag{F.28}$$

The average fuel consumption (F_c) is the mean of the fuel consumption when the ship is loaded and the fuel consumption when the ship is unloaded. The calculations for the fuel consumption when loaded and unloaded is shown in Formulas F.29 and F.30.

$$F_{c,load} = \frac{1}{120,000} * displacement^{\frac{2}{3}} * av\,speed^3 \tag{F.29}$$

$$F_{c,unload} = \frac{1}{120,000} * (ship\,weight + call\,size)^{\frac{2}{3}} * av\,speed^3 \tag{F.30}$$

Where 1/120,000 is a factor for diesel machinery (Lanphen, 2019), the displacement of the vessel is calculated with Formula F.31 and the average speed is in knots.

$$displacement = call\,size + ship\,weight + (1 - \gamma) * DWT \tag{F.31}$$

F.5 Export Terminal

It can be observed from Table F.1 that a jetty, storage tanks and hydrogen conversion plants are always present at the export terminal. The demand that is needed as input of the elements depends on the end-use demand and the losses. this is shown below for all elements (Demand$_{Plant\,in}$, Demand$_{Storage\,in}$, Demand$_{Jetty\,in}$).

- **Centralized:**:
  - Demand$_{Jetty\,in}$ = Demand$_{End-user}$ + Losses$_{Transport\,1}$ + Losses$_{Import\,Terminal}$ + Losses$_{Transport\,2}$ + Losses$_{Jetty}$
  - Demand$_{Storage\,in}$ = Demand$_{End-user}$ + Losses$_{Transport\,1}$ + Losses$_{Import\,Terminal}$ + Losses$_{Transport\,2}$ + Losses$_{Jetty}$ + Losses$_{Storage}$

  - $\text{Demand}_{Plant\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2} + \text{Losses}_{Jetty} + \text{Losses}_{Storage} + \text{Losses}_{Plant}$

- **Decentralized**:
  - $\text{Demand}_{Jetty\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2} + \text{Losses}_{End-user} + \text{Losses}_{Jetty}$
  - $\text{Demand}_{Storage\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2} + \text{Losses}_{End-user} + \text{Losses}_{Jetty} + \text{Losses}_{Storage}$
  - $\text{Demand}_{Plant\ in} = \text{Demand}_{End-user} + \text{Losses}_{Transport\ 1} + \text{Losses}_{Import\ Terminal} + \text{Losses}_{Transport\ 2} + \text{Losses}_{End-user} + \text{Losses}_{Jetty} + \text{Losses}_{Storage} + \text{Losses}_{Plant}$

F.5.1 Amount of Elements

How many elements are needed depends on the demand that is needed as input in an element, this is shown above for all the elements ($\text{Demand}_{Plant\ in}$, $\text{Demand}_{Storage\ in}$, $\text{Demand}_{Jetty\ in}$). Ultimately, the trigger of that element will determine whether expansions are needed.

F.5.1.1 Jetty

The trigger of a jetty is described in Section F.3.1.1.

F.5.1.2 Storage Tank

The trigger of a storage tank is described in Section F.1.1.2

F.5.1.3 Conversion Plant

As with the hydrogen reconversion plant, the trigger for the hydrogen conversion plant is the plant occupancy. The plant occupancy is calculated with Formula F.32. If the plant occupancy becomes greater than 1 (which means that the demand is greater than the online capacity), new plants must be built until the occupancy becomes smaller than 1.

$$Plant\,Occupancy = Demand_{Plant\ in}/(Capacity\ Plants * Operational\ hours * number\ of\ plants\ online) \tag{F.32}$$

F.5.2 Cost of Elements

The total cost of an element is the sum of its capital (CAPEX) and operational (OPEX) costs. How all the costs are calculated is explained below.

F.5.2.1 Jetty

The costs for the jetty are described in Section F.3.2.1.

F.5.2.2 Storage Tank

The costs for the storage tank are described in Section F.1.2.2.

F.5.2.3 Conversion Plant

The capital and operational costs related to a hydrogen conversion plant are explained below.

CAPEX

The capital costs of a hydrogen conversion plant are equal to the investment costs given in Appendix D. The timing of payment of these costs depends on the construction time of the element. The conversion plant is constructed within two years, in these two years the capital costs are also being paid; in the first year 60% is paid and in the second year 40% is paid.

In addition, materials must be purchased to produce the hydrogen carriers. The purchased hydrogen and nitrogen are covered by the annual operating costs. However, the MCH and DBT are recycled and therefore this is partly included in the capital costs. First, the amount of material needed per plant must be calculated, this is done by looking at the hydrogen content of the carrier ($H_{content}$), see Formula F.33.

$$Mat_{ton} = (Plant_{Cap} * Operational\ hours * (100 - H_{content}))/100 \tag{F.33}$$

However, this is not correct for the LOHCs, as they are recycled. Therefore, the tonnage of material for the LOHCs is equal to the volume produced by filling all vessels one time. The capital costs for the materials are calculated with Formula F.34. Where R_r is the recycle rate of the material (%) and M_p is the price for which the material is bought (€/ton). The Formula also takes into account that at the end of the plant's life a certain percentage is sold again, and this is therefore deducted from the capital costs. S_r is the rate of the material that is sold (%) and S_p is the price for which the material is sold (€/ton).

$$CAPEX_{material} = (R_r * Mat_{ton} * M_p) - (S_r * Mat_{ton} * S_p) \tag{F.34}$$

OPEX

The total operational cost is the sum of the costs of insurance, maintenance, energy, labour and the fuel. Additionally, the conversion plant has operational costs that are dedicated to the yearly purchase of material. How all the costs are calculated is described below.

Insurance

Each element in the model requires insurance. The insurance of that element is a certain percentage of the capital cost of that element ($Ins_{\%}$) (Formula F.6). In this case, it is 1% of the capital costs (Lanphen, 2019).

Maintenance

Like insurance, each element requires maintenance. Again, it is assumed that the costs for this are equal to a certain percentage of the capital costs of that element ($Main_{\%}$) (Formula F.7). In this case, it is 1.5% of the capital costs (Lanphen, 2019).

Energy

The energy costs are the expenses for the energy that an element in the model needs to consume each year to function. The energy consumption (E_c) for the conversion plant is given in Appendix C and given in kWh/ton carrier. The energy price (E_p) that is used for the calculations is also given in Appendix C and is given in €/kWh. The total energy costs per year can be calculated with the annual production capacity of a plant (ton carrier/year) and the plant occupancy that is online. The calculation for the energy costs is given in Formula F.35.

$$Plant_{Energy} = Plant_{Capacity} * Operational\ hours * Plant\ Occupancy * E_c * E_p \tag{F.35}$$

Labour

Appendix C shows how many crew members are required per plant. To calculate the total costs for the labour each year, first, it is calculated how many people are needed each year for a plant and next the annual labour costs are calculated by taking a annual salary into account. A maximum shift length of 8 hours is assumed with 200 shifts per year and an annual operating salary of €46,000 on average. The calculations are shown in Formulas F.9 and F.10.

