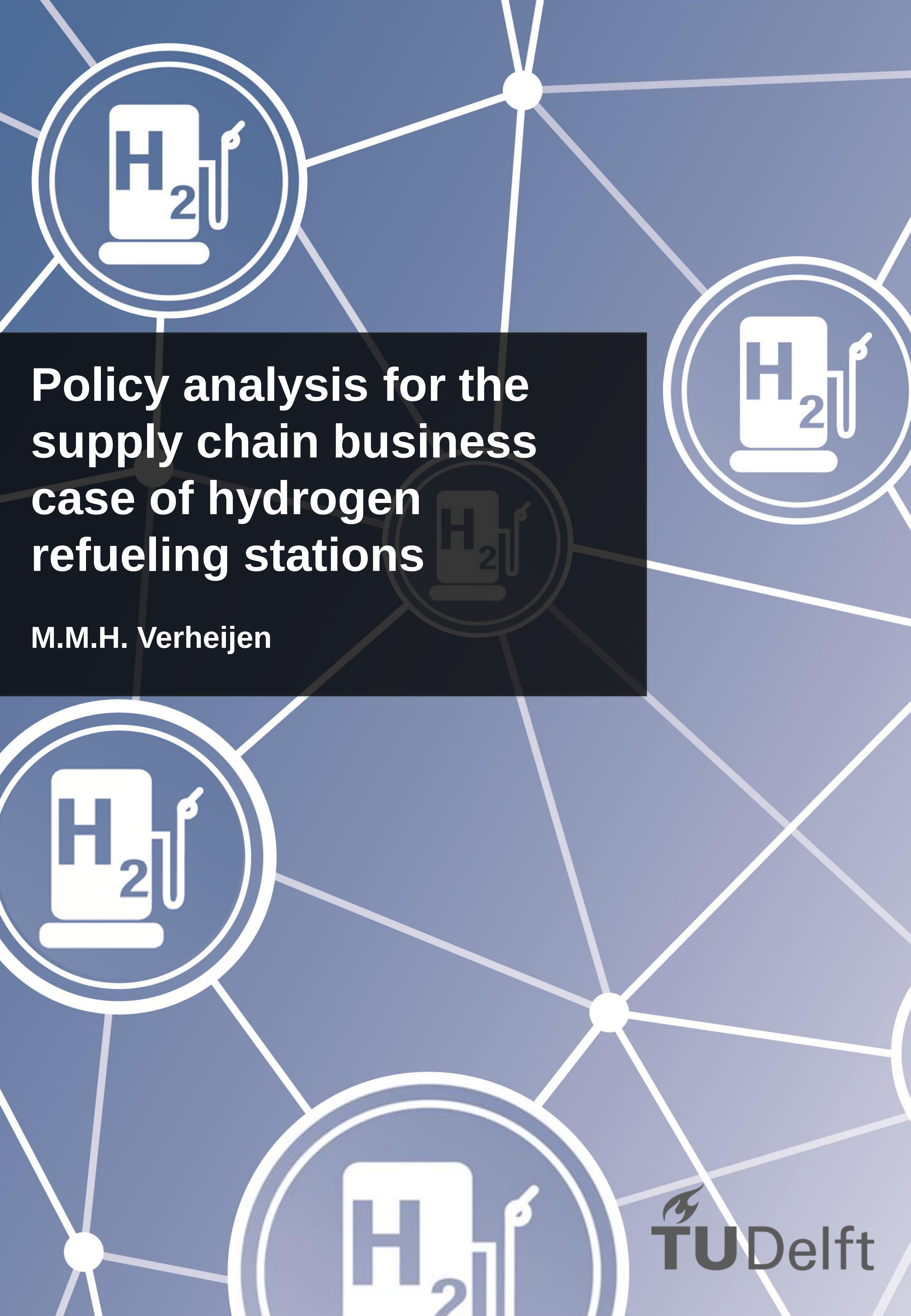

Policy analysis for the supply chain business case of hydrogen refueling stations

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TU Delft

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Policy analysis for the supply chain business case of hydrogen refueling stations

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Preface

This thesis marks the end of my time studying at the Delft University of Technology, during which I have developed myself not only academically but on many levels.

In this acknowledgement I would like to take a moment to thank my supervisors Zofia Lukszo, Aad Correljé, Ad van Wijk, Dirk Schaap and Ruud Dwars who have helped me during this single-largest project which wraps up my TU Delft career.
In particular I would like to thank my chair, Zofia Lukszo, who has helped me with overcoming many barriers along the way. When the wind came in front she knew how to adjust the sails and keep having a positive reinforcement towards me. Which, I can imagine, was sometimes a difficult challenge for her as well. I feel very privileged to have had her as chair for my thesis.

Also I would like to thank my parents, Hubert and Huguette Verheijen and both my brothers, Eduard and Diederick, who have unconditionally supported me through this past semester.
Apart from my family I would like to thank Femke Pragt for accompanying me this summer with motivation in moments of stress, pictionary in moments of chill and celebratory beers for all accomplishments.
Finally, I would like to thank Mark Huistra and all other Lamaaz for being such a large part of my student years and making these past years amazing.

Maurits Verheijen
Rotterdam, November 2021

Executive summary

On the 12th of December, 2015, the United Nations with 196 parties came to an agreement to limit global warming by reducing the greenhouse gas (GHG) emissions globally called 'the Paris Agreement'. In line with this agreement the European Union created the Green deal stating that by 2030 at least 55% of the greenhouse gas emissions need to be reduced (in comparison with 1990) and that in 2050 each member state needs to have a net-zero greenhouse gas economy. The mobility sector has increasingly contributed to the European GHG emissions over the past years and are currently responsible for 25% of these emissions. Therefore, a clear goal was set for the mobility sector to reduce the GHG emissions by 90% by 2050.

Hydrogen could play a key role in achieving the objectives of the European Green deal within the mobility sector. However, it is imperative that production of this fuel is sustainable with low or zero emissions. In addition to hydrogen as a fuel, other means are available for the mobility sector to reduce their GHG emissions. Electricity, bio-fuels and synthetic fuels are as well able to reduce environmental pollution assuming these fuels are produced renewably. Whether each of these four fuel types is sustainable depends on the production process. For production of low carbon hydrogen, two production processes dominate in literature as well as in national policy strategies. These processes include hydrogen production through electrolysis of water powered by renewable energy sources (RES) and through reforming natural gas combined with carbon capture and storage (CCS).

In addition to technical innovation of sustainable fuels, the set goals for reduction of GHG emissions require appropriate (inter)national policy. European and national policies on hydrogen fuels should cover investments, regulation, market creation, and research and innovation. The Netherlands has created a national hydrogen strategy that would aid in reducing the GHG emissions through applications in the mobility sector, the industry sector, heat production and agriculture. Because the mobility sector was responsible for 19% of the GHG emissions in the Netherlands in 2019, this research focuses on the hydrogen application in that specific sector with the aim to provide an answer to the following research question:

What recommendations can be provided to obtain a feasible business case for the supply chain of a hydrogen refueling station with low carbon hydrogen in the Netherlands?

To provide an answer to the main research question, three sub-questions are drafted. These questions are as follows:

1. What are the relevant Dutch policies regarding the supply chain of hydrogen for the mobility sector and how do these compare to the policies in Germany and Japan?
2. How do the supply chains with tube-trailer road delivery and a dedicated hydrogen pipeline infrastructure compare with each other on the equivalent annual costs and institutions?
3. What uncertainties can be identified that influence the development of these two hydrogen supply chains?

This research will first map relevant Dutch and European policies with respect to the production, distribution, storage and dispensing of hydrogen (carriers). Secondly, the Dutch policies will be compared with policies in Germany and Japan. Then the equivalent annual costs (EAC) analysis for both supply chains will be performed to reflect on the economic feasibility and afterwards the supply chain specific institutions will be evaluated. Finally, the uncertainties that have been identified will be mapped and recommendations for Dutch policy will be presented.

The current Dutch policies seem to not always be sufficiently adequate and would improve their value with more flexibility. From the comparisons with Germany and Japan it was concluded that their hydrogen strategies are based on the cooperation of various relevant stakeholders to establish national coverage of hydrogen refueling stations in a cost-efficient manner and more evenly allocate investment risks. In contrast, the Dutch approach is single-station based and, therefore, involves high investment risks resulting in a wait-and-see attitude by possible investors. Furthermore, Germany and Japan provide incentives for the supply side as well as for the demand side of hydrogen and commit to long-term policies, while the Dutch strategy is mainly focused on the supply side and hydrogen production which results in a lack of market creation. Lastly, the German and Japanese governments have taken a proactive role in the decarbonization of the mobility sector whereas the Dutch authorities have only just stepped in recently.
On the positive side was found that the Netherlands has geographical advantages for the application of hydrogen due to its potential for hydrogen import through the Port of Rotterdam and the European backbone, its potential for hydrogen production at the North Sea and the presence of the nationwide gas infrastructure which could be retrofitted for hydrogen distribution.

The two supply chains that have been considered in this research are respectively large-scale hydrogen production with tube-trailer road delivery (Supply chain A); and large-scale hydrogen production with distribution through the hydrogen backbone (Supply chain B). Supply chain A functioned as reference point.
The results of the cost analysis show that with current Dutch and European policy supply chain B has the potential to reduce the equivalent annual costs with approximately 23% compared to hydrogen distribution via tube-trailer road delivery. In this research that is equivalent to a price reduction of approximately 0.90 €/kg hydrogen at the refueling station.
The institutional analyses showed that supply chain B also has the least institutional barriers and can be considered the safest distribution mode for hydrogen to refueling stations.
From the uncertainty analyses and conducted interviews was deducted that the dominant recurring uncertainties are the cost of hydrogen at the pump, the long-term availability of current financial incentives and the lack of market creation. Local governments show the ability to have impact on market creation by demanding additional conditions for city logistics tenders like zero-emission operations which is shown to be an effective way of accelerating the hydrogen share in the economy by Japan. Also, European harmonization is complementary to this market creation and provides long-term policy like the inclusion of the mobility sector in the Emissions Trading System (ETS) and Renewable Energy Units (REU) which are found to be necessary policies for the decarbonization of the mobility sector.

In conclusion four suggestions for future Dutch policy are recommended:

1. Develop long-term committing policy for businesses to base their investments on, like a kilometer charge;
2. Stimulate market creation for hydrogen, by for example using tube-trailer road delivery for the short term until a pipeline network can be operational for hydrogen distribution. And destimulate the use of conventional fuels by for example implementing an additional charge for conventional vehicles;
3. Create a consortium with relevant stakeholders to obtain a cost-efficient nationwide hydrogen refueling station infrastructure and a more even allocation of investment risks;
4. Focus policy on retrofitting the existing gas infrastructure as it would significantly reduce the system costs which is required for hydrogen acceptance and decarbonization in the mobility sector.

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Nomenclature

AFIR	Alternative Fuels Infrastructure Regulation
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditures
CCS	Carbon Capture Storage
EAC	Equivalent Annual Costs
ETS	Emissions Trading System
FCEV	Fuel-Cell Electric Vehicle
FC-HDV	Fuel-Cell Heavy Duty Vehicle
GHG	Greenhouse Gas
HBE	Hernieuwbare Brandstofeenheden
HDV	Heavy Duty Vehicle
HHV	Higher Heating Value
HRSs	Hydrogen Refueling Stations
ISO	International Organization for Standardization
LCOH	Levelized Cost of Hydrogen
LHV	Lower Heating Value
MFS	Mobility and Fuel Strategy
NDC	Nationally Determined Contribution
OPEX	Operational Expenditures
O&M	Operations & Maintenance
PGS	Publicatiereeks Gevaarlijke Stoffen
PSA	Pressure Swing Adsorption
REPLEX	Replacement Expenditures
RES	Renewable Energy Source
REUs	Renewable Energy Units
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership

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1
Introduction

On the 12th of December, 2015, the United Nations with 196 parties came to an agreement to limit global warming by reducing the greenhouse gas (GHG) emissions globally called ’the Paris Agreement’. This agreement provides a framework for the member states to work within. In line with this agreement the European Union created the Green deal stating that by 2030 at least 55% of the greenhouse gas emissions need to be reduced (in comparison with 1990) and that in 2050 each member state needs to have a net-zero greenhouse gas economy [1][2]. Each member state has to meet these guidelines through their nationally determined contribution (NDC). As 25% of the European GHG emissions are produced by the mobility sector and this has only increased over the past years, a clear path is needed to reduce the GHG emissions in the mobility sector by 90% by 2050. Such change requires besides technical innovation, change in (inter)national policy as well. Hydrogen could play a role in achieving the objectives of the European Green deal.
The European Union created a ‘Hydrogen Strategy’ in order to create a cooperative environment for the European nations and to be able to rollout technology more effectively. This ‘Hydrogen Strategy’ resulted in the main application for hydrogen in the mobility sector, the industry sector (chemical bonds), the agricultural sector and for the use of city heat [3]. In July 2021 a package with means to reach the climate goals’ emission reduction of 55% in 2030 was presented in the so-called ’Fit for 55 package’ of the European Council. This ’Fit for 55 package’ has the aim to provide a coherent and balanced framework to reach the European climate goals in a way that is fair and socially just, maintains and strengthens competitiveness and innovations while assuring a level playing field for third country economic operators [4].
To realize this decarbonization through hydrogen investments, regulation, market creation, research and innovation is required. In the long-term renewable hydrogen produced by solar and wind energy has the priority, but in the short and medium term low carbon hydrogen is needed to accelerate the transition and support the development of a viable market. For the transition a phased approach was developed with the support for installing a minimum of 6 GW of hydrogen electrolyzers in the EU and the production of up to one million tons of renewable hydrogen in the period between 2020 and 2024. In the period of 2025 to 2030 this will be increased to 40 GW of hydrogen electrolyzers and a renewable hydrogen production up to ten million tons in the EU. Finally, in the period between 2030 and 2050 maturity of renewable hydrogen technologies should be reached and deployed at hard-to-decarbonize sectors at a large scale. To support this process the European Clean Hydrogen Alliance was created with industry leaders, civil society, national and regional authorities.

The Netherlands also created a national hydrogen strategy that would aid in reducing the greenhouse gas emissions through applications in the mobility sector, the industry sector, heat production and agriculture. This strategy states among other things that in 2030 an electrolyzer capacity of 3-4 GW should be installed which will be coupled to storage facilities, a hydrogen infrastructure for transport and with condition of an additional increase of renewable electricity.

The mobility sector was responsible for roughly 19% of the GHG emissions in the Netherlands in 2019 [5]. Thus the societal relevance and necessity of a net-zero emission alternative for this sector is large.
The few most promising alternatives to substitute conventional fuels in the long-term are electricity, bio-fuels, synthetic fuels and hydrogen as emission-free energy carriers [6]. Whether these energy carriers are sustainable depends on the production process of the energy carriers. This research will focus on the application with mobility. The stored hydrogen in a fuel-cell electric vehicle (FCEV) powers a fuel-cell which combines the hydrogen with oxygen (from the air intake) and produces with this electrochemical conversion process electricity and (pure) water. FCEVs have an advantage over BEVs which is that the driving range is larger, the hydrogen and its tank weigh significantly less than the batteries (which is relevant for heavy-duty vehicles) and the refueling time is similar to that of conventional petrol and bio-fuel vehicles [7][8]. A nationwide refueling infrastructure for hydrogen does however not yet exist in the Netherlands.

The sustainability of hydrogen can be categorized based on the production process. For this research the focus is on low carbon hydrogen. Currently two production processes for low carbon hydrogen are dominant in literature as well as in national policy strategies. These involve hydrogen production through electrolysis of water powered by renewable energy sources (RES) and hydrogen production through natural gas reforming combined with carbon capture and storage (CCS) [9]. This research will consider the latter for large-scale low carbon hydrogen production.

Hydrogen produced from different production processes should be considered as heterogeneous products. Even though no physical differences in the characteristics of the material are present, the production costs and the willingness to pay of consumers differ.
Currently the production costs of renewable hydrogen are higher than for low carbon and high carbon hydrogen in the Netherlands. To reduce the price that the consumer pays for renewable hydrogen Renewable Energy Units (HBE: Hernieuwbare Brandstofeenheden) can be allocated to renewable hydrogen which can be traded in a specific market and could with that revenue reduce the price that consumers pay [10].
The willingness to pay of consumers also differs for hydrogen production processes, because people who aspire to live in a sustainable manner will have a higher willingness to pay for zero-emission hydrogen than for low carbon hydrogen relative to people with lower priorities for sustainability. Because of this difference, the value of class of high carbon, low carbon and zero-emission hydrogen varies and can thus be considered heterogeneous products.

The main factor that can promote the transition to the 'hydrogen mobility' is the hydrogen cost. Therefore it is relevant to evaluate how this cost is affected by the size, process and the management strategies linked to the production as well as the storage and distribution of hydrogen [11]. The main barrier of introducing hydrogen for mobility is the high total cost of ownership (TCO) for the refueling infrastructure [12].

Besides technical and economical also political challenges arise due to the energy transition [13]. Therefore it is relevant to evaluate current policy and reflect what policy (changes) could be considered to stimulate the transition.
This research will focus on the comparison of the business cases of two hydrogen supply chains for a hydrogen refueling station (HRS). This business case will be decomposed into three categories: The economic feasibility, relevant institutions and uncertainties that influence the business case will be identified. This research aims to provide an answer to the following research question:

What recommendations can be provided to obtain a feasible business case for the supply chain of a hydrogen refueling station with low carbon hydrogen?

This main research question is decomposed into three comprehensive sub-questions. These sub-questions are as follows:

1. What are the relevant Dutch policies regarding the supply chain of hydrogen for the mobility sector and how do these compare to the policies in Germany and Japan?
2. How do the supply chains with tube-trailer road delivery and a dedicated hydrogen pipeline infrastructure compare with each other on the equivalent annual costs and institutions?
3. What uncertainties can be identified that influence the development of these two hydrogen supply chains?

This research will first map relevant Dutch and European policies with respect to the production, distribution, storage and dispensing of hydrogen (carriers). This is followed by a comparison of the Dutch policy with the policies enforced in Germany and Japan. Thirdly, the two relevant hydrogen supply chains will be further analyzed. With this analysis the equivalent annual costs per supply chain will be estimated in order to compare the economic feasibility of the two supply chains. Also the supply chains will be compared based on relevant institutions that come along with the supply chains and finally, uncertainties that have been identified will be mapped in a framework and recommendations for Dutch policy will be provided.

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Dutch and European policy analysis

In this chapter the relevant institutions for hydrogen production, distribution, storage and dispensing will be discussed. The following regulations and institutions will be discussed accordingly in this chapter: Permits, safety measures, financial incentives, the Dutch Green deal, the European Green deal, the Emissions Trading System (ETS) and the Renewable Energy Units (REUs).

2.1. Permits

For building a hydrogen refueling station there are some permits that need to be obtained before the start of the project. Some are discussed in this paragraph [14][15][16]:

- Every project which goal it is to build an HRS needs the 'Wabo-milieuvergunning' (permit) and often also requires a building permit.
- The 'Besluit externe veiligheid inrichtingen (Bevi)' provides rules regarding the surroundings and allowing certain people to come near to the HRS. This is not yet required, but it is expected to be a requirement in the future and therefore already included in this research.
- When the production of hydrogen happens on-site an environmental permit is often a prerequisite. For example when hydrogen is produced on-site from wind energy, an environmental permit is required to place the wind turbine. For a wind turbine park, which is defined as three or more wind turbines together, an environmental permit is always obligatory and for ten or more wind turbines with a total capacity of more than 15 MW also an environmental impact report is needed which is more extensive than the environmental permit [17][18].
- It is possible that some provinces or municipalities have their own policy stating where and how many refueling stations are allowed in a certain area. Dependent on where the refueling station would be located the municipality should be contacted before the start of the project. For example, when the HRS is placed at a main road, a permit for 'Wet beheer rijkswaterstaatswerken (Wbr)' is a condition.

In order to obtain the permits, a proper design has to be made in advance including all system components and their placements. There are restrictions with respect to what the minimal distances are that need to be coped with before designing an HRS in order for lethal accidents to have maximum risk of 10^{-6}. These distance restrictions are presented in a report of the National Institute for Health and Environment [19]. For a hydrogen refueling station (HRS) with gaseous hydrogen supplied through a pipeline or by on-site hydrogen production the maximum distance for the risk of a lethal accident occurrence of 10^{-6} is 30 meters and for a maximum risk of 10^{-8} it is 35 meters. For gaseous hydrogen supplied through tube-trailers these distances are respectively 35 meters and 55 meters. For liquid hydrogen supply through a tanker these distances are respectively 30 and 130 meters. The risk of a lethal accident of 10^{-4} or lower is for the hydrogen supply through a pipeline or on-site production lower than or equal to the other two supply modes [19]. Keeping into account a maximum allowable risk of 10^{-6} to obtain the permit, the supply chain through pipeline or on-site production has the lowest distance restrictions, followed by the supply through tube-trailers and the tanker. The gradual increase in the distance for each risk level is presented in figure 2.1, where type 1 (blue line) represents the supply through a pipeline or on-site production, type 2 (red line) represents the gaseous hydrogen supply through tube-trailers and type 3 (green line) represents the liquid hydrogen supply through a tanker. These distances for the maximum risks are based on the frequency of failures per year for the three hydrogen supply modes as well as for the common technical components: storage (440 and 950 bar), piping and the dispensing unit.

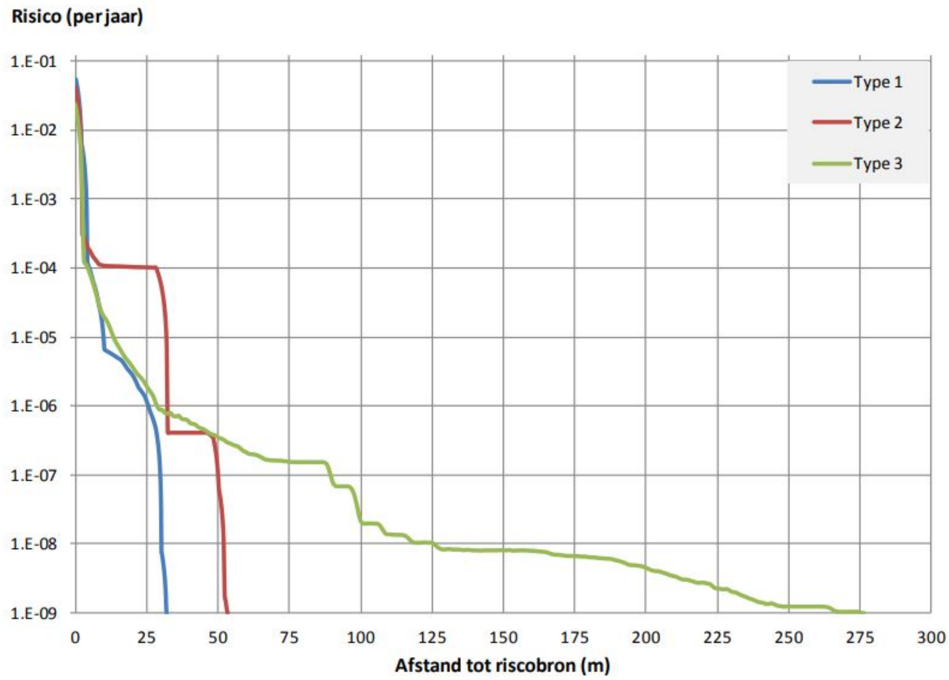

Figure 2.1: Overview of risk distances for an HRS per supply chain mode [19]

2.2. Safety measures

Hydrogen is in many ways different from LPG, gasoline or Diesel fuel. Therefore different safety measures are being enforced. That does not mean that hydrogen is more dangerous than these conventional fuels. Hydrogen has a lower explosive limit of 4% volume in the air, whereas for methane this is 5% volume. However, hydrogen is 14 times lighter than air causing it to dissipate quickly in open space resulting in a faster dispersion than is the case for natural gases and thus it will be less likely that these volumes of hydrogen in the air will occur in open space than for for example methane [14]. As hydrogen refueling stations are open at the sides, wind is able to reach which will, together with the buoyant force of the hydrogen, result in a hydrogen cloud to disperse [20]. However, hydrogen does have a lower ignition energy than natural gas or gasoline, therefore specific guidelines to deliver hydrogen to vehicles are presented in the report 'Publicatiereeks Gevaarlijke Stoffen 35 (PGS35)' [15][21]. It is assumed that at a temperature lower than 585°C (the autoignition temperature of hydrogen) the probability of an autoignition occurring is zero [20].

When an accident would occur, the flame would be almost invisible and odorless and so there are different approaches and guidelines to handle those situations [22][23]. For first responders, the primary measure to combat hydrogen fires are cutting off the supply and refraining from quenching the flames [20]. To discover a hydrogen flame special flame detectors are required, which have to meet the requirements of ISO 26142:2010 [20].

For the base safety level, during the design phase of the hydrogen refueling station the requirements of the Seveso-guidelines, the NEN-EN-ISO 14001 and the ISO 45001, NTA 8620 of the 'Besluit activiteiten leefomgeving' have to be met [21]. Also the European Pressure Equipment Directive (PED) needs to be taken into account for all stationary pressure equipment that operate with a pressure greater than 0.5 bar. This European directive allows standardization in the European Union for pressurized equipment.

At major leakages in a pipe or tank that operates at 700 bar the flame in case of a fire is nearly invisible and could have a greater reach than 1 meter [21]. But due to the diffusion coefficient of hydrogen in the air, in open spaces the hydrogen gas will disperse rapidly in the air and thus dilute quickly resulting in a lower explosive risk [21]. For hydrogen refueling stations with a rooftop it is important that the hydrogen is not able to gather somewhere and create a hydrogen cloud, since this would increase the explosive risks [21]. This is of relevance to incorporate in the design of the hydrogen refueling stations.

2.3. Financial incentives

In order to stimulate the rise of alternatives on fossil fuels the Dutch government and European Union have created various financial incentives to drive this transition. A list of these financial incentives for hydrogen supply chains for hydrogen refueling stations can be found in Appendix A. From these national and European incentives can be concluded that the focus is primarily on the production and storage of emission-free or emission decreasing technologies. Distribution of renewable energy is stimulated to a lesser extent.
A distinction between the European incentives and the Dutch incentives is that the European incentives have a focus on cross-border innovations whereas the Dutch incentives are more or less related to regional projects. Both can be applied complementary however. No stimulants were found that contradict each other. The main goal of the incentives is to reduce the GHG emissions and to increase research to innovative solutions for emission reduction and energy efficiency increase.

2.4. Dutch green deal

A green deal is a method for experimenting in practice and learning from doing when the current policy is preventing innovation or experiments in the process to make sectors more sustainable. A green deal is an agreement between the government and the party that wants to work more renewably, but is in this process held back by current policy. In a green deal, the government is able to change law and legislation, act as a mediator or help in the creation of a market through, for example, support to the entry of foreign markets [24][interview]. So was a green deal made with Stad aan 't Haringvliet in the Netherlands, where the aim of the experiment is to practice the effects of substituting conventional house heating for heating with hydrogen [25].
A barrier that was dissolved by this green deal is that this project uses the existing gas infrastructure for the hydrogen distribution which energy companies are not allowed to do at the moment. Similarly this issue should be resolved for the use of the existing gas infrastructure to supply refueling stations with hydrogen for which a green deal could be made or current barriers should be revised.
Because technological innovations with hydrogen in the mobility sector are more dynamic than national policy, sometimes policy hinders the development. In order not to hinder the development of hydrogen applications in the mobility sector, it could be advisable to make Dutch green deals with parties in the future to provide more experimental space for the sustainable developments in this sector.

2.5. European Green deal

The European Green deal, launched in December 2019, emphasizes the need for a holistic approach where all European actions contribute to reaching the European climate goals and decarbonizing the European Union. The Green deal underlines the need for a just and inclusive transition where support will be given to countries that struggle with reaching the European Green deal goals [26].
In July 2021 the 'Fit for 55' package was presented with actions that will contribute to reaching the sustainability goals of the Green deal [26]. Actions that have been presented in the Fit for 55 package are for example among others that member states have to expand their charging and refueling infrastructure up to 1 electric charging station every 60 km and a hydrogen refueling station every 150 km on major highways. But the two most relevant actions from the Fit for 55 package for the mobility sector will be the revision of the Renewable Energy Directive 2 (RED2) and the Alternative Fuels Infrastructure Regulation (AFIR).
The Fit for 55 package is currently in the council phase and can therefore not yet demand adjustments in national laws and regulations of the member states. The European Commission and the European member states are still in negotiations about the exact content of the Fit for 55 package. After these two parties reach an understanding the package will be discussed in the European Parliament after which national laws and regulations can be adjusted accordingly. It is likely that the process from the council phase until the final Fit for 55 package version will take at least two more years.

2.6. Emissions Trading System

The European Union introduced the Emissions Trading System (ETS) in 2005. The ETS facilitates a market where emissions have a certain value by allocating rights to companies to emit GHG. These rights are called 'European Union Allowances' (EUAs). This causes that the sectors where it is cost-efficient to reduce CO_2 emissions will reduce their emissions [27][28].
The ETS is worlwide the largest market for GHG emissions and covers approximately 45% of European GHG emissions in 31 countries [29]. The system was divided in four phases where in each phase an expansion of the system would be presented to new sectors. It was found that the ETS reduced the GHG emissions in the period 2008 - 2016 by 1 billion tons of CO_2 which was approximately 3.8% of the European emissions [30]. Currently the ETS is in its fourth phase (2021 - 2030) [27][29]. In phase three and four the free allocations of allowances have been reduced as due to the previously over-allocations of free allowances the carbon price was too low to make a significant impact [29][31]. Therefore a price floor could be introduced [31]. A price floor will fast forward the decision moment for sustainable investments and political support for the implementation of such additional institution is getting traction [28][31]. When the price floor for carbon was introduced in the UK, the consumption of coal for electricity generation decreased by 76% in the period 2013 to 2016 [28]. Currently the price of allowances is approximately 53 €/ton CO_2 and it is expected that a price in the range of 50 - 90 €/ton CO_2 will make low carbon hydrogen competitive with high carbon hydrogen [32][33][34].
The road mobility sector is not yet included in the Emissions Trading System, but will be from 2026 [27][35]. Including the whole mobility sector in the ETS could further reduce the GHG emissions in a cost-efficient manner as price mechanisms are statically efficient [36]. Whereas standards-based regulatory instruments may, but are generally not, cost efficient [36]. Extending the ETS to the mobility sector would result in a more harmonized carbon-pricing regime through the EU member states and reduce geographic distortions caused by differentiated pricing [36].

Apart from including the mobility sector in the ETS, other policies also focus on additional duties or limitations for vehicles based on their CO_2 emissions. In June 2019 new rules were already adopted for heavy duty vehicles that limit the allowable emissions from new trucks by 15% from 2025 and by 30% from 2030 [37]. And at the moment the European Council is drafting a proposal that is called the 'Eurovignette' directive which stimulates member states to charge heavy duty vehicles on the basis of their CO_2 emissions and thus incentivizing the transition towards renewable vehicles [37].

2.7. Renewable Energy Units

Renewable Energy Units (REU) are units that companies (within the implementation system Energy for Transport) can create for their obligation to reduce their emissions. Only companies that are enrolled in the Register Energy for Transport are eligible for creating REUs [38].
A single Renewable Energy Unit represents 1 GJ of renewable energy that is supplied to the Dutch mobility sector. Three categories of Renewable Energy Units are distinguished [38]:

- Renewable Energy Unit Advanced (REU-A);
- Rnewable Energy Unit Conventional (REU-C);
- Rneewable Energy Unit Other (REU-O).

Hydrogen can be categorized as Renewable Energy Unit Advanced as it is a liquid or gaseous renewable fuel. Currently the value of the REU-A is approximately 13 €/GJ [39]. Also renewable electricity can create REUs. However, if hydrogen is directly produced through electrolysis powered by renewably generated electricity without receiving the electricity from the grid, the Renewable Energy Units can only be created for either the electricity or the hydrogen [interview]. The direct application of renewable hydrogen in FCEVs and synthetic fuels are eligible for REUs based on the regulation 'Besluit energie en vervoer'. The Renewable Energy Directive 2 (RED 2) also approves the creation of REUs when the application of renewable hydrogen in refinery processes for gasoline or diesel substitutes high carbon hydrogen [40].
Renewable Energy Units are integrated in the Dutch law and cannot be traded with companies in other countries nor bought from companies in other countries [38]. The Renewable Energy Directive 2 will make it possible for these transactions to occur and the H2Platform advises as well to facilitate these trades as long as the Renewable Energy Units cannot be claimed in the European member state where the renewable hydrogen is produced as well as the member state where it is distributed to [40].
From the year 2018 to 2021 there has been a yearly minimum set for the total renewable energy that is supplied to the mobility sector. In 2018 this minimum was 8.5% and in 2021 this minimum is 17.5%. Also for the REU-A there is a minimum of 1.2% in 2021 and for the REU-C there is a maximum of 5.0% in 2021 [41]. These percentages are fractions of the total amount of energy that is supplied by the company. Only companies that supply more than 500,000 liter gasoline or diesel to the mobility sector have the obligation to meet the set minimum of Renewable Energy Units [41].