Fuel

There are no fuel costs for the conversion plant.

Purchased Material

As stated above, there are also costs for materials that have to be purchased every year. Firstly, hydrogen must be purchased for the production of each carrier. In addition, nitrogen has to be purchased for ammonia, toluene for MCH and DBT for perhydro-DBT.

The annual cost of the purchased hydrogen is calculated by looking at how many tonnes of hydrogen are needed each year per plant (H_{ton}, Formula F.36) and multiplying this by the hydrogen price (H_p), see Formula F.37.

$$H_{ton} = (Plant_{Cap} * Operational\ hours * H_{content})/100 \tag{F.36}$$

$$H_{purchased} = H_{ton} * H_p \tag{F.37}$$

The annual cost of the purchased material is calculated by considering how many tonnes of material is needed each year per plant (Mat_{ton}, Formula F.33) and multiplying this by the material price M_p. For DBT and MCH this also needs to be multiplied by the percentage of the material that is not recycled (100 - R_r), see Formula F.38.

$$Mat_{purchased} = Mat_{ton} * M_p * (100 - R_r) \tag{F.38}$$

G | Model Validation: The End-Use Model

In this Appendix the End-Use Model is validated. This is done by checking whether the outputs of the models also correspond to the expected results. The End-Use Model consists of a terminal investment module (OpenTISim) that has been modified to run for a reconversion plant linked to a transport mode to the hinterland.

The modified openTISim module is validated by checking whether the modelled results also correspond to hand calculations. In this validation, an example is used where the carrier is Ammonia, the transport to the hinterland is done by NH_3-barges and the plant is located at the end-user (decentralized). The model time frame is 10 years starting in 2020. The demand of the end-user equals 1 million tonnes H_2 in 2020 to 2024 and 2 million tonnes H_2 in 2025 to 2029. The end-user location is at a distance of 800 km from the import terminal and annual operational hours of 5840 hours/year is assumed. It is validated whether the model generates the right amount of elements online each year, the corresponding throughput and demand and the correct costs for the elements, see Figure G.1.

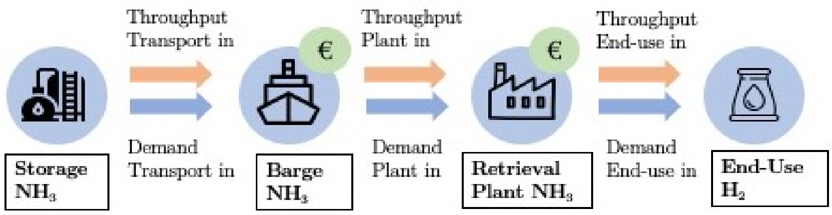

Figure G.1: The supply chain with ammonia barge transport and a reconversion plant at the end-use location

G.1 Number of Elements

The supply chain consists of barge transport of ammonia and reconversion plants at the end-user. To calculate the number of elements online each year, the capacity of one element and the associated losses must first be considered.

The capacity of a barge is given in Appendix C and is equal to 1208 tonnes H_2 per vessel. With a given distance (x) of 800 km, an average speed (v_{av}) of 13 km/h and the loading and unloading time (t_l, t_{ul}), the duration of one trip can be calculated. This also includes an uncertainty factor (u_f) that includes delay. See Appendix E, Formula E.22 for the full equation. The duration of one trip and the annual operating hours are now used to calculate the annual capacity of one ship (Formula G.1); in this example, a ship can transport 26,835 tonnes of H_2 to the hinterland per year.

$$Barge_{yearcap} = (Annual\ operational\ hours/\ Trip\ duration) * Barge_{cap} \tag{G.1}$$

The loss of the load in a barge is given as a specific percentage of the load per day (0.08 %/d). To calculate the annual loss, one has to look at how many days a ship travels when loaded. With a distance of 800 km and an average speed of 13 km/h, a ship sails in approximately 3 days to the end-use location. With a loss of load of 0.08 %/day, the transport losses per year are equal to 0.24% of the total transported load.

The capacity of an ammonia H_2 retrieval plant is equal to 39 tonnes H_2 /hour. With 5840 operational hour/year, this gives an annual capacity of 227,760 tonnes H_2/year. The loss of an ammonia H_2 retrieval plant is 1%.

Using the losses, it is now possible to calculate the demand with which the amount of barges and power plants should be calculated. The number of barges is calculated with $Demand_{TransportIn}$ and the number of plants with $Demand_{PlantIn}$. These are calculated with the demand at the end-user (which is given) and the corresponding losses.

For an end-user demand of 1,000,000 tonnes H_2:

- $Demand_{TransportIn}$ equals 1,012,424 tonnes H_2
- $Demand_{PlantIn}$ equals 1,010,000 tonnes H_2
- 38 barges and 5 retrieval plants are needed to meet this end-user demand

For an end-user demand of 2,000,000 tonnes H_2:

- $Demand_{TransportIn}$ equals 2,024,848 tonnes H_2
- $Demand_{PlantIn}$ equals 2,020,000 tonnes H_2
- 76 barges and 9 retrieval plants are needed to meet this demand

The construction time of a barge is 1 year and the construction time of a plant is 2 years. Figures G.3 and G.2 show the results of the model. It can thus be concluded that the amount of elements and when they are online are therefore modelled correctly.

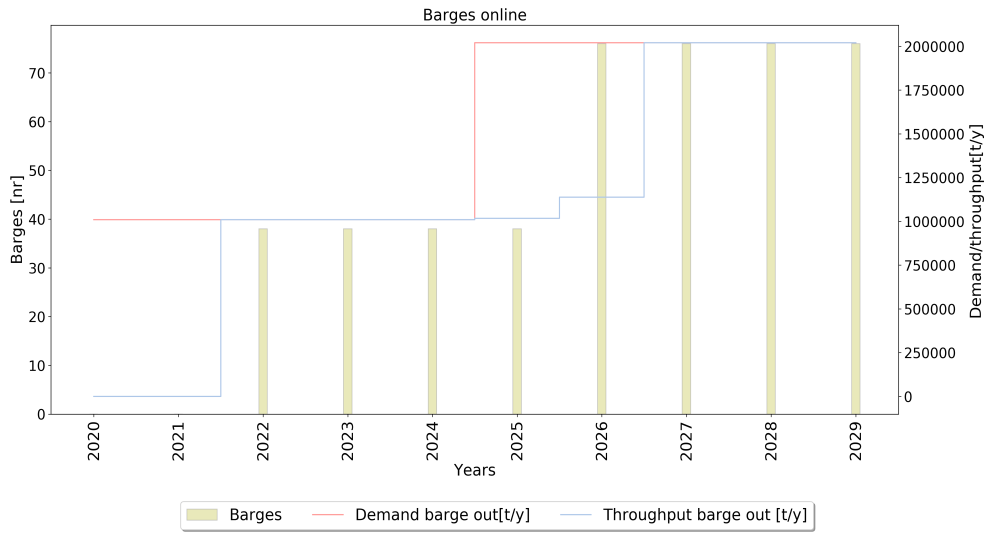

Figure G.2: The amount of barges over the years, with the throughput and the demand