2.8. Conclusion on Dutch and European policies

The Dutch policies show that with respect to safety measures and minimizing the refueling station area the optimal supply chain would be by a pipeline infrastructure. And with respect of resilience towards future demand is this likely to be the optimal hydrogen supply chain as well which would thus benefit from already focusing Dutch policy on this supply chain.
The Dutch and European financial incentives dominantly focus on the production and the demand of hydrogen, but to a lesser extent on the supply chain in-between. As the supply chain is a crucial factor for the rollout of hydrogen in the mobility sector it is necessary that this aspect will be incentivized as well.
Current Dutch and European policies do not yet show serious threats to the extent that fast transitions have to be established by companies. However, gradually the policies do increase their impact over time. Especially including the mobility sector in the ETS and the implementation of REUs are likely to result in companies making adjustments in their processes and fast forward their investment decisions. Resulting in a decarbonization of the mobility sector.
The action plans to reach the European Green deal goals will provide handles for member states to base their policies on and to reach a GHG reduction on European level. If current Dutch policy would hinder these actions, Dutch Green deals could be made with the necessary parties as a transition solution.

3
Dutch policy comparison with Germany and Japan

At the start of this project the decision was made to compare the Dutch approach for decarbonizing the mobility sector by incorporating hydrogen supply chains with the approaches in Germany and Japan. As well Germany as Japan have taken more action with respect to hydrogen in the mobility sector than the Netherlands. Therefore lessons could be learnt from comparing the Dutch approach with the approach of Germany and Japan.

3.1. Dutch policy comparison with Germany

Germany started with the NIP (National Innovation Programme Hydrogen and Fuel Cell Technology) in 2006 (until 2016) to coordinate and organize the transition towards a more sustainable sector in the transport. Firstly an infrastructure strategy was to be created for the rollout. Secondly, this transition plan was to be implemented and a central organizatory system was to be created for the various stakeholders to be aligned. That way the chicken-egg issue would be resolved and thus the infrastructure and vehicle rollout would be developed in parallel [42]. The budget for this national innovation programme was €1.4 billion [43]. This coordinated process would result in a maximum area coverage of the HRSs at a minimal cost. Six metropolitan areas in Germany were distinguished and were used as a base to expand from to the rural areas [42]. These six metropolitan areas are presented in figure 3.1.
The German Hydrogen Council was launched in 2017 by 25 people from sectors as leading global energy, transport and industry companies in order to bring together political and private stakeholders. All with the point of view that hydrogen would be a key element in the energy transition in Germany [44] [45].

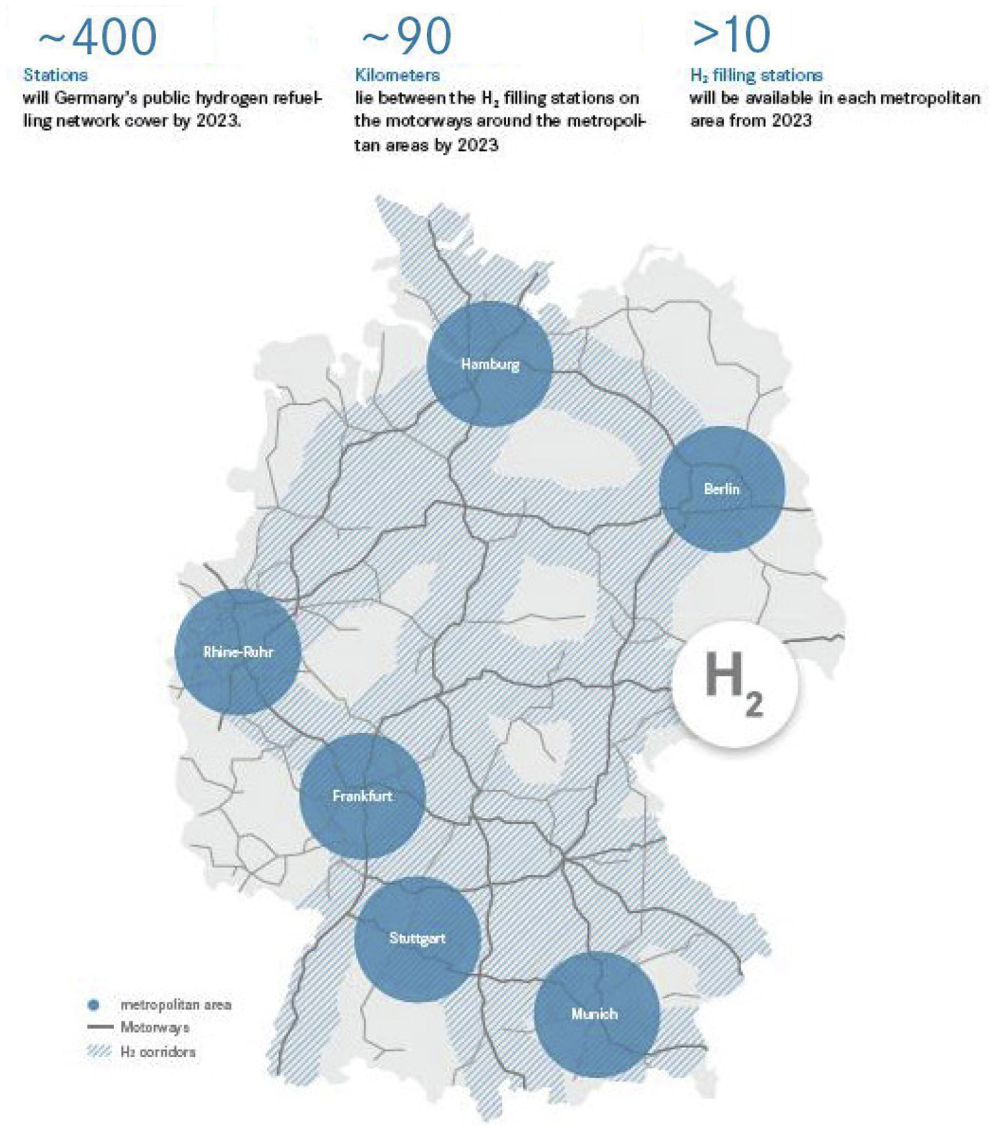

Figure 3.1: Germany metropolitans for hydrogen expansion in 2023 [42]

As a follow-up Germany installed the NIP 2 for the period of 2016 to 2026 with the focus on market introduction of the technologies and funding research and development. The budget for this NIP 2 was €250 million until 2019 and envisaged another €481 million until 2022 [43]. Examples of projects that received funding from NIP 2 are:

- Deutsche Post DHL Group for the implementation of 500 fuel cell street scooters in their delivery service;
- MAN & Shell with Anleg GmbH and TU Braunschweig for the development and testing of commercial HDVs and mobile and self-sufficient refueling devices;
- FAUN Environmental Technology GmbH & Co. KG for the development of garbage collection trucks and sweepers than are powered by a fuel-cell;
- EvoBus GmbH for developing a battery electric city bus with a fuel-cell range extender.

The government was also financially supporting the expansion of HRSs to achieve the target of having 100 hydrogen refueling stations in operation. At the end of 2019 Germany had approximately 500 FCEVs on the German roads and the second largest hydrogen refueling network in the world with 90 HRSs [44]. The majority of these stations that are in operation are in the hands of the industrial joint venture H2 Mobility [43].
The Mobility and Fuel Strategy (MFS) of Germany was introduced in 2013 and it is intended to identify alternative fuels to conventional fuels that can be applied in a broad spectrum. The aim of the MFS is to reduce the CO2 emissions and increase the application of renewable energies in the mobility sector [46] [47].

One of the differences in the approach of Germany and the Netherlands is that the German approach is nation wide coordinated whereas the Dutch coordination is single-station based [48]. In Germany the goal was defined and the process to reach that goal was discussed in a coordinated setting with stakeholders from all relevant sectors. This could be the result of the underlying embedded differences in the refueling station infrastructure of the Netherlands and Germany as in Germany the fuel station operators are differently defined than in the Netherlands. In the Netherlands the fuel stations operators have a permit for single fuel stations for a certain amount of time [interview]. When this period has expired the fuel station will be auctioned to the highest bidder of fuel suppliers. There is no overall coordination of adequate fuel supply in the Netherlands. Refueling stations will only exist where there is a demand and thus a feasible business case [interview]. Whereas in Germany the refueling stations are coordinated into an adequate fuel supplying system. This supply is characterized by five vertically integrated oil companies and many minor independent stations. These five oil companies are BP (Aral), ConocoPhilipps (Jet), ExxonMobil (Esso), Shell and Total with a market share of respectively 21.5%, 10.5%, 7.5%, 20% and 9%. In total these 5 oil companies own 68.5% of the fueling stations representing 7213 stations in Germany. This is an oligopolistic market with high barriers for newcomers [49]. The refueling station operators receive from Tank & Rast GmbH (the successor of the government-owned GfN service facilities company) a license for the supply of fuel to these refueling stations proportional to their market share [50].
Research established that by applying a national covering system approach in Germany, an average cost of hydrogen production reduction of 10% can be realized compared to an individual HRS optimization approach as is the case in the Netherlands [51].

Currently there are 92 HRSs and the dispensing price of 1 kg of hydrogen is €9.50 throughout Germany [52]. As can be observed in figure 3.1 the goal for 2023 is to have 400 operational HRSs.
In June 2020, Germany presented their hydrogen strategy in which 38 goals and measures are discussed for the period of 2020 to 2023. This national hydrogen strategy (NWS) has the goal of boosting (green) hydrogen through the entire value chain of hydrogen. The NWS shows that more than €10 billion will be invested into hydrogen applications of which €3.4 billion will be made available for the development of a hydrogen infrastructure until 2023 [53].

Besides stimulating the supply side of hydrogen for the mobility sector, Germany also stimulates the demand side. Like the strategy of the NIP, it is relevant to stimulate both in parallel. Germany stimulates the demand side by several means. Three of these are discussed accordingly:

- Germany stimulates the consumption of FCEVs by subsidising $4000,- per vehicle [8];
- Recently Germany changed the maximum subsidy for the extra costs of zero-emission vehicles from 60% for small companies and 40% for large companies to 80% which is in contradiction to the European guideline of the AGVV (Algemene Groepsvrijstellingsverordening) [54]. As the AGVV is a guideline of the European Commission a deviation from this guideline does require a notification in Brussel;

- The NWS of Germany also advocates a CO_2 differentiation of the truck toll in order to favor the climate-friendly alternatives over conventional trucks and to harmonize hydrogen applications and fuel-cells in the mobility sector [53].

To conclude on the comparison that has been made between the current policy of the Netherlands and Germany both with respect to hydrogen, it can be found that the core of the governance differs from the Dutch governance. The policy-making structure as well as the coordination in Germany has a national scope whereas the Dutch policy-making structure and coordination is single station based. This enables Germany to reach a full national covering fuel supplying system for hydrogen where in the Netherlands only hydrogen will be supplied where a market can exist.
Also by taking a nationalistic approach, the overall system costs for the hydrogen infrastructure can be reduced by approximately 10%. With the costs of hydrogen as the dominant factor for the transition towards market creation and decarbonizing the the mobility sector this is a relevant method to consider applying also for the Netherlands.
On the demand side, Germany stimulates the consumption of FCEVs with greater financial means than the Netherlands and by simultaneously stimulating the hydrogen supply Germany can solve for the chicken-egg issue.
Germany is clearly prioritising hydrogen higher as a means to reach the climate goals and decarbonize the mobility sector than the Netherlands [interview]. Besides the fact that Germany invests more public money into the transition towards a hydrogen economy than the Dutch government or that Germany aims at a national coverage of HRSs, Germany also stimulates both sides (supply and demand) in parallel whereas the Netherlands focuses dominantly on stimulating the supply side.

A difference to consider however, is the fact that Germany is geographically a larger country where people have to travel for multiple hours more regularly than in the Netherlands. This causes that for example Battery Electric Vehicles become a less attractive alternative for private mobility than hydrogen for FCEVs. Also due to the larger surface Germany has, it is able to install more decentralized renewable energy plants which could produce hydrogen decentrally to supply the mobility sector.

3.2. Dutch policy comparison with Japan

In order to establish an understanding of the Japanese policy with respect to the 'hydrogen society' it is creating, it is relevant to first have an understanding of the Japanese history regarding its energy production. Japan has limited access to oil or gases in its grounds. Imported nuclear energy was dominant in the Japanese energy mix. This changed when in 2011 the nuclear Fukushima Dashii plant exploded and caused radical changes in the Japanese policy regarding its energy management. After this disaster, Japan rapidly closed all its nuclear energy plants and became heavily dependent on imports of fossil fuels (88% of the total energy consumption) [55]. The import of these energy sources raised the costs for energy. In order to lower the retail prices and increase competition, the Japanese government liberalized the national electricity market in 2016 and the gas market in 2017 [55]. As a result of these policy changes, an increasing share of renewable energy in the Japanese energy mix occurred. The geographic lay-out of Japan however is characterized by the lack of an existing gas infrastructure and only a few large densely populated areas and in-between low-populated areas [55][56]. The renewable energy production plants are mainly located in these low-populated rural areas. The main renewable energy production in Japan is from solar energy. Japan has the third largest installed solar energy plant capacity in the world [57]. This renewable energy production in the rural areas caused the challenge of distributing this energy to the urban areas. Hydrogen could offer a solution for two challenges. Namely, the unbalance in energy demand and generation caused by the intermittency of the solar electricity production and for the distribution of the generated electricity from the rural areas to the densely populated urban areas [55][58]. Therefore the Japanese government aims at creating a 'hydrogen society'. To reach this 'hydrogen society' Japan would need at least 20% of total energy demand to be covered by hydrogen [55]. This also means that hydrogen is assumed to be a multi-sector solution for achieving the decarbonisation goals [56]. In 2014, in Japan, the 'Strategic Energy Plan' was created and approved of by the Cabinet which stated that for reaching the 'hydrogen society' it is essential that Japan would formulate a road map towards this goal [59]. This hydrogen strategy was reiterated on December 26th, 2017 [56]. An aspect of this strategy was the bilateral agreement with Australia to import hydrogen which will later this chapter be discussed in more depth.

Japan has set the following hydrogen goals: by 2030 the total emissions should be reduced by 26% compared to 2013 and in 2050 a carbon neutral society must be achieved. In order to reach these goals Japan has created an action plan with 14 priority technology areas: 1) Offshore wind industry; 2) Fuel ammonia industry; 3) Hydrogen industry; 4) Nuclear industry; 5) Automobiles battery industry; 6) Semiconductors information and communications industry; 7) Shipping industry; 8) Distribution, human resources, land infrastructure industry; 9) Food, agriculture, forestry and fisheries; 10) Aircraft industry; 11) Carbon recycling industry; 12) Housing and building industry/nex-generation solar power industry; 13) Resource recycling industry; 14) Lifestyle-related industry. Area 1 through 4 are categorized as energy-related industries, 5 through 11 are transportation and manufacturing industries and 12 through 14 are home and office industries [60].

The MOE (Ministry of the Environment) and METI (Ministry of Economy, Trade and Industry) are planning to invest 77 billion ¥ (which is approximately 0.592 billion €) to invest in fuel-cell businesses and hydrogen in 2021. This is the same amount as has been invested by the Japanese government in 2020 [60]. MOE invests around 10% of this budget in the decarbonization of the society (in innovations in the technological and social systems practice) and the METI invests the other 90% in the realization of the hydrogen society. An overview of the Japanese investment plans is presented in figure 3.2.

Ministry	Classification	Name	Budget Amount	Budgeted Amount Total
MOE	Toward a Decarbonized Society In the technological and social systems practice of innovation	Project to promote a hydrogen society using renewable energy	3.58 bn. yen	6.58 billion yen
		Social infrastructure development project using hydrogen	3 bn. yen	
METI	Strengthening efforts to realize a hydrogen society *1	Subsidy for the introduction of clean energy vehicles	13 bn. yen	70 billion yen
		Subsidies for hydrogen station construction projects to promote fuel cell vehicles	12 bn. yen	
		R & D projects to utilize innovative fuel cell technologies and other technologies to realize a hydrogen society	5.25 bn. yen	
		Demonstration project to build hydrogen supply chain using unused energy	14.12 bn. yen	
		R & D projects for the construction of low-cost hydrogen supply infrastructure utilizing ultrahigh-pressure hydrogen technology	3 bn. yen	

Figure 3.2: An overview of Japan's 2021 investment plans for the hydrogen society [60]

As can be observed in the figure, around 1/3 of the total budget will be allocated to the introduction of clean energy vehicles (like fuel-cell electric vehicles) and to the construction of hydrogen refueling stations. This is not strange since half of the car manufacturers that have currently commercially available fuel-cell electric vehicles (FCEVs) are Japanese from origin [61]. Around 38% of the total amount of FCEVs worldwide are located in Japan [62]. Japan has the goal to increase this amount to 200,000 FCEVs on its roads by 2025 and 800,000 by 2030 [60]. Also the Japanese government wants to have 320 hydrogen refueling stations by 2025 and 900 by 2030 [60][63]. To achieve this target an expansion of the existing refueling stations takes place [60].
Many local governments use Japanese FCEVs as official vehicles to create public awareness and the MOE invests in 52 projects for the introduction of fuel-cell forklifts for the industry [60]. Japan is also transitioning from FCEVs to heavy duty vehicles like buses. In 2020 there were 18 fuel-cell buses in operation in Japan [64]. This transition is among other reasons for the Olympics in 2021 where the athletes will be transported to and from the Olympic Village by fuel-cell buses which is also intended to increase the public awareness [62].

In 2017, Japan already invested 61 million US$ (converted 102 ¥ = 1 US$) in the hydrogen infrastructure [8]. The Japanese government, for the most part the Ministry of Economy Trade and Industry (METI) has spent up to now 1.5 billion US$ on hydrogen programs [56]. This resulted in the fact that in 2020 Japan was worldwide leading with the largest amount (96) of hydrogen refueling stations followed by Germany and the US [65].

Already the hydrogen demand exceeds the capacity of the country to produce renewable energy from wind and solar due to a lack of suitable locations. Thus import and international trade in hydrogen has become attractive [66]. Japan is outsourcing its hydrogen supply to other countries where green hydrogen can be produced at lower costs [56][67].
In 2018, the government of New Zealand and the government of Japan have signed a Memorandum of Cooperation on green hydrogen. This memorandum aims to encourage the cooperation of Japanese and New Zealand companies for establishing green hydrogen supply chains to supply Japan [67]. The price of hydrogen from import using cryogenic hydrogen in ships is approximately 15 US$/kg (in 2020) form Saudi Arabia to Japan, but over time when the scale increases in size this price could potentially drop to 1.7 US$/kg in 2030 [66]. NEDO (the New Energy and Industry Technology Development) is able to provide funding for demonstration projects of Japanese energy technologies in other countries [56]. NEDO used to fully fund the projects, but in 2018 this changed to 50% fundings for large companies and 67% funding for small and medium sized companies. In 2017, the budget for NEDO was 14 billion ¥ (which is approximately 126 million US$) [56].
In 2018, the HESC (Hydrogen Energy Supply Chain) pilot launched. This pilot is a bilateral economic relationship between METI and the Department of Industry, Innovation and Science of Australia. This is a $500 million pilot where hydrogen is produced from brown coal and liquefied in Victoria's Latrobe Valley (Australia) to be transported to Kobe (Japan) [68][69]. In January 2020, a joint statement on cooperation was signed by both parties to further explore opportunities for developing and transporting hydrogen as a clean, secure, affordable and sustainable source of energy [70]. The liquid hydrogen terminal in Kobe is the largest in Japan with a volume of 2,500 m^3 [71]. The first liquefied hydrogen from Australia to Japan was shipped in 2021 and is thus currently operational.

Japan handles a relatively strict regulation with respect to hydrogen compared to other countries, because Japan handles hydrogen similar to how industrial gases are handled in large-scale chemical plants where there is a high risk of explosions. This means among other things that larger distances are applied for the hydrogen refueling stations than for conventional refueling stations, which is an expensive criterion in a dense city like Tokyo. Another example of these strict regulations is that the whole hydrogen refueling station is equipped with sensors that detect if there is a hydrogen leakage and if so it will immediately shut down the pump. Also, self-service pumps are not allowed in Japan which means that the refueling itself needs to be executed by licensed personnel which limits the amount of opening hours of the refueling station drastically [56]. These examples are barriers causing the enrollment of a hydrogen infrastructure and the development and construction of hydrogen refueling stations (HRSs) in Japan to be relatively expensive to other countries. The cost of constructing a hydrogen refueling station is approximately 2 to 3 times as expensive in Japan compared to Europe [56]. In order to financially support the investments and to coordinate the development of the hydrogen refueling stations a consortium of 11 car manufacturers, infrastructure developers and investors established the joint-venture called Japan H_2 Mobility (JHyM) [56][64]. This joint-venture aimed at creating a pool for private investments as well as government grants in order to finance the construction of hydrogen refueling stations. This resulted in a cost reduction of approximately 10-20%. Using this scheme, 80 HRSs are expected to be built. This joint-venture also aims at standardizing equipment, optimizing driver usability and supporting the deregulation of industry standards [56].

The Government subsidizes the hydrogen refueling stations as well as the fuel-cell vehicles themselves [64]. Currently there are two car manufacturers in Japan that produce FCEVs: Toyota and Honda. Toyota has the largest share of FCEVs in Japan. The price of the Toyota Mirai is 7.24 million ¥ (66,000 US$) and the price of the Honda Clarity is 7.66 million ¥ (69,000 US$). A single refill of the tank costs for the Mirai approximately 5,000 - 6,000 ¥ (which is similar to 46 - 66 US$) which is a reasonable price compared with gasoline (which costs 140 ¥/L in Japan) [56]. The costs of the car when bought are partly being subsidized by the METI and the local governments. METI subsidizes 2.02 million ¥ (or 18,400 US$) and local governments subsidize up to half of this depending on the local government [56]. Only the Toyota Mirai is available for purchase, the Honda Clarity is optional for leasing. When the lease lasts a period of at least 4 years, the same subsidies apply as for purchasing an FCEV. For taxi-drivers the FCEV would be subsidized for a third of the purchasing cost (2.23 - 2.36 million ¥) by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Local governments subsidize taxi-drivers for another 1.11 - 1.18 million ¥ which reduces the final consumption price to 3.36 - 3.55 million ¥ (30,000 - 32,000 US$). For fuel-cell buses a similar regulation is enforced. The purchasing costs of a fuel-cell bus is approximately 105 million ¥ (945,000 US$) and the Ministry of Environment (MOE) subsidizes a third (35 million ¥) and local governments are expected to also provide an additional subsidy of 35 - 50 million ¥ which would finally reduce the purchasing costs to 20 - 35 million ¥ (which is 180,000 - 315,000 US$) [56]. The initial purchasers of the FCEVs in Japan were governmental bodies and enterprises. Currently also many private consumers own an FCEV, approximately 40% of the total FCEVs in Japan are owned by private consumers [56].

From the information above it can be concluded that the Japanese approach differs from the Dutch approach to decarbonize the economy. Japan heavily invests in hydrogen as a multi-sectoral solution for energy storage, balancing supply & demand and distributing the produced energy. Ironically, Japan is disadvantaged to the Netherlands, because where Japan lacks an existing gas pipeline infrastructure, the Netherlands has a well developed gas infrastructure and where Japan lacks the potential for wind and solar energy production plants, the Netherlands has a relatively high renewable energy potential on land and at the North Sea. However, Japan focuses dominantly on hydrogen by actively increasing public awareness through governmental bodies, creating agreements with other countries a providing financial support for these agreements to establish a long-term hydrogen import potential and developing a joint-venture to minimize the costs for establishing a national covering hydrogen refueling infrastructure for the mobility sector.

3.3. Overall conclusion on the differences in the three policy approaches

In the approach of Germany and Japan several similarities can be found. These are for example the creation of a consortium to assemble relevant stakeholders and create a coordinated refueling infrastructure with nation wide coverage, simultaneously stimulating the hydrogen supply as well as the hydrogen demand and as a government committing to hydrogen as a long-term solution to reach the climate goals.
Creating a consortium has the ability to accelerate the process of developing a nationally covering refueling infrastructure while reducing the overall costs and allocating the risks of high investments more evenly among all stakeholders. Both countries simultaneously financially stimulate the hydrogen demand and supply. For the demand Japan invested $147 million in FCEVs and Germany subsidizes $4000 per vehicle, whereas in the Netherlands the demand has a lower priority [8].
And both countries made a long-term commitment to hydrogen as means to reach the climate goals as Japan invested $61 million in the hydrogen infrastructure and Germany $466 million [8].
Geographically the two countries also differ from the Netherlands. In the Netherlands the need to drive for more than three hours is rare, whereas for Japan and Germany the travel distances are larger. This results in the fact that in the Netherlands most people could suffice with BEVs whereas these are less opportune for countries like Germany and Japan where the travel distances are larger [interview].

Lessons learned could be that with current policy, the Netherlands is bound to only develop a hydrogen infrastructure at locations where it is lucrative while it has great potential for developing a nationally covering infrastructure by retrofitting the existing gas pipeline infrastructure. And that in order to decarbonize the mobility sector in the Netherlands it is advisable to create a consortium with relevant stakeholders, stimulate, like Germany and Japan, the demand side simultaneously with the supply side and to make a long-term commitment to hydrogen as it is a fitting means to reach the Dutch climate goals.

4

Supply chain analyses

In this research the following two supply chains were selected to be analyzed:

1) Supply chain A: Large-scale hydrogen production with distribution via tube-trailers;
2) Supply chain B: Large-scale hydrogen production with distribution via the hydrogen backbone.

These supply chains differ in operational costs as gas transport through a pipeline network is generally the cost-effective alternative, but also in readiness. With readiness is meant that where supply chain A can be developed in (roughly estimated) a year time, supply chain B has to wait until the hydrogen backbone is developed and operational which will be in 2027. Also will supply chain A result in a more logistically complicated system whereas supply chain B is a continuously operating flow and supply chain A is considered the base case in the Netherlands for the currently existing hydrogen refueling stations, while it can be expected that supply chain B would in the long-term be a more suitable alternative. Therefore the decision was made to compare these two supply chains for a hydrogen refueling station with a functional unit of 2000 kg/day as demand and is located in the Netherlands.

A comparison will be made between these two supply chains based on two aspects. These are respectively the equivalent annual costs (EAC) of the supply chain, consisting of the capital expenditures (CAPEX), operational & maintenance expenditures (OPEX) and the replacement expenditures (REPLEX), and the second aspect is the relevant institutions for the supply chains.

The definition of the total annual costs will be explained in more detail in this chapter.

In order to compare the hydrogen supply chains four joint conditions for the two supply chains will be considered. The first condition is the functional unit of 2000 kg hydrogen per day that will be dispensed. This functional unit of 2000 kg per day is taken into account, because there is a general forecast that the early adopters of hydrogen will consist dominantly out of heavy duty vehicles (HDVs) which refuel more than private FCEVs [72][73]. HDVs tend to use ten to twenty times more hydrogen than fuel-cell passenger cars [64]. A recent report from the Ministry of Economic Affairs and Climate states that the expected share of heavy duty vehicles that are powered by hydrogen will be in the range of 15-50% [72].

The second condition is that the hydrogen refueling station needs to have a fast fill installation with a hydrogen dispensing flow rate of at least 7.2 kg/minute. With a lower flow rate refueling a fuel-cell heavy duty vehicles (FC-HDVs) becomes too time-consuming which brings extra costs with it as the truck cannot be utilized optimally [54]. Opposite to a fast fill installation (with a refueling time of 5 minutes for light duty vehicles and 15 minutes for heavy duty vehicles) is a slow fill installation. A slow fill installation is an installation that allows refueling overnight as refueling a heavy duty vehicle would take typically 8 - 10 hours. A slow fill installation would not require a refrigeration unit since the flow rate is less or equal to 1.8 kg/min for hydrogen at 350 bar and could thus be economically attractive [21][74]. However, this slow fill installation is not likely to be located at publicly accessible refueling stations, but could be encountered at companies or industries with a hydrogen installation that use fuel-cell vehicles that do not operate at night [21]. Therefore in this research the fast

fill installation will be applied.
In a report of TKI Nieuw Gas it is discussed that FC-HDVs would require even a flow rate of 10 kg/min [75]. As it is assumed that a flow rate of 7.2 kg/min would suffice as it will provide a similar refueling time as is currently the case with conventional fuel and is likely to improve the business cases compared to a flow rate of 10 kg/min this value is incorporated in this research.
The third condition for the two supply chains is that the dispensed hydrogen in both supply chains has to be pure enough (at least 99.99%) as is required for application in FCEVs.
The fourth condition is that the hydrogen refueling station needs to be able to provide hydrogen for private FCEVs, which refuel hydrogen at 700 bar as well as FC-HDVs, which refuel hydrogen at 350 bar. This requires from the technical system that the hydrogen must be stored at 880 bar before the hydrogen enters the refrigeration unit, in order to be able to refuel FCEVs with 700 bar hydrogen requirements and has to be stored similarly at 400 bar to be able to refuel heavy duty vehicles with 350 bar hydrogen requirements [76].

Besides these joint conditions, both supply chains also have several similar components and therefore have joint costs that will be made. These joint costs that will be made for both supply chains are the CAPEX, OPEX and REPLEX of the high pressure compressors, the high pressure storages, the refrigeration units, the hydrogen dispensers and the energy consumption.
The equivalent annual costs will be explained as follows: The equivalent annual costs (EAC) consists of the CAPEX, OPEX and the REPLEX. The CAPEX are the capital expenditures required for the investment before or at the start of the system. The OPEX are the operational & maintenance expenditures required for the proper functioning of the system (components) during the timespan. The REPLEX are the replacement plus the depreciation expenditures of the system components. A component needs replacement when the expected lifetime is reached. After this expected lifetime, a new component has to be purchased. For example, the lifetime of compressors is approximately 10 years. Then after 10 years, the compressor would have to be replaced for the refueling station to keep being operational, these are the replacement expenditures. During the 20 years timespan all components will also be depreciated, these are the depreciation expenditures. Even when the expected lifetime exceeds the 20 years timespan, a REPLEX will be accounted for as the component will be depreciated.

The EAC can be calculated by summing the annual costs of all components in the supply chain. For the cost comparison of the two supply chains, the CAPEX and REPLEX will be converted to costs per year over a timespan of 20 years. This will be indicated by the letter 'a' which stands for annual. The operational & maintenance expenditures are already yearly costs, therefore these do not need the notational letter 'a' in subscript. The formulas for calculating the annual costs of the supply chains over a timespan of 20 years are as follows [77]:

$$EAC_{supply chain} = C_{supply chain_{CAPEX,a}} + C_{supply chain_{OPEX}} + C_{supply chain_{REPLEX,a}}$$

$C_{supply chain_{CAPEX,a}}$ are the total capital expenditures of the supply chain converted to yearly costs over a timespan of 20 years.
$C_{supply chain_{OPEX}}$ are the total operational & maintenance expenditures of the supply chain.
$C_{supply chain_{REPLEX,a}}$ are the total replacement and depreciation expenditures of the supply chain converted to yearly costs over a timespan of 20 years.

The annual expenditures of the supply chain can be calculated by summing the annual expenditures of all components in the supply chain. This is mathematically formulated as:

$$C_{supplychain_{CAPEX,a}} = \sum C_{component_{CAPEX,a}}$$
$$C_{supplychain_{OPEX}} = \sum C_{component_{OPEX}}$$
$$C_{supplychain_{REPLEX,a}} = \sum C_{component_{REPLEX,a}}$$

Because the capital expenditures and the replacement expenditures are not yearly costs, but rather costs that will be made at a single moment in time, these costs can be converted to annual expenditures by applying the following formulas:

$$C_{component_{CAPEX,a}} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot C_{CAPEX}$$
$$C_{component_{REPLEX,a}} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \cdot \frac{C_{REPLEX}}{(1+i)^t}$$

C_{CAPEX} are the capital expenditures (or investment costs) of the component.
C_{REPLEX} are the replacement expenditures of the component, thus the costs for a new component.
i is the nominal interest rate, which is assumed to be 3% [77].
n is is the considered timespan which is in this research 20 years.
t is the year of replacement which is equal to the expected lifetime of the component.
The operational & maintenance expenditures (OPEX) are already yearly costs, therefore these do not need to be converted.

The CAPEX, OPEX and REPLEX of the joint components (the high-pressure compressor, high pressure storage, refrigeration units, the dispensing units and the energy consumption for the compression, cooling, dispensing and purifying of hydrogen) are presented in table C.1.
Note that the CAPEX and REPLEX in table C.1 are converted to annual costs as has been indicated by the letter 'a' in the subscript. The calculations of these costs can be found in Appendix C.