G.2 Throughput and Demand

The online throughput at the end-user is equal to the minimum of the demand, the online capacity of the plants and the online capacity of the barges (Formula G.2).

$$Online\,Throughput\ =\ min(Demand,\ capacity\,plants\,online,\ capacity\,barges\,online) \tag{G.2}$$

In 2022 until 2024, the demand at the end-user is equal to 1,000,000 tonnes H_2. There are 5 power plants online that have a combined capacity (with taking account for the losses) of 1,127,412 tonnes H_2.

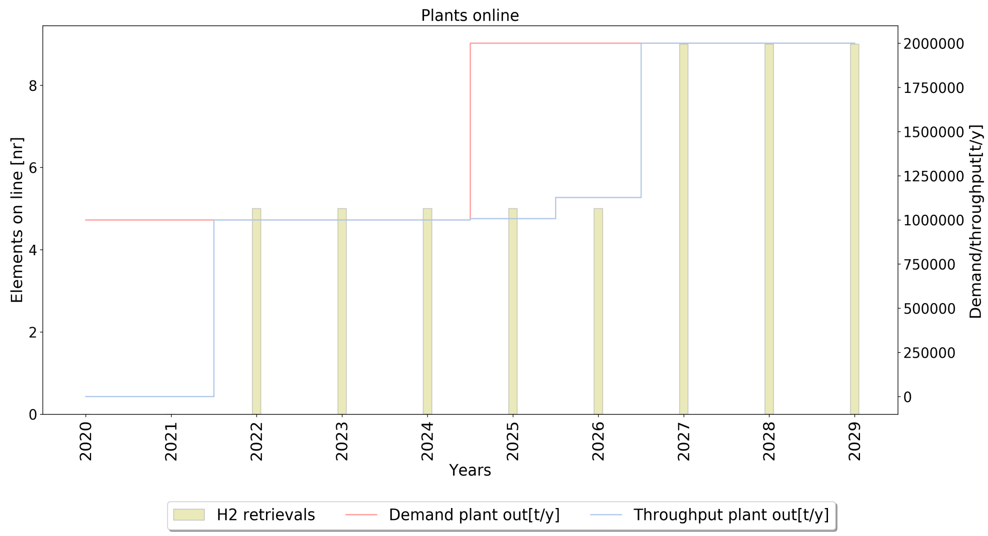

Figure G.3: The amount of plants over the years, with the throughput and the demand

There are 38 barges online with a combined capacity (with taking account for the losses) of 1,007,085 tonnes H_2. Hence, in 2022 through 2024 the online throughput is 1,000,000 tonnes H_2.

In 2025 the Demand becomes 2,000,000 ton H_2, however there are still only 38 barges and 5 plants online. In this year the minimum is thus 1,007,085 ton H_2, so this is the throughput in 2025. In 2026, there are 76 barges but still only 5 plants. 76 barges have a combined capacity (with taking account for the losses) of 2,014,170 tonnes H_2. In 2026, the minimum is therefore the capacity of the power plants and the online throughput is therefore 1,127,412 tonnes H_2.

In the years 2027 to 2029, there are 76 barges and 9 plants online and a end-user demand of 2,000,000 tonnes H_2. The plants together have a capacity (with taking account for the losses) of 2,029,342 tonnes H_2. In these years the minimum and the online throughput is thus equal to 2,000,000 tonnes H_2.

Figures G.3 and G.2 show that the throughput is indeed modelled correctly. The throughput in 2022 to 2024 is 2,000,000 tonnes H_2, in 2025 it is 1,007,088 tonnes H_2, in 2026 it is 1,127,412 and in 2027 to 2029 it is 2,000,000 tonnes H_2.

G.3 Costs

It is now necessary to validate the costs. This is done by firstly examining the costs of the plants, then the costs of the barges, and finally the combined costs.

G.3.1 Costs Plant

All the values and calculations that are used in this example can be found in Appendix C and E. The capital cost of the ammonia reconversion plant is equal to 225 M€ per plant with an additional 200,000 € in mobilisation costs. 60% of this is paid off in the first year of construction and 40% in the second year of construction. In 2022, 5 plants will be built, so 675.6 M€ has to be paid off in 2020 and 450.4 M€ in 2021. In 2027, 4 new plants are added; thus, 540.48 M€ has to be paid in 2025 and 360.32 M€ in 2026.

The operational costs of the plant are the sum of the costs for insurance, maintenance, energy, labour and fuel. The insurance is 1% of the capital costs and the maintenance is 1.5%. This is therefore respectively equal to 2.25 M€ and 3.375 M€ per plant per year. Hence for five plants the insurance and maintenance costs are equal to 11.25 M€ and 16.875 M€ and for nine plants 20.25 M€ and 30.375 M€. There are no fuel costs for the power station.

The energy costs are calculated using the plant capacity, the operational hours/year, the plant occupancy, the energy consumption and the energy price. The capacity of one plant is 227,760 tonnes H_2/year. The energy consumption of an ammonia plant is 5889 kWh/ton H_2 and the energy price is 0.09 €/kWh. In Table G.1 the total energy costs are calculated for each year.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Plants (#)	0	0	5	5	5	5	5	9	9	9
Capacity ($*10^6 \| ton\ H_2$)	0	0	1.139	1.139	1.139	1.139	1.139	2.050	2.050	2.050
Throughput ($*10^6\ ton\ H_2$)	0	0	1.000	1.000	1.000	1.007	1.127	2.000	2.000	2.000
Plant occupancy (-)	0	0	0.878	0.878	0.878	0.884	0.990	0.976	0.976	0.976
Energy cost /plant ($*10^8$€)	0	0	1.059	1.059	1.059	1.067	1.195	1.178	1.178	1.178
Enery cost total ($*10^8$€)	0	0	5.30	5.30	5.30	5.34	5.97	10.60	10.60	10.60

Table G.1: Calculation of the energy costs

Three persons are needed to keep a retrieval plant running. It is assumed that a single person can work a maximum of 200 shifts of 8 hours per year. For 5840 operational hours, 11 persons are needed each year with an annual salary of 46,000€. For five plants, this is therefore equal to 2.53 M€ and for nine plants it is 4.56 M€.