Table 4.1: Joint costs for both supply chains, see Appendix C for all references and calculations

Plant section	**CAPEX,a [€/year]**	**OPEX [€/year]**	**REPLEX,a [€/year]**
High pressure compressor	252,000	150,000	187,500
High pressure storage	19,000	3,000	8,000
Refrigeration unit	280,000	22,000	210,000
Dispensing unit	35,000	16,000	26,000
Energy consumption	N/A	351,500	N/A

The number of the refrigeration units and dispensing units increase based on the hydrogen demand. These required amounts are 1, 2 and 4 units for hydrogen refueling stations with a hydrogen output of respectively 100 kg/day, 1000 kg/day and 2000 kg/day [78]. Therefore in this research for each supply chain the decision has been made to implement 4 refrigeration and dispensing units. Thus the CAPEX, OPEX and the REPLEX of these two units have in the analyses been multiplied by four.
The CAPEX, OPEX and REPLEX of all other components for both supply chains can be found in Appendices D and E.
Among the component list is the energy consumption of the system components. Because the energy for the operation of these components will be provided by the electricity grid, this energy consumption is in both supply chains monetized by multiplying the energy consumption by the average

electricity price in the Netherlands in 2020. The costs for the electricity grid enforcement are out of the scope of this research.

The price €5.24 per kg hydrogen ±5% was the estimated price of renewable hydrogen in 2017. This price is expected to decrease to €2.92 per kg hydrogen ±25% in 2025 and decrease even further towards 2030 [79]. However, for the short to medium term it can be expected that low carbon hydrogen will be commonly applied in the Netherlands which is produced by natural gas reforming. As can be obtained from Appendix B the costs for SMR with CCS are rising over time. The levelized costs of hydrogen through SMR with CCS of the past 3 years are considered (2019 - 2021). These prices have an average of approximately 2 €/kg. The expected hydrogen price of the hydrogen that will be transported through the backbone is also €2 per kg hydrogen [80].Because the production costs for hydrogen are similar in both supply chains with a price of €2 per kg hydrogen and they do not affect the differences in costs for distribution, the hydrogen production costs will be disregarded in the supply chains comparison. As 2000 kg per day is demanded, the yearly costs for the hydrogen are as follows:
2 [€/kg] · 2000 [kg/day] · 365.25 [days/year] = 1,461,000 [€/year]
The costs are approximately 1,461,000 €/year.
The hydrogen production costs are disregarded in the analyses, however it should be noted that the hydrogen costs are a relatively large fraction (approximately 40%) of the yearly costs of the hydrogen supply chains.

4.1. Supply chain A: Tube-trailer road delivery

4.1.1. Technical system

Currently there are 8 hydrogen refueling stations operable in the Netherlands [81]. Six of these refueling stations receive their hydrogen via tube-trailer road delivery. The supply chain of hydrogen delivery via tube-trailers contains the components listed below [62][82][83]:

- Centralized hydrogen production with PSA
- Off-site hydrogen storage
- Low pressure compressor
- Tube-trailer
- On-site medium pressure hydrogen storage
- High pressure compressor
- On-site high pressure hydrogen storage
- Refrigeration unit (4x)
- Hydrogen dispenser (4x)
- Grid connection

The hydrogen is produced at a large-scale production plant where it is likely to be stored at a pressure of 200 to 300 bar [84]. The hydrogen will be compressed at the plant to 500 bar in order for the tube-trailer to be able to supply 1000 kg of hydrogen per load [12]. The hydrogen will then be stored in a buffer at the hydrogen refueling station at 500 bar which consists out of a cascade of multiple pipes. From the medium pressure storage, the hydrogen is allowed to flow to the 350 bar dispenser where heavy duty vehicles are able to refuel at 350 bar, but will also be connected to a high-pressure compressor which will compress the hydrogen to a pressure of approximately 880 bar for vehicles that refuel at 700 bar [85]. The hydrogen before dispensing will be pre-cooled by a refrigeration unit. The technical system is graphically presented in figure 4.1.

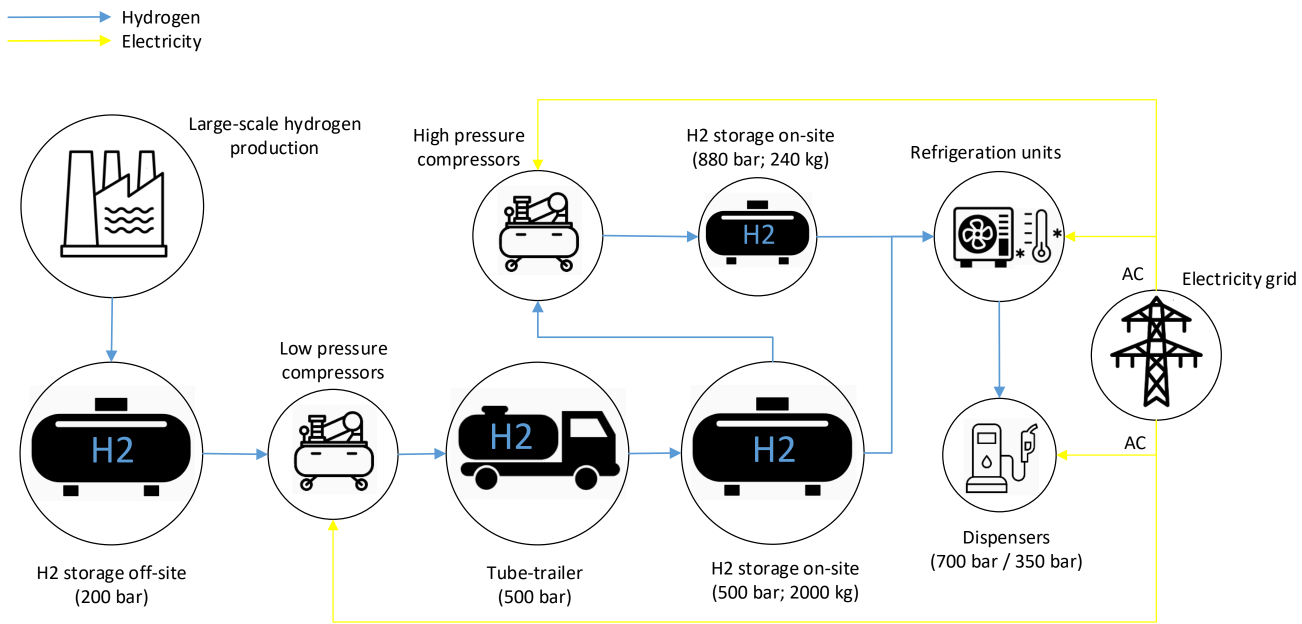

Figure 4.1: Tube-trailer supply chain schematically displayed

The production process at the centralized hydrogen production plant is out of the scope of this research. However, it is plausible that until 2030 the hydrogen will be produced by natural gas reforming combined with carbon capture and storage (CCS) technologies. Therefore the price assumption of the hydrogen is based on the average levelized cost of hydrogen from steam methane reforming (SMR) combined with CCS as presented in Appendix B.
Even though it is expected that tube-trailers that operate at 500 bar will in 2025 still be more expensive per kg of hydrogen than tube-trailers that operate at 200 bar [12], the 500 bar trucks provide a good balance between costs and deliverable volumes [86].
The on-site medium pressure hydrogen storage will have a capacity of 2000 kg and the high-pressure storage will have a capacity of 240 kg. This is extrapolated from a different study that for a hydrogen refueling station with a hydrogen demand of 1875 kg per day had a low pressure storage of 1875 kg and a high pressure storage of 225 kg [51]. This study especially incorporated the hydrogen demand of heavy duty vehicles and therefore this data is extrapolated to fit the case in this research with a hydrogen demand of 2000 kg/day.

4.1.2. Cost analysis

According to a recent report 'HyWay 27' from the Ministry of Economic Affairs and Climate is the mode to transport small volumes per year cost-efficiently via compressed hydrogen tube-trailers [72]. The overview as presented in 'HyWay 27' is shown in figure 4.2. The functional unit of the supply chain in this research is a hydrogen production of 2000 kg per day. In contrary to the literature where is noted that the lower heating value (LHV) should be considered for the analyses, in this research the higher heating value (HHV) will be applied [80][87][88]. Hydrogen has an energy density of 142 MJ/kg (higher heating value) [89][90]. Thus per year the energy that needs to be transported to the hydrogen refueling station is 103,731,000 MJ which is the same as 0.104 PJ. According to the report of the Ministry of Economic Affairs and Climate, the cost-efficient transportation mode for transport distances up to 100 km would be compressed gas tanks.

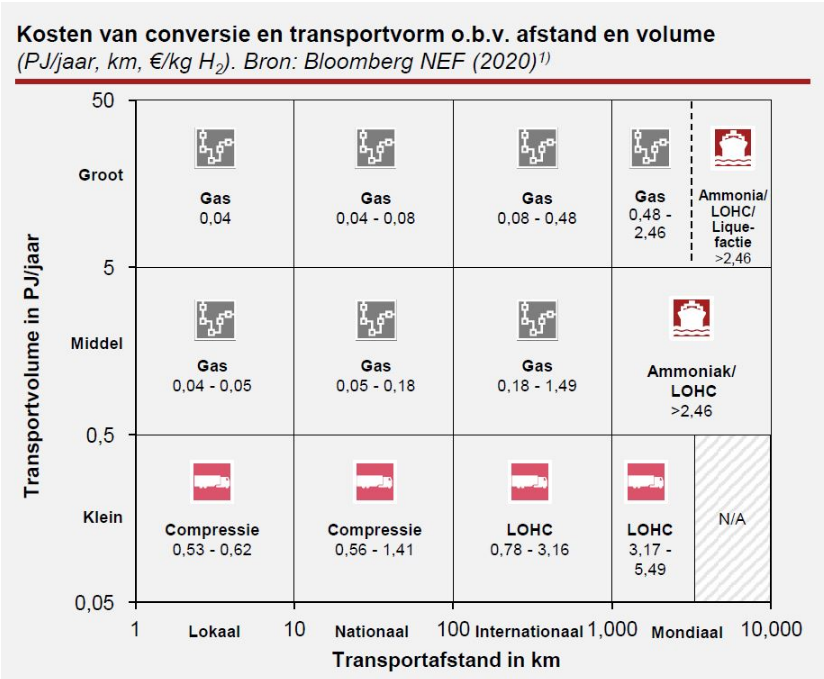

Figure 4.2: Overview of the cost-efficient transportation modes based on transport distance and volumes [72]

The ratio of the weight of the tube-trailer vessel and the transported material, which is in this supply chain hydrogen, influences the business case of transportation using tube-trailers [91] [interview]. Currently this is done using compressed hydrogen in tubes at approximately 250 bars. But for this supply chain a tube-trailer with 500 bar will be applied, because when it makes 2 round trips the total delivered amount of hydrogen adds up to approximately 2000 kg. For the smaller tube-trailers or with a lower operating pressure more round trips would be required and that would increase in the operational costs. For the larger tube-trailer or at higher pressures the investment costs would increase increasingly [62] [86].

The transport costs consist of the variable costs due to the driving distance. The transportation costs for hydrogen by tube-trailer are estimated at approximately 1.78 €/km [92]. Because the tube-trailer has a maximum capacity of 1000 kg per trip it will have to make two round trips in order to supply 2000 kg per day at the refueling station. Therefore a transportation cost of $2 \cdot 1.78 = 3.56$ €/km is considered. For the cost analysis the transportation cost needs to be converted from daily costs to yearly costs. Therefore the 3.56 €/km will be multiplied by 365.25 days per year which is approximately 1300 €/km. It is plausible that the costs of transporting hydrogen would deviate a bit because the driver might be required to have additional certificates [interview]. But, it is not likely that the costs will be significantly higher or lower. Concluding, the costs for transporting hydrogen by tube-trailer road delivery is €1300 per kilometer for two round trips with a delivery of 2000 kg. Assuming a distance of 100 km between the hydrogen production facility and the hydrogen refueling station, this cost is:
1300 [€/km/year] · 100 [km] = 130,000 [€/year]
The transportation costs by tube-trailer are approximately 130,000 €/year.

The hydrogen considered in this research is low carbon hydrogen which is produced through an SMR process. Because the hydrogen is produced through SMR it does not meet the purification requirements for application in fuel-cells, thus a purification step is required. A Pressure Swing Adsorption (PSA) process for the purification step is expected to add approximately 0.40 US$/kg to the hydrogen price in 2025. Converted to € this is approximately 0.36 €/kg.
As 2000 kg of hydrogen per day is demanded and on average there are 365.25 days in a year, the total yearly costs for the hydrogen purification are:
0.36 [€/kg] · 2000 [kg/day] · 365.25 [days/year] = 262,980 [€/year]
The yearly costs for the low carbon hydrogen purification are estimated at €263,000.

An overview of all costs is presented in Appendix D. The distributions of the CAPEX, OPEX and REPLEX are visually presented in figures 4.3, 4.4 and 4.5 and are enlarged presented in Appendix F.

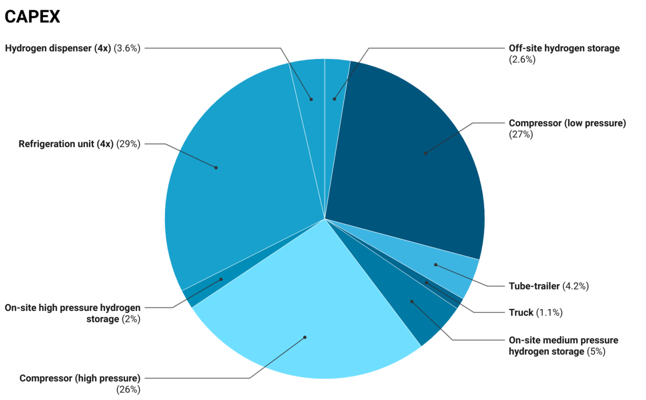

Figure 4.3: Cost distribution of the CAPEX of supply chain A

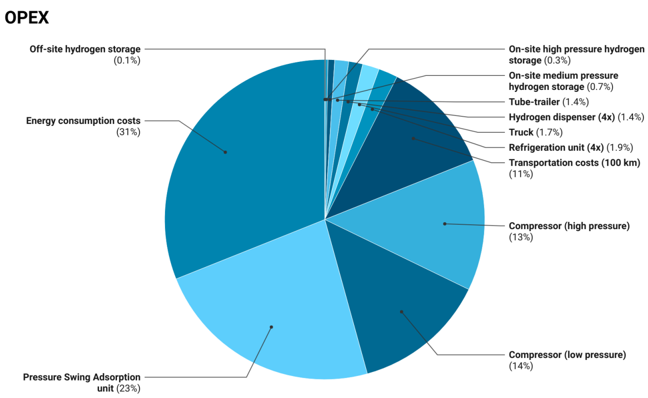

Figure 4.4: Cost distribution of the OPEX of supply chain A

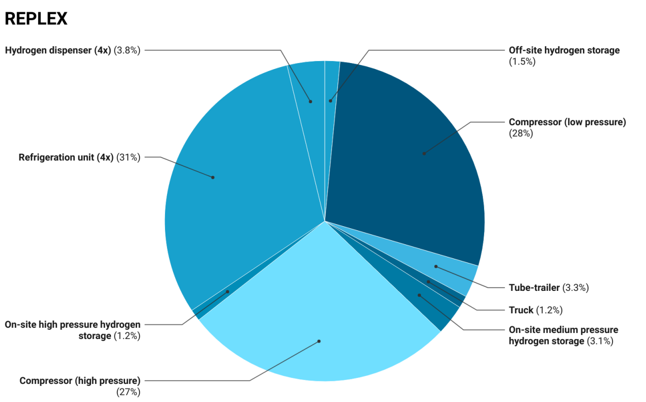

Figure 4.5: Cost distribution of the REPLEX of supply chain A

The subsidy that this supply chain would be eligible for is the DKTI-regulation. This regulation was, as is noted in Appendix A, specifically created for leveling the difference in costs between conventional fuel trucks and the sustainable alternative. This regulation could subsidize part of the difference in costs between the investment cost for a conventional truck and a hydrogen truck. However, the application for the DKTI regulation is currently closed.

4.1.3. Relevant institutions

Specifically for the supply chain with tube-trailer road delivery for the hydrogen distribution several institutions apply, the most relevant being the maximum weight of the tube-trailer. The European Union enforces a maximum weight of vessels that is allowed to drive on public roads. The weight ratio of the vessel and the transported hydrogen are relevant for the business case. These limits are presented in the report 'Regelingen Voertuigen' for the Netherlands. This maximum weight differs slightly between the European countries. The EU guidelines prescribe a limit of 40 tons, but the Netherlands enforces 50 tons as the maximum weight of the vessel [93]. This means that a limited amount of tubes can be transported simultaneously and thus a higher pressure in the tubes would be beneficial for transporting higher hydrogen volumes.

For the storage of hydrogen the requirements of the WBDA 2016 have to be implemented. And when the storage is mobile, like in the tube-trailer road delivery supply chain, the ADR-regulations have to be enforced as well [21]. In this ADR the guidelines for the safety measures of tube-trailers are discussed. An example of such requirement for the hydrogen storage tanks is that it is not allowed that it fails within 60 minutes of a regular fire, according to NEN-EN 1363-1 [21].
When the hydrogen is supplied using vehicles, it is a condition that that vehicle has enough space to drive, manoeuvre and park the vehicle at the HRS [21]. Other specific guidelines for the supply of hydrogen are discussed in the report SAE J2601 [94].

4.2. Supply chain B: Hydrogen backbone

The European hydrogen backbone will consist of 6.800 kilometers of pipelines in 2030 and will gradually grow to a mature backbone with approximately a 23,000 km length by 2040 [80][95]. Approximately 1100 km of the backbone will be located in the Netherlands by 2030 of which 70% - 90% exists out of retrofitted natural gas pipelines [80]. The purity of the hydrogen that will be transported through the backbone is unclear yet, but expectations are that the hydrogen purity will be approximately 98% [72][80].
The European Commission reported that ultimately the hydrogen transported through the backbone will be renewable hydrogen, but that low carbon hydrogen has a role in the short to medium term [80]. Especially in the 2020s, when hydrogen shares are small, blending shares of hydrogen with methane for transport makes sense [80]. This hydrogen blend could then be purified on-site at the HRS.

4.2.1. Technical system

In the Netherlands the hydrogen backbone can be connected to the existing gas pipeline infrastructure to develop a national covering infrastructure. A supply chain with hydrogen transportation through the pipeline infrastructure can have supply on demand. Due to line packing storage is possible in a pipeline infrastructure. Therefore on-site hydrogen storage can be minimized. For the retrofitted pipeline infrastructure it is necessary that the pressure does not shift majorly [interview]. Large and quick fluctuations in pressure will lead to weaknesses in the material that the tubes are made of and is thus not desired [interview]. This is already the case for fluctuation of +/- 10 bar, pressure changes every hour or even 5 times a day [interview]. For a newly designed dedicated hydrogen pipeline to the backbone it could be possible to quickly change the pressure inside the tube. However, pressure swings in the infrastructure, due to the hydrogen demand of a hydrogen refueling station, are not expected in this system and are therefore neglected.
A presentation of the location and length of the hydrogen backbone infrastructure in the Netherlands in 2030 is displayed in figure 4.6.

Figure 4.6: Hydrogen backbone infrastructure in the Netherlands in 2030 [96]

The supply chain of hydrogen delivery via the hydrogen backbone and the existing gas infrastructure in the Netherlands contains the components listed below:

- Centralized hydrogen production
- Connection to the Backbone
- Retrofitted gas pipeline infrastructure
- Valve and metering unit
- Pressure Swing Adsorption unit
- Low pressure compressor
- On-site medium pressure hydrogen storage
- High pressure compressor
- On-site high pressure hydrogen storage
- Refrigeration unit (4x)
- Hydrogen dispenser (4x)
- Grid connection

The hydrogen will be produced at large-scale centralized hydrogen production plants which will be connected to the hydrogen backbone. In order to distribute the hydrogen to decentralized locations, the existing 8 bar natural gas infrastructure can be retrofitted to transport hydrogen. Because the hydrogen for application in fuel-cell electric vehicles has a purity requirement of 99.99% the hydrogen has to be purified on-site [97]. This purification can be done via multiple techniques [98]. The purity of the hydrogen feed from the backbone can be assumed to be approximately 97.5% - 98.5% [72][80]. Therefore only purification techniques that perform with similar purities of hydrogen feed will be considered and that can provide a purity of >99.99% hydrogen output. These are: pressure swing adsorption (PSA), polymer membranes or metal membranes. PSA systems have a relatively fast process cycle, are able to produce high purity hydrogen flows at a continuous rate and are able to produce a high purity hydrogen output flow at the same pressure of the input hydrogen flow [99]. Also PSA does not require (rare or noble and) expensive metals like Pd as a metallic membrane would [100][101]. Therefore the decision was made to apply a Pressure Swing Adsorption (PSA) system for the hydrogen purification. The company HyGear also applied a PSA system for the purification for the hydrogen refueling station.
After the purification step, the hydrogen enters the low pressure compressor that will compress the hydrogen to 400 bar in order for HDVs to refuel at 350 bar. Part of the hydrogen from the low pressure compressor will be connected to a high pressure compressor to be further compressed to 880 bar so that vehicles are able to refuel hydrogen at 700 bar.
The hydrogen before dispensing will be pre-cooled by a refrigeration unit. The technical system is graphically presented in figure 4.7.

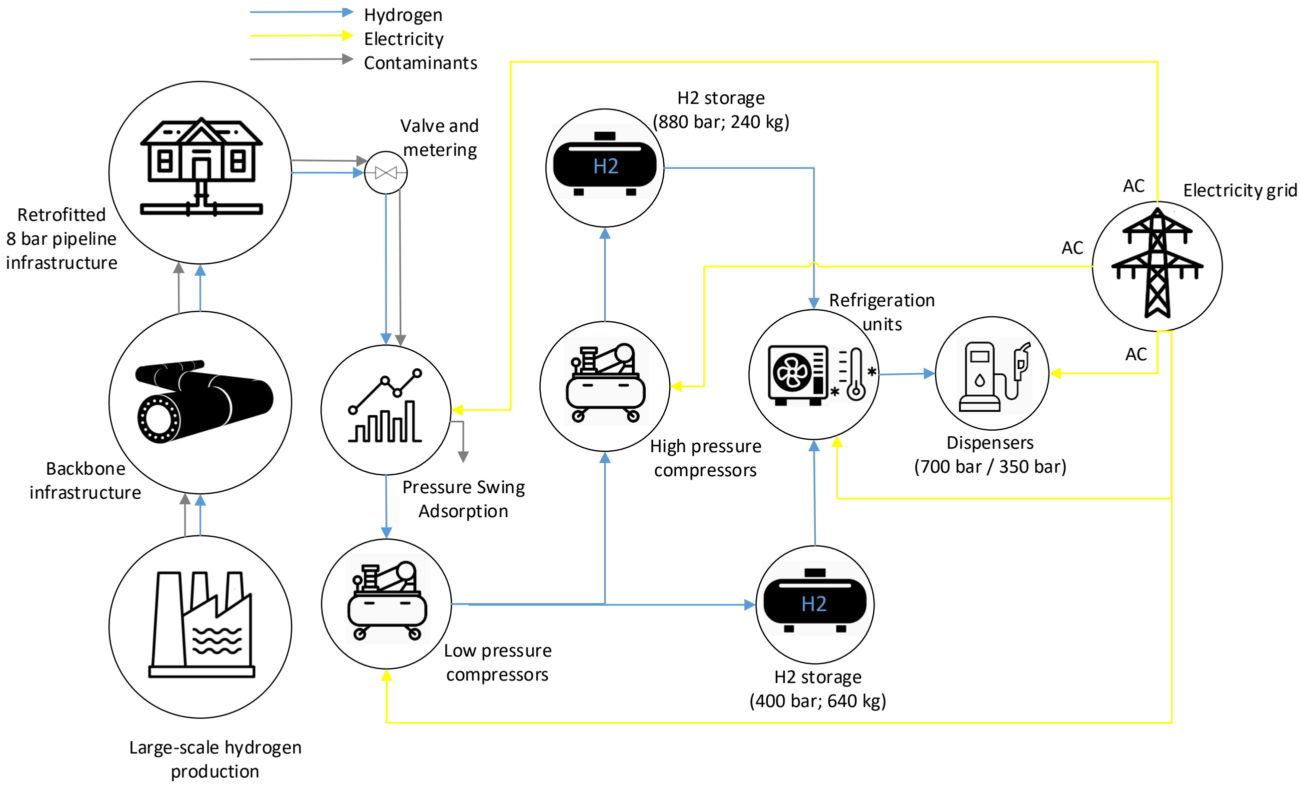

Figure 4.7: Hydrogen backbone supply chain schematically displayed

HyET Group is a company that has among other things developed a membrane that is integrated with a compression unit for the application in pipeline infrastructure. The Electrochemical compression technology has the ability to simultaneously separate and purify hydrogen from a wide range of mixed gas streams [102]. This technology can achieve a purity that is high enough for the application in the mobility sector and the required pressure [interview] [102]. This technology would have the ability to significantly lower the CAPEX and OPEX of hydrogen supply chains, therefore it would be interesting to consider this process in further research. Also it could accelerate the possibility to use the current natural gas infrastructure for natural gas and hydrogen simultaneously as it could be separated on-site by this technology. To optimally utilize this technology it would be relevant to adapt the current limits for mixing hydrogen with natural gas through the pipeline infrastructure to increase the hydrogen flow. These limits differ per country in Europe and for the Netherlands the limit of blending hydrogen with natural gas is 0.02 volume percent [103]. For comparison, in Germany the blending is limited to <10 volume percent. It would be advisable to further research whether this limit in the Netherlands could be raised safely and if so to raise the limit.

4.2.2. Cost analysis

Gasunie in the Netherlands has offered to develop the hydrogen backbone in the Netherlands based on the existing gas infrastructure. The total cost of the adjustments of the existing infrastructure is estimated at 1 - 1.5 billion € [104]. The main industry locations will be directly connected to the hydrogen backbone due to their large hydrogen demand. Other sectors are expected to connect to branch outs of the backbone [104]. Especially the two main leading markets, industrial applications and the mobility sector, are expected to gradually apply more hydrogen in their energy mix to reach a climate-neutral economy cost-effectively for which the backbone could be a large influence [32].

The costs for connecting a hydrogen refueling station to the hydrogen backbone are per component presented in Appendix E. The distributions of the CAPEX, OPEX and REPLEX are visually presented in figures figures 4.8, 4.9 and 4.10 and enlarged presented in Appendix F.

The main barrier of developing a pipeline infrastructure for hydrogen are the high up front investment costs. The costs of a new pipeline (including gas metering) require an investment of approximately €2.75 million per kilometer [80]. (The costs of a new pipeline infrastructure are approximately €3 million per kilometer [interview]). However the advantage of the Netherlands is that there is already an existing gas pipeline infrastructure. The costs of retrofitting the existing infrastructure are approximately 0.84 million €/km [72]. Thus approximately 72% less expensive than creating a new pipeline infrastructure.
Besides the actual pipeline also a connection is needed. As cost indication, the connection costs for a pipeline of approximately 10 - 15 cm are a few million € [interview]. But, these connection costs can be depreciated over 30 years or more, thus the final operational costs will be considerably less. Similarly as indication, a pipeline connection of 200 meters for the supply of 100 kg hydrogen per hour (or 2,400 kg per day) will be in the order of magnitude of 1.5 million euros [interview]. Both these costs will be made by the infrastructure operator which is most likely to be Gasunie for the Netherlands. The costs for the infrastructure operations will be divided among all users that will be connected to the infrastructure [interview]. Therefore in this research a single transportation cost has been assumed which is 0.13 €/kg/1000 km [80]. The lifetime of the pipeline infrastructure is approximately 50 years [72] (50 - 100 years [8]). But fluctuations in the pressure could decrease the lifetime expectations of the infrastructure [8]. However, as the pressure in the infrastructure is not likely to change due to the demand of a single hydrogen refueling station, the lifetime of 50 years is considered.

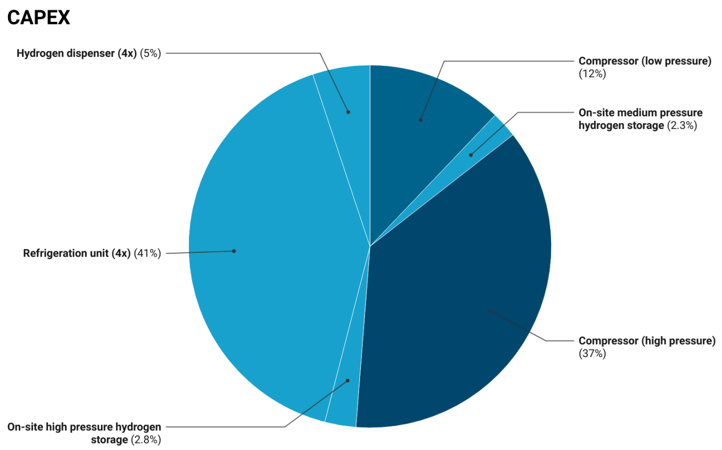

Figure 4.8: Cost distribution of the CAPEX of supply chain B

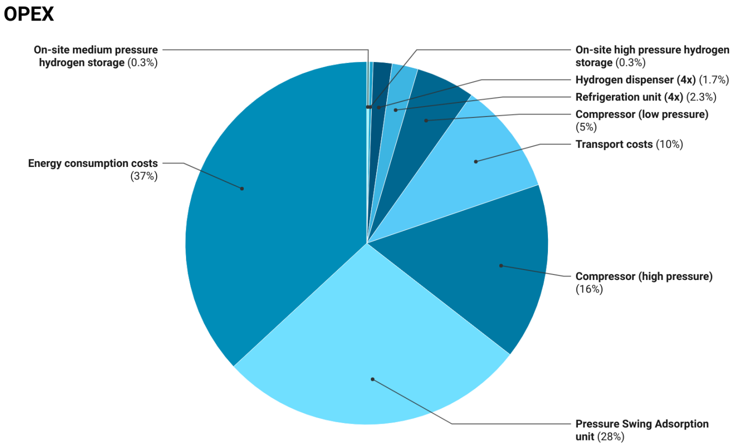

Figure 4.9: Cost distribution of the OPEX of supply chain B

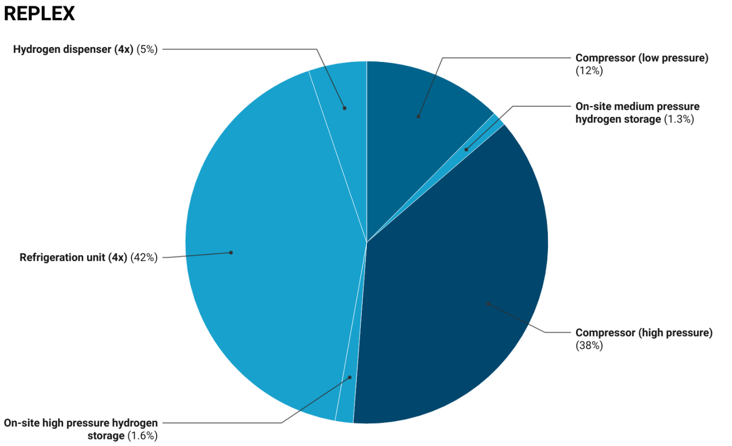

Figure 4.10: Cost distribution of the REPLEX of supply chain B

From these figures can be deducted that within the investment costs the components with compressors are dominant for supply chain B. This suggests that the investment in this supply chain would benefit significantly from cheaper or subsidized compression units. And it is expected that the compressor costs will reduce significantly (almost halve) in the future [105]. Thus the economic prospects of supply chain B are promising.

There are subsidies available for smaller hydrogen backbone projects, however Gasunie is aiming at a cooperation with the Dutch government to not apply for a single subsidy but to have the government co-finance the entire infrastructure [interview]. In September 2021, the national budget has been presented where was made known that the Dutch government will invest 750 million € in the development of the hydrogen backbone [106].
Examples of other stimulances are the Innovation fund, Heaven and RED2 for parties that Gasunie works together with, but not for Gasunie itself. Gasunie is eligible for IPCEI (International Project with Common European Interest) which is not a subsidy, but it is an international recognition that a government is allowed to provide financial support for projects that are eligible for IPCEI.

4.2.3. Relevant institutions

The risk guidelines with respect to external safety that transport companies need to meet when transporting dangerous materials differ. These companies need to comply with the 'Besluit externe veiligheid buisleidingen (Bevb)' guidelines which distinguishes three categories: natural gas, oil and chemicals [72]. This means that the handling of hydrogen through pipelines has different guidelines than the handling of natural gas.
Before the start of the building of the hydrogen refueling station and decision whether or not the station will be connected to the hydrogen backbone, a tracé study would have to be executed in order to gain insights into the safety measures that have to be taken into account for the placement of the pipelines and whether or not permits or permissions from stakeholders are required [interview]. However, this is only of relevance when the existing pipeline infrastructure does not yet reach the location of the hydrogen refueling station and thus new pipelines would have to be placed.
For underground pipelines there are certain requirements. These are [21]:

- The pipeline has to be made out of corrosion resistant materials or has to be protected from corrosion;
- The pipeline has to be placed in clean sand with a minimum layer thickness of 10 cm;
- The pipeline has to be buried with a ground cover of at least 60 cm;
- The ground that covers the pipeline has to be marked;
- The pipeline has to be protected from mechanical influences.