Figure G.4 shows the costs of the power plants for all years that are produced by the model. The costs obtained from the model correspond to the calculated costs above. It can therefore be concluded that the model calculates the costs for the power plants correctly.

	year	capex	maintenance	insurance	energy	labour	fuel
0	2020	675600000.0	0.0	0.0	0.000000e+00	0.0	0
1	2021	450400000.0	0.0	0.0	0.000000e+00	0.0	0
2	2022	0.0	16875000.0	11250000.0	5.300100e+08	2530000.0	0
3	2023	0.0	16875000.0	11250000.0	5.300100e+08	2530000.0	0
4	2024	0.0	16875000.0	11250000.0	5.300100e+08	2530000.0	0
5	2025	540480000.0	16875000.0	11250000.0	5.337667e+08	2530000.0	0
6	2026	360320000.0	16875000.0	11250000.0	5.975396e+08	2530000.0	0
7	2027	0.0	30375000.0	20250000.0	1.060020e+09	4554000.0	0
8	2028	0.0	30375000.0	20250000.0	1.060020e+09	4554000.0	0
9	2029	0.0	30375000.0	20250000.0	1.060020e+09	4554000.0	0

Figure G.4: Table with the costs of the plants resulting from the model

G.3.2 Costs Transport

The capital cost of an ammonia barge equals 20 M€, there are 38 barges in 2022 until 2025 which equals to 760 M€. The delivery time of a barge is one year, so the 760 M€ is paid in full in 2021. In 2026, 38 more barges will be added, so 760 M€ will again be paid off in 2025.

The operational costs of the barges are the sum of the costs for insurance, maintenance, energy, labour and fuel. The insurance is 1% of the capital costs and the maintenance is 1.5%. In 2022 to 2025 this will be 7.6 M€ and 11.4 M€ respectively. And in 2026 to 2029 it will be 15.2 M€ and 22.8 M€ respectively. There are no energy costs for the barges.

Two persons are needed to operate a ammonia barge. It is assumed that a single person can work a maximum of 200 shifts of 8 hours per year. So for 5840 operational hours per year, 8 people are needed, which all have an annual salary of 46,000€. For 38 ships this is equal to 13,984 M€ per year and for 76 ships this is equal to 27,968 M€ per year.

The ammonia barge runs on diesel, the barge consumes 1 litre to transport 1 tonne over 275 km. The weight of an unloaded ammonia barge is 4400 tonnes and the weight of a fully loaded ammonia barge equals 11244 tonnes. When the barge is unloaded the fuel consumption will be equal to 16 l/km and when loaded it is equal to 41 l/km. The duration of a trip is approximately 263 hours, hence in a year with 5840 operational hours 23 trips are made. This equals a distance of 17770 km and results in a consumption of approximately 1 million litres of diesel per year. For 38 boats and a diesel price of 0.66 €/litre, this equals 25.4 M€ and for 76 boats it equals approximately 50.8 M€ per year.

Figure G.5 shows the costs of the barges for all years that are produced by the model. the costs obtained from the model correspond the the calculated costs above. It can therefore be concluded that the model calculates the costs for the barges correctly.

	year	capex	maintenance	insurance	energy	labour	fuel
0	2020	0.0	0.0	0.0	0	0.0	0.000000e+00
1	2021	760000000.0	0.0	0.0	0	0.0	0.000000e+00
2	2022	0.0	11400000.0	7600000.0	0	13984000.0	2.535554e+07
3	2023	0.0	11400000.0	7600000.0	0	13984000.0	2.535554e+07
4	2024	0.0	11400000.0	7600000.0	0	13984000.0	2.535554e+07
5	2025	760000000.0	11400000.0	7600000.0	0	13984000.0	2.535554e+07
6	2026	0.0	22800000.0	15200000.0	0	27968000.0	5.071109e+07
7	2027	0.0	22800000.0	15200000.0	0	27968000.0	5.071109e+07
8	2028	0.0	22800000.0	15200000.0	0	27968000.0	5.071109e+07
9	2029	0.0	22800000.0	15200000.0	0	27968000.0	5.071109e+07

Figure G.5: Table with the costs of the barges resulting from the model

G.3.3 Combined Costs

The total costs calculated above are presented in Table G.2. The total costs resulting from the model are presented in the cash flow Figure G.6. By comparing this figure with the results from Table G.2, it can be concluded that the model is also correct for the combined costs.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
CAPEX plant (M€)	675.6	450.4	0	0	0	540.5	360.3	0	0	0
OPEX plant (M€)	0	0	560.7	560.7	560.7	563.7	627.7	1115.2	1115.2	1115.2
CAPEX barge (M€)	0	760	0	0	0	760	0	0	0	0
OPEX barge (M€)	0	0	64.4	64.4	64.4	64.4	116.8	116.8	116.8	116.8
CAPEX total (M€)	**675.6**	**1210.4**	**0**	**0**	**0**	**1300.5**	**360.3**	**0**	**0**	**0**
OPEX total (M€)	**0**	**0**	**625.1**	**625.1**	**625.1**	**628.1**	**744.5**	**1232**	**1232**	**1232**

Table G.2: Total costs for the plants and barges

Figure G.6: The CAPEX and OPEX cashflows of the plants and barges combined for each year

H | Model Validation: The Supply Chain Model

In this Appendix the Supply Chain Model is validated. This is done by checking whether the outputs of the models also correspond to the expected results. The Supply Chain Model consists of terminal investment modules (OpenTISim) for the export terminal, the import terminal and the end-use location. The transport between these terminals is simulated with openCLSim.

The Supply Chain Model module is validated by checking whether the modelled results also correspond to hand calculations. In this validation, an example is used where the carrier is Liquid Hydrogen (LH_2), the transport between the export terminal and import terminal is done with LH_2-sea going vessels. The H_2 retrieval plant is located at the end-user (decentralized) and the transport to the hinterland is done by LH_2-barges. The model time frame is 10 years starting in 2020. The demand of the end-user equals 2 million tonnes H_2 over the entire modelled time frame. The distance between the export terminal and import terminal is 10,000 km and the distance between the import terminal and the end-user location is 500 km. Annual operational hours of 5840 hours/year are assumed. It is validated whether the model generates the right amount of elements online each year, the corresponding throughput and demand and the correct costs for the elements, see Figure H.1.

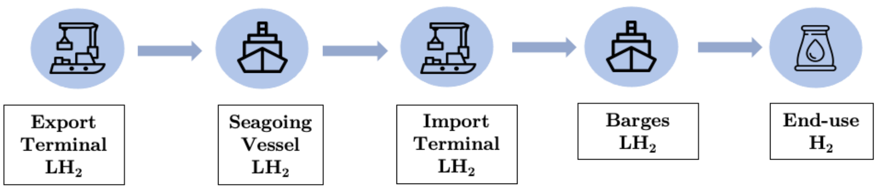

Figure H.1: The supply chain that is validated in this Appendix

H.1 Number of Elements

Whether the model correctly calculates the number of elements is checked by looking at the number of elements at the export terminal, the import terminal and the end-user location and also the elements needed for the transport between these terminals, denoted with transport supply chain 1 (sea going vessels) and transport supply chain 2 (barges).

H.1.1 End-user Location

The demand at the end-user location is given and is equal to 2,000,000 ton H_2. The hydrogen content of LH_2 is 100%, hence the demand is equal to 2,000,000 ton LH_2. The H_2 retrieval plant has zero losses. The storage's at the end-user location have a dwell time of 15 days and a loss of 0.06 %/day, this equals an average loss of 0.9%.

- $Demand_{PlantIn}$ = 2,000,000 ton LH_2. For this demand, 3 plants should be in operation.
- $Demand_{StorageIn}$ = 2,018,000 ton LH_2. Taken into account the dwell time of 15 days, 26 storage's should be included.

Figure H.2 shows the computation of the model for the elements present at the end-use location. The number of elements modelled corresponds to the number of elements calculated by hand above.

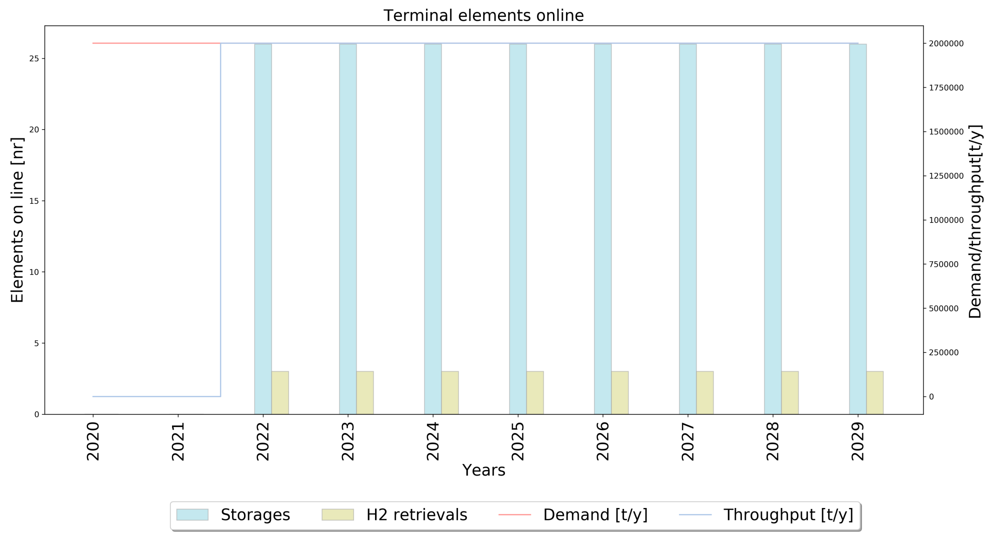

Figure H.2: The number of elements at the end-use location over the years, with the throughput and the demand

H.1.2 Transport to Hinterland

During transport, there is also loss of cargo. The capacity of 1 barge is 710 tonnes LH_2. The distance is 500 km and the average speed is 13 km/h. It is assumed that a barge takes approximately 48 hours to load and unload. With this it can be calculated that a boat takes about 2 days. The loss of a barge is equal to 0.3 %/d so the total loss of cargo is about 0.6%. The demand that must therefore be loaded into the barges is equal to the demand that must be stored by the end-user with these losses included.

- $\text{Demand}_{BargeIn}$ = 2,030,000 ton LH_2. For this demand, 57 barges should be in operation each year.

Figure H.3 shows the computation of the model for the elements present at transport between the end-use location and the import terminal. The number of elements modelled corresponds to the number of elements calculated by hand above.

H.1.3 Import Terminal

The import terminal consists of a jetty with a pipeline on the jetty and storages. The demand that needs to go into the storages is equal to the demand that goes into the barges with the losses of storage. The dwell time at the import terminal is equal to 30 days, hence the average loss is equal to 1.8%. There are no losses over the jetty.

- $\text{Demand}_{StorageIn}$ = 2,066,000 ton LH_2. For this demand, 53 storages should be built.
- $\text{Demand}_{JettyIn}$ = 2,066,000 ton LH_2. For this demand, 1 Jetty and 1 pipeline should suffice.

The number of jetties (and pipelines) depends on the number of berths. How many berths are needed depends on the waiting factor, this waiting factor cannot exceed 0.3. With a LH_2-ship between the export and import terminal with a capacity of 18886 tonnes LH_2 the waiting factor with 1 berth is equal to 0.09. 1 berth and therefore 1 jetty will be enough. It is assumed that there is one dedicated pipeline present on the jetty, hence one pipeline is also suffcient.

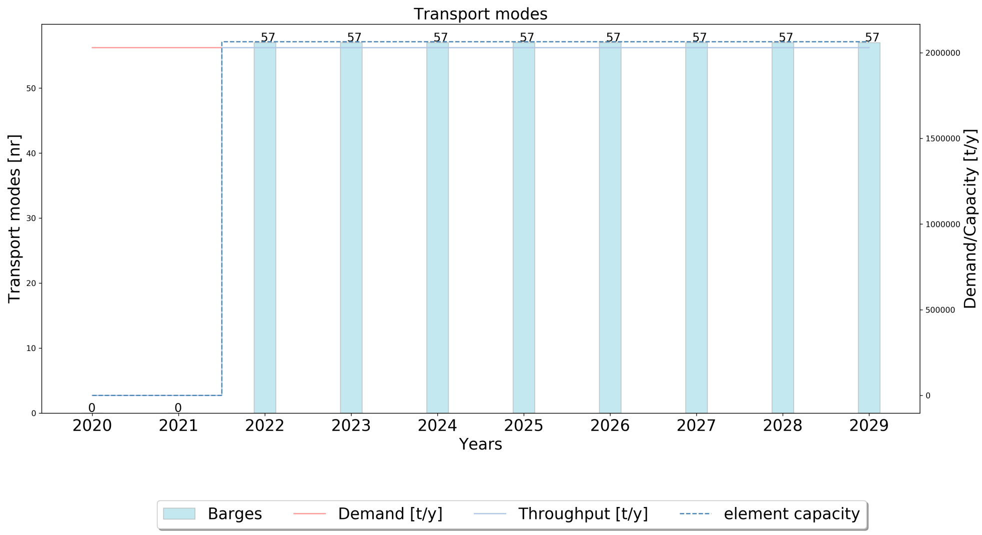

Figure H.3: The number of vessels between the import terminal and the end-use location over the years, with the throughput, capacity and the demand

Figure H.4 shows the computation of the model for the elements present at the import terminal. The number of elements modelled corresponds to the number of elements calculated by hand above.