When Gasunie is asked to install these pipelines, they have the knowledge how to handle these issues and what (not) to do [interview]. Also commercial parties may not be allowed to make a connection to the infrastructure of Gasunie. And when the pipeline has to go through someone's land it is more likely that that person is willing to cooperate when Gasunie is the involved party then when it is a commercial party [interview]. However, Gasunie is not the cheapest stakeholder that could place a dedicated hydrogen pipeline or perform a tracé study [interview].

The use of an underground pipeline infrastructure in considered safer than road distribution via tube-trailers [107].
Hydrogen transport through pipelines is relatively safe compared to natural gas transport, which is currently distributed through the pipeline infrastructure, because hydrogen has only one third of the energy density of natural gas [108].
Another reason why distributing hydrogen through a pipeline infrastructure is relatively safe is that using a pipeline infrastructure with on-demand hydrogen supply, there is a minimum amount of on-site hydrogen storage required at the refueling station. Whereas for hydrogen supply by tube-trailers, the hydrogen for the vehicles will be gathered at the refueling station before dispensing. Thus relatively less hydrogen is stored on-site with pipeline hydrogen supply and therefore that is considered a safer alternative.

4.3. Comparison of the supply chains

The two supply chains will in this section be compared. First the supply chains will be compared based on the costs and secondly differences of the institutional analyses results will be discussed.

4.3.1. Costs

The investment costs of retrofitting the existing gas pipeline infrastructure and developing the hydrogen backbone are relatively high from a perspective of a single hydrogen refueling station. But when looked at the entire system and the lower operational expenditures compared to using tube-trailers for hydrogen road delivery this is more nuanced. Developing a dedicated hydrogen pipeline infrastructure will result in a national distribution network for hydrogen providing the supply of hydrogen for all kinds of sectors and demands.

Table 4.2: Cost comparison of the two supply chains

Cost [M€/year]	**Supply chain A (Tube-trailers)**	**Supply chain B (Backbone)**
CAPEX	0.972	0.685
OPEX	1.132	0.953
REPLEX	0.686	0.50
EAC	2.79	2.14

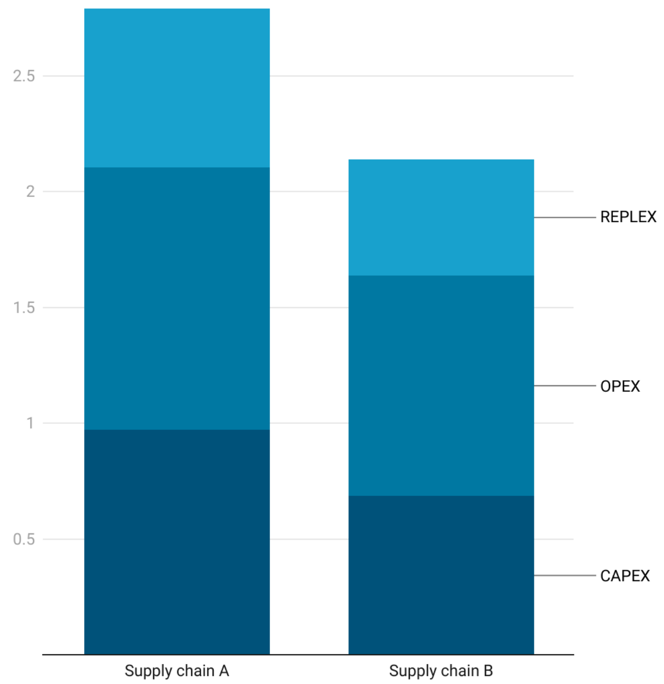

Figure 4.11: Cost comparison of the two supply chains based on the CAPEX, OPEX and REPLEX converted to yearly costs

From table 4.2 and figure 4.11 can be deducted that the difference in costs is approximately 0.65 million €/year for a single hydrogen refueling station when the hydrogen is supplied via a pipeline infrastructure compared to tube-trailer road delivery. That is a cost reduction of approximately 23%. This suggests that in order to reach the break-even point for a hydrogen refueling station, the HRS would require a revenue of €650,000 more per year when the hydrogen is delivered by road than when the hydrogen is supplied by a pipeline network. That is a major impact on the business case for refueling stations. Especially for the limited margins that heavy duty vehicles in the mobility sector have to cope with.

The total volume of hydrogen that is supplied in a year is:
2000 [kg] · 365.25 [days/year] = 730,500 [kg/year].
That means that the costs for distributing hydrogen over a distance of 100 km using tube-trailers is approximately:
2.79 [M€] / (0.73 · 10^6) [kg] = 3.82 [€/kg].
Distributing the hydrogen through a national pipeline network would result in a distribution cost of approximately:
2.14 [M€] / (0.73 · 10^6) [kg] = 2.93 [€/kg].
Thus distributing hydrogen through a pipeline network could potentially reduce the hydrogen price at the filling point with almost €0.90 per kg hydrogen.

If the refueling station could be connected to a dedicated hydrogen pipeline infrastructure, the CAPEX, OPEX and REPLEX could be reduced and therefore a lower hydrogen price could be provided at the pump. This is likely to increase the willingness of transport companies to buy FC-HDVs and thus accelerate the application of hydrogen in the mobility sector. If the hydrogen is produced without emitting or emitting less carbon dioxide like is the case in this research, the sector would decarbonize.

4.3.2. Policy

Generally speaking, the policies that apply to a hydrogen supply chain in the Netherlands are complementary to the policies from the European Union. There were no contradictions found in the literature or during the conducted interviews. What was found however is that the current policies lag behind the drive of technical experiments and projects. Barriers due to current policy are relevant to resolve for the progress of the hydrogen economy and reductions in emissions. An example of these barriers that was mentioned in this chapter is the limit of blending hydrogen with natural gas where the technology of HyET Group could have a major impact for the acceleration of using the existing gas network infrastructure for the transportation of hydrogen. While this technology is being developed current limits for blending hydrogen with natural gas in the Netherlands should be raised to the maximum allowed ratio where safety requirements are still met. Policy should not be the barrier for the application of such technology, therefore it is needed that already, before the technology has matured enough to be implemented, the process of policy adjustment starts so that when the technology is ready to be used it can directly be applied.

With respect to the two supply chains that have been considered in this research, the policy differs per supply chain.
For supply chain A with tube-trailer road delivery the policy barriers are not limiting the business case, however, tube-trailers for hydrogen transport would have to make at least two round trips per day to supply 2000 kg of hydrogen to the refueling station. Thus the movement on the road would increase by higher demands and therefore it is less desirable than the alternative distribution modes.
For supply chain B the main policy barriers lay in the construction of the infrastructure. When the station would be in operation, the policy is not likely to be a bottleneck for the business case. Supply chain B is considered to be the safest distribution mode for hydrogen.
For refueling stations where it is difficult to connect to a dedicated hydrogen pipeline infrastructure, the obvious alternative is to let a tube-trailer supply the hydrogen. Therefore it is also relevant to de-

sign enough space at these refueling stations that it would be possible for a tube-trailer to enter the station, manoeuvre and exit the station conform all Dutch norms and safety regulations.
To conclude, the policy barriers as well as the annual costs are least for supply chain B where the hydrogen is supplied through the existing pipeline infrastructure.
When in the short term no dedicated hydrogen pipeline is present near the hydrogen refueling station, it could be interesting to look at placing a new pipeline to the nearest hydrogen network. The costs of this would have to be estimated based on a tracé study and compared to the costs of using tube-trailers for the interim.

4.4. Conclusion supply chains comparison

The geographical position of the hydrogen refueling station is decisive for what supply chain can be applied for the hydrogen supply.

Supply chain A where tube-trailers supply hydrogen refueling stations via road delivery is relatively expensive (>23%) compared to a pipeline infrastructure. For the short term, the supply of hydrogen to outlier locations using tube-trailers could be beneficial for as long as the demand is lacking. Also the development of the hydrogen backbone infrastructure takes at least until 2027 before it is put into use and the natural gas pipeline infrastructure becomes available for alternative purposes like hydrogen distribution. Therefore the tube-trailer road delivery supply chain is especially useful for the short term when there are not many locations where the existing gas infrastructure could be retrofitted for hydrogen distribution.

There where the location of the refueling station is convenient for connecting it to the hydrogen backbone or a local dedicated hydrogen pipeline infrastructure there will be hydrogen available [interview]. The hydrogen backbone has the main purpose of transporting hydrogen to large industries. Thus where this hydrogen is being delivered at these industry parks, it would be possible to connect a refueling station that is located there to the backbone [interview]. That means that in several outsider locations in the Netherlands, there are possibilities for the mobility sector to be supplied with hydrogen via the backbone [interview].
The equivalent annual costs are smallest for a hydrogen refueling station with a hydrogen backbone connection and the policy is least limiting as well. Therefore this supply chain is considered to be a viable alternative to tube-trailer road delivery for hydrogen supply to refueling stations.

5
Uncertainties

In this chapter uncertainties for a hydrogen supply chain for the mobility sector are identified and categorized in the framework presented in figure 5.1. The input for these uncertainties finds its origin in interviews with several relevant stakeholders, literature and governmental reports.

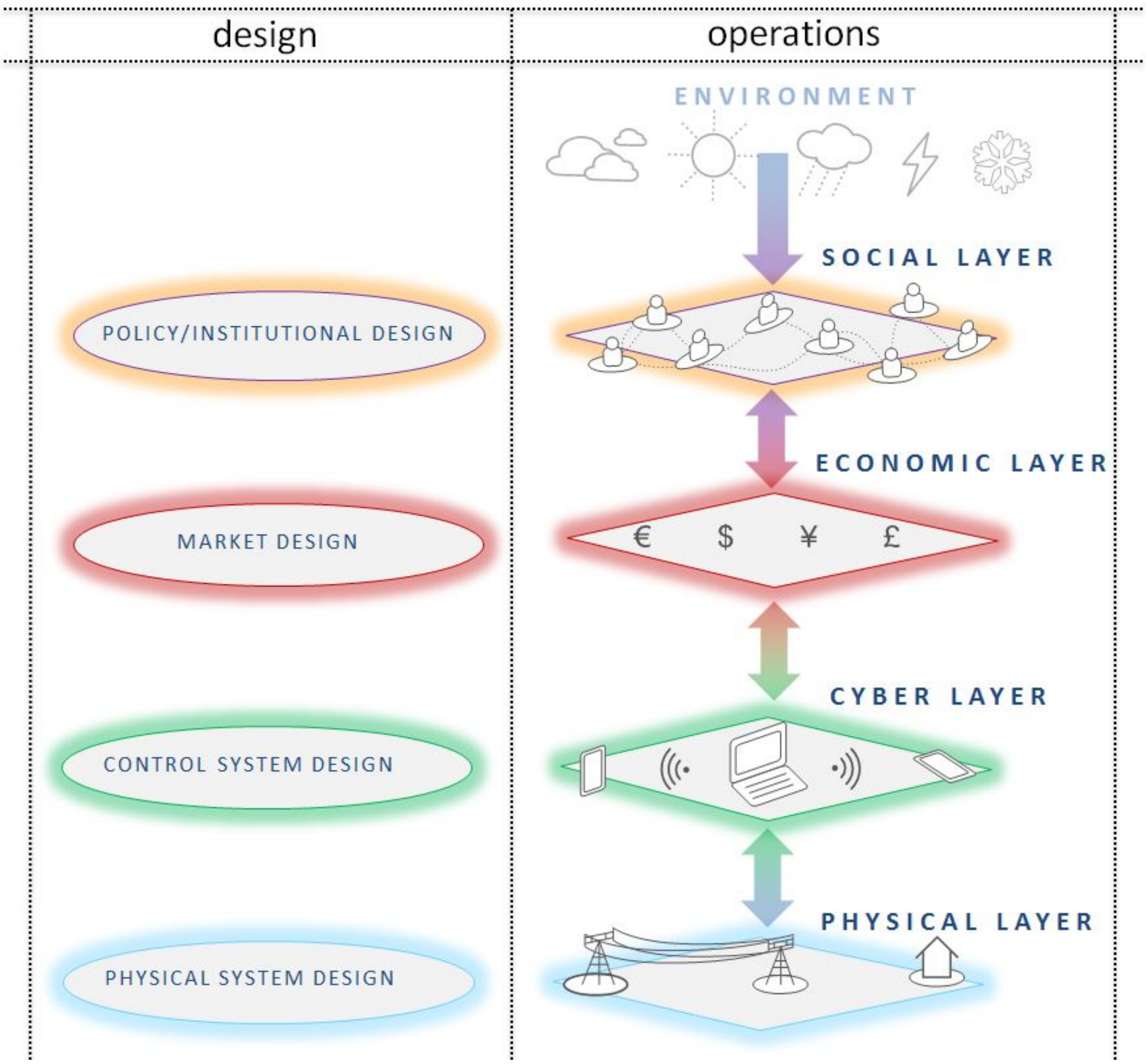

Figure 5.1: Complex socio-technical system [109]

5.1. Environment

The environmental influences and uncertainties are not relevant for the supply chain through pipelines or via tube-trailer road delivery. The environment does influence the production of hydrogen from renewable energy sources like wind and solar energy. But in this research for the coming years the assumption was made that low carbon hydrogen will be dominant in the supply chains for hydrogen in the mobility sector. Therefore the environment will have little impact on these two supply chains.

5.2. Policy/institutional design

There are quite some uncertainties for the policy/institutional design that have to be accounted for as was noted during the conduction of the interviews. These can be categorized in public acceptance, policy from a business perspective, the power of policy and European policy.

5.2.1. Public acceptance

The definition of public acceptance considered in this research is as follows: "Community acceptance refers to the specific acceptance of siting decisions and renewable energy projects by local stakeholders, particularly residents and local authorities" [110]. A well-known example of public acceptance is NIMBY (Not In My Backyard) which suggests that people are willing to accept public changes as long as they are not the ones experiencing negative external effects caused by the project. Community acceptance has a particular feature namely a time dimension: before, during and after a project. This time dimension typically has a U-curve pattern, which goes from a high acceptance before the project, to a relatively low acceptance (but on average usually still positive) during the project, to a higher level of acceptance when the project is running [110].
Another important aspect of public acceptance is the distributional justice, meaning how the costs and benefits are allocated [110]. Examples of questions that surface in this respect are: "Is there a fair decision making process giving all relevant stakeholders an opportunity to participate?" and "Does the local community trust the information and the intentions of the investors and actors from outside the community?" [110].

Public acceptance includes a wide variety of attitudes and behaviors that continuously evolve by social and cultural events and trends. These attitudes and behaviors include among others resistance, tolerance, acceptance and support. It has been demonstrated in the literature that public acceptance is a key factor in the adoption and diffusion of energy technologies [111]. In supply chain A it can be expected that public acceptance will be more of a barrier than in supply chain B.

Communities in England acknowledged that not only the technical feasibility is a constraint for the energy transition, but perhaps that social and political factors like public acceptability, existing institutional interests or political support, are even more important constraints [112].

The decentralized approaches result in more small-scale hydrogen plants like local electrolysis with on-site wind turbines or PV modules compared to the centralized large-scale renewable hydrogen plants. This causes an increase in number of siting decisions that need to be taken and thus also an increase in number of sites. Therefore energy output causes a relative increase in visual impact [110]. For supply chain B it can be expected that the visual impact is minimal as it connects large-scale centralized hydrogen production facilities to hydrogen demanding facilities through an underground pipeline infrastructure.
A possibility to increase the public acceptance for supply chain A could be by increasing the capac-

ity of the tube-trailer by increasing the hydrogen pressure in the tubes or by liquefying the hydrogen so that the hydrogen truck could supply plural refueling stations with a single trip. This would result in less traffic on the road.

The mobility and transportation sector is a visible sector for the entire community. It is important that the community and all kinds of stakeholders are involved in the experiments, innovations and developments that are happening in order to gain a larger support base. Especially from the near environment of these projects. A doom-scenario is that the users of hydrogen vehicles are not sufficiently included in the process and therefore eventually will not accept the result [75].

5.2.2. Business perspective

There is an enhanced desire from businesses for consistent long-term policy [interview]. Long-term policy certainty from the government, includes subsidies as well as law and guidelines [interview]. From the business perspective stakeholders are willing to make the transition towards a more sustainable approach of operating. However, this is currently not possible at competing prices. For example, in 2021 a fuel-cell electric heavy duty vehicle costs respectively €450,000 and €480,000 for trucks that travel 90,000 km per year and trucks that travel 140,000 km per year [54]. In 2021 the prices of battery electric heavy duty vehicles for similar travel distances are between €320,000 and €370,000, whereas the prices of conventional diesel trucks range between €80,000 and €85,000. The shortage of the Total Cost of Ownership (TCO) on FC-HDVs in 2021 is approximately 30% - 35% when only the MIA/VAMIL regulation is applied to the business case [54]. From the report of the Ministry of Infrastructure and Water Management, the H2Platform and Deltalinqs it can be observed that a maximum shortage of the TCO that is doable for carrier companies to make the switch to zero-emission HDVs is 1%-2% which is equal to €2500,- per vehicle per year [54]. To stimulate the demand of FC-HDVs a required total for subsidies is estimated at 112 million € until 2025 [54].