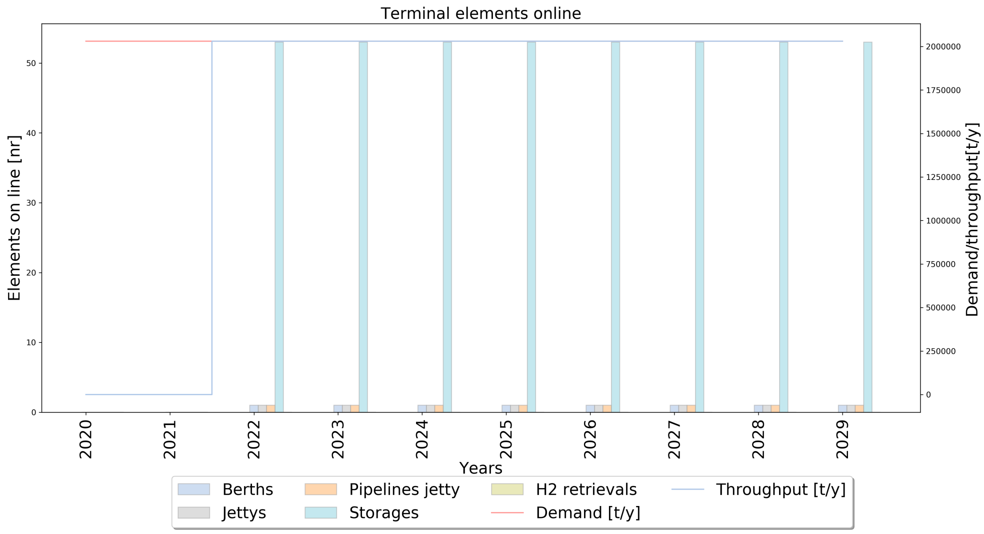

Figure H.4: The number of elements at the import terminal over the years, with the throughput and the demand

H.1.4 Overseas Transport

The capacity of a sea going vessel for LH_2 is equal to 18886 ton LH_2. Because of boil-off (and because this is used as the fuel) there will be a loss of cargo. The distance between the export terminal and import terminal is 10,000 km. With an average speed of 25 km/h, the duration of one trip will be 16.7 days. The loss of the vessel is equal to 0.3%/day, hence the loss of load will be equal to 5%.

- $\text{Demand}_{VesselIn}$ = 2,166,000 ton LH_2. For this demand, 11 vessels should be in operation each year.

Figure H.5 shows the computation of the model for the elements present at the transport between the export terminal and import terminal. The number of elements modelled corresponds to the number of elements calculated by hand above.

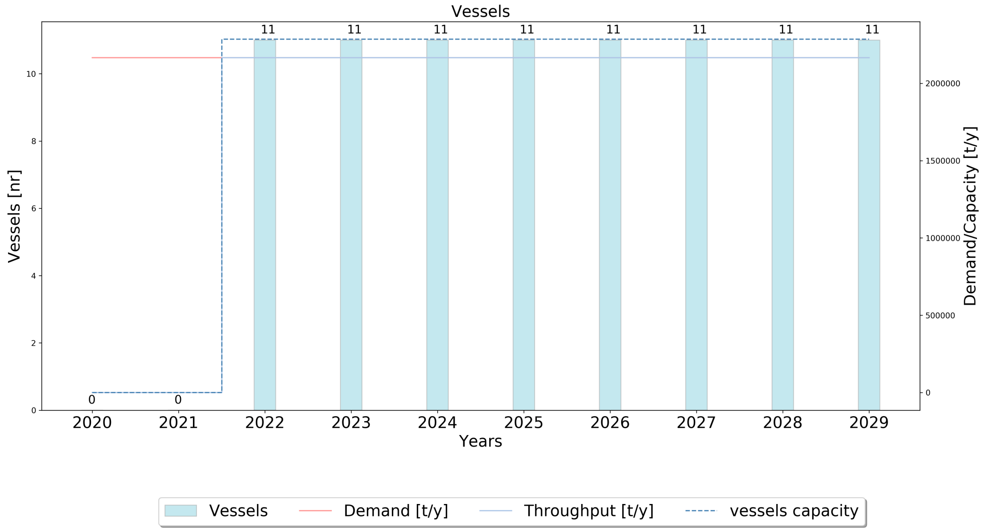

Figure H.5: The number of vessels between the export terminal and import terminal over the years, with the throughput, capacity and the demand

H.1.5 Export Terminal

The export terminal consists of a jetty with a pipeline, storages and conversion plants. There is only a loss present at the storages. The dwell time at the storages is again 30 days, hence the average loss will be 1.8%. Again one jetty and one pipeline are sufficient, because only one berth is needed.

- $Demand_{JettyIn}$ = 2,166,000 ton LH_2. For this demand, 1 jetty and 1 pipeline are sufficient.
- $Demand_{StorageIn}$ = 2,202,000 ton LH_2. For this demand, 57 storages should be built.
- $Demand_{PlantIn}$ = 2,202,000 ton LH_2. For this demand, 13 plants should suffice.

Figure H.6 shows the computation of the model for the elements present at the export terminal. The number of elements modelled corresponds to the number of elements calculated by hand above.

H.2 Throughput and Demand

The demand and the throughput are checked for the export terminal, import terminal and end-user location and for the transport between these terminals, denoted with transport 2 (sea going vessels) and transport 1 (barges). The throughput is equal to the minimum capacity or the demand, see Formula H.1. Table H.1 shows the capacity of all the elements that are online, the demand and the eventual throughput. As can be seen in Figures H.2 , H.3,H.4, H.5 and H.6 , the throughput and demand in the model are the same as the ones calculated here.

$$Throughput = min(Demand, Capacity\ Elements) \tag{H.1}$$

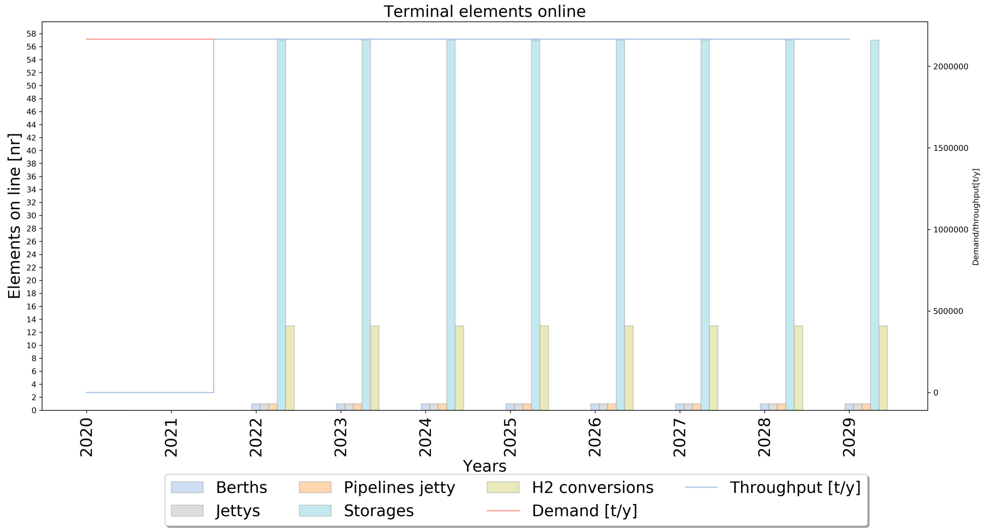

Figure H.6: The number of elements at the export terminal over the years, with the throughput and the demand

	End-user		**Transport 2**		**Import Terminal**		**Transport 1**		**Export Terminal**	
	element	ton LH_2	element	ton LH_2	element	ton LH_2	element	ton LH_2	element	ton LH_2
Capacity	Plant Storage	2,400,240 2,041,788	Barge	2,063,970	Jetty Storage	17,070,904 2,081,053	Vessel	2,285,206	Jetty Storage Plant	17,070,904 2,238,114 2,277,600
Demand		2,000,000		2,030,000		2,030,000		2,166,000		2,166,000
Throughput	2,000,000		2,030,000		2,030,000		2,166,000		2,166,000	

Table H.1: The capacity, demand and throughput

H.3 Costs

Now it still has to be checked whether the costs are calculated correctly. Again, this is done for the export terminal, import terminal and end-user location and for the transport between these terminals, denoted with transport supply chain 1 (sea going vessels) and transport supply chain 2 (barges). The costs are split between the capital costs (CAPEX) and the operational costs (OPEX). Finally, it is checked whether the modelled costs correspond to the hand calculations.

H.3.1 End-use Location

There are 26 storage tanks and 3 reconversion plants at the end-use location. The capital costs and operating costs are briefly explained below.

The capital cost of the plant is 59 M€ per plant with €200,000 for the mobilisation of the plant. For three plants this equals 177.6 M€. A storage tank for LH_2 has a cost of 350 M€ with a mobilisation cost of €100,000. For 26 storage tanks this equals 9102.6 M€. The storage tanks and the power plants both have a construction time of 2 years. Consequently, 60% will be paid off in the first year of construction and 40% in the second year. The capital cost in 2020 is therefore equivalent to 5568.12 M€ and in 2021 3712.08 M€.

The operational costs consist of maintenance, insurance, labour and energy use. The plant's maintenance is 1.5% of the capital costs and for the storage it is 1%. This is equal to 93,655 M€ per year. The insurance for the power station and the storage is equal to 1% of the capital costs, this is an annual amount of 92.77 M€. Each storage facility always needs one operator, while three operators are needed to operate the plant. With 8 hours per shift, 200 shifts per year and an annual salary of 46,000 euros, this comes to 5.88 M€ per year.

A storage tank uses 610 kWh/ton of LH_2 and a retrieval plant uses 600 kWh/ton. With the throughput and an energy price of 0.09 €/kWh, this results in energy costs of 130.2 M€ for 26 tanks and 107.97 M€ for 3 plants. Altogether, this makes for an annual energy cost of 238.21 M€.

Figure H.7 shows a Table with the costs that are calculated with the model, hence the model calculates the cost correctly.

	year	capex	maintenance	insurance	energy	labour
0	2020	5.568120e+09	0.0	0.0	0.000000e+00	0.0
1	2021	3.712080e+09	0.0	0.0	0.000000e+00	0.0
2	2022	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
3	2023	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
4	2024	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
5	2025	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
6	2026	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
7	2027	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
8	2028	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0
9	2029	0.000000e+00	93655000.0	92770000.0	2.382141e+08	5876500.0

Figure H.7: Table with the costs of the elements at end-use location resulting from the model

H.3.2 Overseas Transport

For the transport from the import terminal to the end-user, 57 barges are needed. The capital cost of one barges is equal to 40 M€, for 57 barges this is 2280 M€. The construction time for a barge is one year, so it will all be paid off in one year.

The operational costs of a barge consist of maintenance, insurance, labour and fuel. The maintenance of the barge is 1.5% of the capital costs, which equals 34.2 M€ per year. The insurance is equal to 1.5% of the capital costs, i.e. 22.8 M€ per year. Two employees are needed per barge, resulting in labour costs of 19.14 M€ per year.

An LH_2-barge uses boil-off gas as fuel when the boat is loaded, and diesel when the boat is unloaded. With a vessel weight of 1500 tons and a fuel consumption of 275 km/l/ton the final fuel consumption is 5.45 l/km. The distance between the import terminal and the end-use location is 500 km. With an average speed of 13 km/h, this means a barge can cover 25,500 km per year. On average, a barge therefore uses 138,975 l/year which, with a fuel price of 0.66 €/l, results in an annual amount of 5.238 M€.

Figure H.8 shows a Table with the costs that are calculated with the model, hence the model calculates the cost correctly.

H.3.3 Import Terminal

There are 54 storage tanks and a jetty with a pipeline at the Import Terminal. The capital costs and operational costs are briefly explained below.

The capital cost of the jetty consists of the cost of the dolphins, jetty and catwalk, together amounting to 2.96 M€. No equipment is required at the import terminal. The capital cost of the pipeline is calculated with the values from Table D.3. With a mobilisation expenditure of 30,000 euros this equals

	year	capex	maintenance	insurance	fuel	labour
0	2020	0.000000e+00	0.0	0.0	0.000000e+00	0.0
1	2021	2.280000e+09	0.0	0.0	0.000000e+00	0.0
2	2022	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
3	2023	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
4	2024	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
5	2025	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
6	2026	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
7	2027	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
8	2028	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0
9	2029	0.000000e+00	34200000.0	22800000.0	5.238259e+06	19140600.0

Figure H.8: Table with the costs of barge transport resulting from the model

7.83 M€. An LH_2-storage costs 350 M€ and has 100,000 in mobilisation costs. For 53 storage's this therefore equals 18555.3 M€. The storage tanks and the jetty both have a construction time of 2 years. So 60% will be paid off in the first year of construction and 40% in the second year. The jetty's pipeline will be built in one year and will therefore be fully paid off in 2021. Thus, in 2020 the capital cost is equal to 11,134.9 M€ and in 2021 7431.13 M€.

The operational costs consist of maintenance, insurance, labour and energy. The maintenance and insurance for all elements is equal to 1% of the capital costs, so this is equal to 185.6 M€. One operator is required for the pipeline and one operator for each storage tank. This results in annual labour costs of 9.07 M€.

The pipeline and the storage tanks need energy to function. An LH_2-storage tank uses 610 kWh/ton of LH_2. For the given throughput and an energy price of 0.09 €/kWh this equals 543.5 M€ per year for 53 tanks. The pipeline uses 100 kWh/ton of LH_2, so this equals 18.6 M€ per year. Together this gives an annual energy cost of 562 M€.

Figure H.9 shows a Table with the costs that are calculated with the model, hence the model calculates the cost correctly.

	year	capex	maintenance	insurance	energy	labour
0	2020	1.113496e+10	0.0	0.0	0.000000e+00	0.0
1	2021	7.431134e+09	0.0	0.0	0.000000e+00	0.0
2	2022	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
3	2023	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
4	2024	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
5	2025	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
6	2026	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
7	2027	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
8	2028	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0
9	2029	0.000000e+00	185607600.0	185607600.0	5.622360e+08	9066600.0

Figure H.9: Table with the costs of the elements at the import terminal resulting from the model

H.3.4 Transport Supply Chain 1

For the transport from the export terminal to the import terminal, 11 vessels are needed. The capital cost of one vessel is equal to 334 M€, for 11 vessels this is therefore 3674 M€. The construction time for a vessel is 2 years, so in 2020, 2204.4 M€ will be paid off and in 2021, 1469.6 M€.

The operational costs of a vessel consist of maintenance, insurance, labour and fuel. The maintenance of the vessel is 1.5% of the capital costs, which equals 55.1 M€ per year. Insurance is equal to 1% of the capital costs, i.e. 36.7 M€ per year. Twenty people are needed per vessel, resulting in labour costs of 36.9 M€ per year.

An LH_2-vessel uses boil-off gas as fuel when loaded, and diesel when unloaded. With a ship weight of 48,008 tonnes this results in a fuel consumption of 33.8 tonnes/day. With a fuel price of 388 €/ton, this equals 26.5 M€ per year.

Figure H.10 shows a Table with the costs that are calculated with the model, hence the model calculates the cost correctly.

	year	capex	maintenance	insurance	fuel	labour
0	2020	2.204400e+09	0.0	0.0	0.000000e+00	0.0
1	2021	1.469600e+09	0.0	0.0	0.000000e+00	0.0
2	2022	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
3	2023	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
4	2024	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
5	2025	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
6	2026	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
7	2027	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
8	2028	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0
9	2029	0.000000e+00	55110000.0	36740000.0	2.650382e+07	36938000.0

Figure H.10: Table with the costs of the sea going vessel transport resulting from the model

H.3.5 Export Terminal

At the Export Terminal there are 57 storage tanks, a jetty with a pipeline and 13 conversion plants. The capital costs and operating costs are briefly explained below.

The capital costs of the jetty consist of the costs of the dolphins, jetty and catwalk, together amounting to 2.96 M€. Equipment is needed at the export terminal, this adds up to 3.96 M€. The capital cost of the pipeline is calculated with the values from Table D.3. With mobilisation costs of 30,000 euros this equals 7.83 M€. An LH_2-storage costs 350 M€ and has 100,000 mobilisation costs. For 57 storages this is therefore equal to 19955.7 M€. A conversion plant costs 439 M€ with 200,000 in mobilisation costs. For 13 power stations, this becomes 5709.6 M€.

The storage tanks, the jetty and the conversion plants all have a construction time of 2 years. So 60% will be paid off in the first year of construction and 40% in the second year. The jetty's pipeline will be built in one year and will therefore be fully paid off in 2021. In 2020, the capital costs are therefore equal to 15400.9 M€ and in 2021, 10275.1 M€.

The operational costs consist of maintenance, insurance, labour and energy. The maintenance for the power station is 1.5% and for the other elements this is 1%. This results in an annual amount of 285.2 M€. The insurance for all elements is 1% of the capital costs and thus equals 256.7 M€ per year. One staff member is needed for the pipeline, one for each tank and three for each power station. This results in annual labour costs of 16.28 M€.

The pipeline, the storage tanks and the conversion plants require energy to operate. An LH_2-storage tank uses 610 kWh/ton LH_2. For the given throughput and an energy price of 0.09 €/kWh this equals 623.8 M€ per year for 57 tanks. The pipeline uses 100 kWh/ton LH_2 so this is equal to 19.5 M€ per year. A conversion plant uses 6400 kWh/ton of LH_2 and this equals 1272.5 M€ per year. Combined this gives an annual energy cost of 1915.9 M€.

In addition, a conversion plant also requires hydrogen. The hydrogen is purchased at a price of 2.70

€/kg. For the given throughput this equals 6.12 M€ per year.

Figure H.11 shows a Table with the costs that are calculated with the model, hence the model calculates the cost correctly.

	year	capex	maintenance	insurance	energy	labour	purchaseH2
0	2020	1.540156e+10	0.0	0.0	0.000000e+00	0.0	0.000000e+00
1	2021	1.027553e+10	0.0	0.0	0.000000e+00	0.0	0.000000e+00
2	2022	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
3	2023	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
4	2024	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
5	2025	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
6	2026	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
7	2027	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
8	2028	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09
9	2029	0.000000e+00	285212600.0	256677600.0	1.913029e+09	16286300.0	6.149520e+09

Figure H.11: Table with the costs of the elements at the export terminal resulting from the model

I | Python code

This Appendix contains a QR Code that directs to the Github website where the python packages for this code are available.

In the folder *'notebooks'* you can find some more simple codes that give a clear understanding of how the terminal investment simulation works. The folder *'notebook_examples_NoorAbrahamse'* contains some examples that have been developed in this report.

Figure I.1: QR code leading to the python packages

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List of Abbreviations

BT	Benzyltoluene
CAPEX	Capital Expenditures
CCUS	Carbon, Capture, Utilisation and Storage
CGH_2	Compressed Gaseous Hydrogen
CO_2	Carbon Dioxide
DBT	Dibenzyltoluene
DWT	Deadweight Tonnage
FCV	Fuel Cell Vehicles
GHG	Greenhouse Gasses
H_2	Hydrogen
HVDC	High Voltage Direct Current
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
LOA	Length Overall
LPG	Liquefied Petroleum Gas
LOHC	Liquid Organic Hydrogen Carrier
MCH	Methylcyclohexane
MoU	Memorandum of Understanding
MPa	Mega Pascals
N_2	Nitrogen
NG	Natural Gas
NH_3	Ammonia
nm	Nautical Mile
NRW	North Rhine-Westphalia
OPEX	Operational Expenditures
PJ	Peta Joule
PSA	Pressure Swing Adsorption
tpd	Tons per Day
WACC	Weighted Average Cost of Capital