From a business perspective it is clear that the current prices require subsidies. Nevertheless, uncertainties are identified with respect to these subsidies:

- Whether or not these subsidies and tax reductions (like excise duties) will still be applicable as soon as a large fraction of vehicles is zero-emission [interview]. The government has to compensate this loss in tax money or it will have to stop the subsidies and tax reductions at some point. Whether or not that will happen should be made explicit and communicated to relevant stakeholders. This is also applicable to other tax reductions [interview]. Especially with respect to zero-emission zones and tax reductions it is important that clear long-term policy is made explicit [interview].

- When the budget limit for a certain subsidy is almost reached, who will decide which stakeholder that applied for it will receive it [interview]? The more projects start, the more subsidies are requested. At some point this money from the government will run out and who or what is going to decide who's or what project will receive the remainder of this subsidy [interview]? This makes the investment uncertain.

- Current policy is not always adequate. An example of this is that the New Energy Coalition applied for the DKTI regulation for tractors, but because these vehicles are not allowed on the road they were not eligible for this regulation [interview]. While for the Dutch emission targets it would be beneficial if these tractors would convert to zero-emission vehicles. This shows that due to certain limitations and rigidness of these regulations, they are not always adequate [interview].
  A second example is that Gasunie is not 100% certain that Gasunie will be the actor to receive

> the rights of being the main distributor of hydrogen. Therefore, the investments that Gasunie currently makes are not guaranteed to be earned back. This withholds Gasunie currently from committing to large investments [interview]. Gasunie requires a 100% certainty from the government. At this moment in time, there has been a debate whether Gasunie should have this role, where a vast majority of Dutch politicians from the House of Representatives was in favor of Gasunie. But the new cabinet formation has to make an official statement regarding this topic. Without the certainty, investments will be postponed.

It can be concluded that companies have the need for more clarity, long-term certainty and flexibility regarding the current policy for hydrogen [75]. As well for possible tax reduction (like excise and energy taxes) as for stationary energy applications and subsidies for operational costs like a production subsidy. This is required to create a feasible business case.
In the short term and medium long-term law and legislation, safety and risk management, standardization and the need for infrastructure are required conditions for the implementation of hydrogen in the mobility sector [75]. This should be stimulated by more flexible policies.

5.2.3. The power of policy

With policies the government is able to force companies to make more investments towards a more sustainable operation in certain sectors. But with the current Dutch policy, there are no threatening reasons for companies with heavy duty vehicles to make the transition to zero-emission vehicles until the late 20's [54].
An example of the Dutch government having an impactful role for stimulance is at the shrimp cutters sectors in the Wadden Sea. In the Wadden Sea, as of 2023, it is no longer allowed for shrimp cutters to pollute nitrogen. Therefore it is required that the entire fleet has to make the transfer towards sustainable alternatives. Due to the change in the Dutch policy progression can be seen in this sector [interview].
It is relevant for the Dutch policymakers to create policy where they can make the most contributions. One of the means for local governments to enforce policy is by setting additional conditions for public worker companies like trash collection companies [75]. One of the conditions that a local government is able to set refers to the company having to operate conform zero-emission. As has been discussed already in chapter 3, Japan actively uses local governments for stimulating sustainable alternatives and creating awareness. This could also be accomplished by local governments in the Netherlands. The Japanese approach focuses on accountability of local decentralized governments. A similar approach in the Netherlands would be municipalities demanding from companies to operate conform zero-emissions.
Another example of a tool that local governments can apply is the 'green deal'. This allows a stakeholder to deviate slightly from law and legislation creating additional experimental space [interview]. This means that green deal projects are able to remove barriers in current policy that withhold the projects from making progress in becoming more sustainable.

5.2.4. European policy

It is relevant that harmonization takes place between the European countries with respect to their policy approaches [75]. For example, as was noted in chapter 2, the Emissions Trading System (ETS) does currently not apply to the mobility sector and for the longer term where hydrogen import will play a larger role certificates for the hydrogen origin become more relevant for a transparent competition. Other examples of these standardizations should be in the available hydrogen subsidies and CO_2 taxations, which have to be implemented on a European scale [interview]. When and to what extent these policies will be implemented on a European scale is uncertain.

5.3. Market design

The market introduction of a new fuel as well as the establishment of customer acceptance have to overcome obstacles due to a lack of refueling station density, the lack of diversity in the available cars and the high premiums [113]. A barrier for the market introduction of hydrogen in the mobility sector is the mismatch between the hydrogen supply side and the hydrogen demand side. Therefore in this section the hydrogen supply side and the demand side are distinguished in order to establish a clearer perspective of the various uncertainties that are present in this field.

5.3.1. Hydrogen supply

There is no agreement concerning the tariff for hydrogen distribution in the Netherlands, because hydrogen distribution is excluded from the regulated law and legislation. Therefore it has to be distributed by a commercial sub-company of an energy supplier who would be able to decide themselves the tariffs for the hydrogen distribution [interview]. An acceptable price range for an HRS operator for hydrogen is approximately 4 to 7 €/kg depending on the application in the mobility sector [73].

In the research of Katikaneni et al. (2014) they compared three hydrogen refueling station sizes, respectively with a hydrogen output of 100 kg/day, 1000 kg/day and 2000 kg/day. The research showed that there is a significant penalty in hydrogen production costs towards market entry for station sizes with a hydrogen output of 100 kg/day. The cost benefit became modest for station sizes of 1000 kg/day and 2000 kg/day hydrogen output [78]. Thus it is relevant for the HRS operator to have a minimum demand of 1000 kg/day. This suggests that the first hydrogen refueling stations would have to be placed at locations where there is a sufficient large demand and no competing suppliers. An example of such location is the harbor where ships, heavy duty vehicles and operational vehicles like forklifts all come together [75].

In the long-term there will be a market for hydrogen refueling but for the near-future this will not be the case. Therefore currently the initial investments need a lot of subsidy [interview]. It is uncertain how long it will take for the market to accept hydrogen as fuel. A station operator cannot estimate how long it will need to take its losses, because it is uncertain when there will be enough demand from for example heavy duty to make the business case for a refueling station positive [interview].

The risk of investing in an HRS is shown in the schematic visualization of the cumulative annual cash flow in figure 5.2.

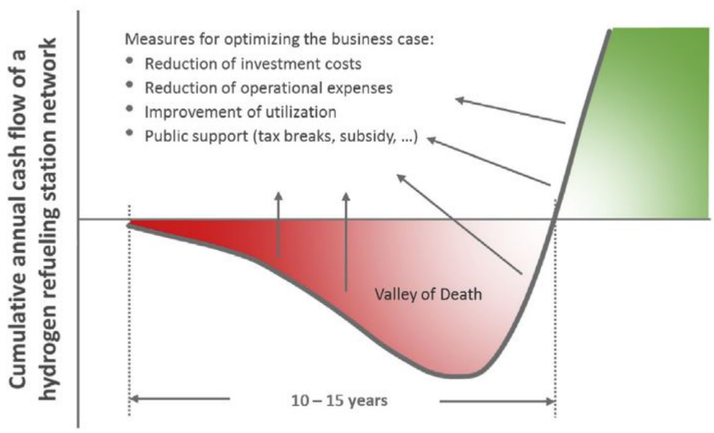

Figure 5.2: Schematic visualization of the cumulative annual cash flow of a hydrogen refueling station [114]

Early investors in hydrogen refueling stations are likely to have a money-losing business case for about a decade before being able to write hard numbers [56][interview].

5.3.2. Hydrogen demand

The price of hydrogen at the pump is an uncertainty. The levelized cost of hydrogen (LCOH) differs per production method and so the price could differ per refueling station. For companies in the transportation sector it is a requirement to get a reasonable and constant fuel price. For distribution companies a desirable price would be around €3,- to €5,- per kg hydrogen at the pump [54]. The higher price that companies in the transportation sector would have to pay to become zero-emission, they cannot incorporate in the price that they give their clients. More than 60% of the carrier companies that responded to the survey of the Ministry of Infrastructure & Water Management, the H2Platform and Deltalinqs, are pessimistic about the willingness of their clients to pay more for the service if that would mean that the vehicles would operate conform zero-emission [54]. This shows as well that the margins in the mobility sector are small to the extent that the price of hydrogen and the investment costs in vehicles are necessary to be competitive compared to conventional alternatives.
An assessment with 85 respondents from Dutch carrier companies, shows that many companies are prepared to make the change to zero-emission vehicles as long as the costs are competitive to the costs of diesel-fueled vehicles. It showed that the maximum costs these companies are prepared to pay extra are €2500 per vehicle [54]. When the costs rise above €2500 per vehicle the willingness to transfer to zero-emission vehicles reduced fastly. Additionally, companies that can suffice with one tank per day are for 60% prepared to adapt their fleet to zero-emission vehicles, whereas companies that have to refuel once per day are prepared to adapt only 40% of their fleet towards zero-emission vehicles [54].
A recommendation from the Ministry of Infrastructure & Water Management, the H2 Platform and Deltalinqs is that it will be beneficial for the transition towards zero-emission vehicles to immediately start with a kilometer charge and to provide a discount of 75% for zero-emission vehicles. And as a fallback alternative the excise duty of diesel can be raised of which these extra incomes can be used for providing financial incentives to the transition towards zero-emission vehicles [54]. The kilometer charge is planned to start in 2027 with a price of €0.13 per kilometer. The uncertainty identified with this kilometer charge is the question what will happen to the discount zero-emission vehicles receive when the major fraction of vehicles are zero-emission, while they are still not paid off [interview].

The maximum subsidy currently available from the AGVV (Algemene Groepsvrijstellingsverordening) is 60% of the difference between a conventional vehicle and zero-emission vehicle for small companies and 40% for large companies [54]. It is recommended to increase this limit to above the AGVV guideline, although this does require notification in Brussel [54]. As was discussed in chapter 3, Germany applies currently a maximum subsidy percentage of 80% of the extra cost of zero-emission vehicles [54].

5.4. Control system design

With the transition towards hydrogen in the mobility sector, some new challenges occur. These challenges lay in the technical equipment, as well as human capital and in a cyber market.

Challenges that lay in the technical equipment are mainly present at the hydrogen refueling stations. Innovation is required in the measuring equipment at a hydrogen refueling station, like the flow meter with a proper range and accuracy as well as for quantity and purity control of the hydrogen [75]. Especially for an HRS that receives hydrogen with potential carbon, sulfur or nitrogen contaminations, like is the case with hydrogen production from for example ammonia cracking, biomass gasification or steam methane reforming [58]. For the application of hydrogen in FCEVs the hydrogen must contain less than 100 parts per million by volume (ppmv) of nitrogen and ammonia has to be limited to even 100 parts per billion by volume (ppbv). Sulfur and carbon compound concentrations have to be limited to respectively 2 and 0.2 ppmv [58]. In order not to poison the fuel-cell in vehicles it is relevant to be able to measure the purity of the hydrogen before it is being dispensed.

Also the human capital raises uncertainties with respect to hydrogen. An example of a challenge related to human capital is that the maintenance requires new educated employees with new certified characteristics. This all adds up to a more unstable business case [interview]. Normally with diesel trucks agreements are made that a stranded truck is serviced within an hour on sight by a mechanic. With hydrogen this will be more difficult, because engineers need to be schooled. The margins for heavy duty carrier companies are already limited. Due to these kinds of challenges the risk with the investments in fuel-cell electric heavy duty vehicles increases.

Also challenges occurs in the cyber layer at the certificates for the origin of hydrogen. In a letter from the House of Representatives in June 2021, uncertainties regarding the system for the guarantees of origin are mentioned. This letter intends to increase the final usage of renewable energies. Four challenges and uncertainties with respect to the origin of hydrogen certificates have been identified [75][115]:

- Currently the certificates for the origin of hydrogen are not recognized when the hydrogen is imported from countries outside of the European Union. Therefore there is need for the application of a European system for the determination of the hydrogen's origin.

- Currently in order to contribute to the Dutch renewable energy targets the electricity that will be applied for the production of hydrogen is required to have its origin in the Netherlands.

- It is still undecided whether or not the certificates regarding the origin of hydrogen and other gases that are produced using non-renewable sources will be included, by the Dutch government. This is due to the lack of clarity from the European law and legislation regarding this topic.

- It is still uncertain what kinds of hydrogen will be distinguished. Examples of different kinds of hydrogen are low carbon, high carbon and zero-emission hydrogen.

Two final uncertainties that will be discussed are the price of GHGs in the Emissions Trading System of the EU and the long-term application of the Renewable Energy Units (REUs) [28][40].
A decrease in the amount of allowances (EUAs) that will be allocated over time in the ETS will inherently raise the price for polluting and thereby improving the feasibility of a low carbon hydrogen supply chain. The rate of this allowance decrease is adaptable and thus uncertain.
Similarly is the long-term application of the Renewable Energy Units uncertain. The Renewable Energy Units provide a level of support for the business case of hydrogen supply in the mobility sector [40]. Whether these REUs will still be applied after 2030 is uncertain while the investments that are made in the foreseeable future have a scope beyond 2030 and will thus have to take into account this policy. If no decision will be made concerning the long-term application of REUs it is likely that dominantly short term projects will be developed in the coming years with relatively higher unfeasible business cases [40]. Simultaneously there is an ongoing discussion whether to or not to multiply the REUs of renewable hydrogen with a factor to stimulate the production of renewable hydrogen by improving the business case. This would mean that for every GJ renewable hydrogen

that is produced, the producer would receive 2 GJ of REUs with a factor two. The value of the factor for renewable hydrogen and whether or not this factor will be applied is uncertain.

5.5. Physical system design

The uncertainties of the physical system design are categorized in the following sections: situation specific conditions and uncertainties in the physical design of the two supply chains.

5.5.1. Situation specific conditions

For each region or municipality in the Netherlands there are different characteristics that define the region. It is relevant to identify these situation specific conditions per region in order to evaluate whether it would be advisable or even possible to create an investment plan for a hydrogen refueling station with a suitable hydrogen supply chain. It is not likely that completely new refueling stations will be constructed, but rather that existing refueling stations will be upgraded to also supply hydrogen for FCEVs and electricity for recharging BEVs [interview]. Before creating the investment plans, it should be clear if a refueling station is able to upgrade and whether or not there will also be a demand for the hydrogen and additional electricity charging points. Five examples of criteria for these existing refueling stations are the possibility to expand the station area, whether or not a hydrogen refueling station is publicly accepted, whether or not it has the ability to add an additional road access for tube-trailers, the possibility to produce hydrogen on-site or nearby and the distance of the HRS to a usable dedicated hydrogen pipeline infrastructure. The geographic location of the hydrogen refueling station is relevant for these five criteria. Existing refueling stations that meet enough criteria so that hydrogen market creation can be established will further in this research be referred to as 'high potential refueling stations'.

For example, when the refueling station is located at the side of a Dutch highway, it is likely that there is no existing pipeline infrastructure nearby [interview]. Then it should be analyzed whether or not building a connection to a dedicated hydrogen pipeline infrastructure would be the best option to supply hydrogen.

Also for the required permits there is a difference if the location is in the city center, near a public highway or on an industrial terrain. If the HRS is located at a public location it is plausible that obtaining the right permits will be more difficult [interview].

5.5.2. Uncertainties in the physical design of the backbone supply chain

It is not yet defined what the exact characteristics are of the gas that will be transported through the hydrogen backbone. It is necessary for the actor that is responsible for the purification step that that actor knows what other materials or particles need to be separated. These contaminations could for example be sulfurs, carbons or nitrogens [72] [75] [interview]. Also it has not yet been made definite what the guaranteed delivered pressure of the hydrogen from the backbone will be. The expectation is that 30 - 50 bar hydrogen will be applied through the backbone. However, it could be possible that Gasunie (or a different distributor) guarantees a different pressure range. For example a pressure range of 8 - 80 bar and thus keeps the distributor the option of alternating the pressure to balance the hydrogen supply out [interview]. The same applies to Stedin who keeps 8 bar pressure on the pipelines, but guarantees a pressure of 1.5 bar [interview]. The guaranteed pressure would impact the technical system of the supply chain as in this example more compression on-site would be required to reach a dispensing pressure of 700 and 350 bar.

Besides the purity and the pressure of the hydrogen that will be transported through the backbone it is also uncertain when a connection to a dedicated hydrogen pipeline infrastructure could be made. How long it will take for (part of) the existing natural gas pipeline infrastructure to become available for hydrogen is uncertain. Due to the outphasing of the gas exploitation from the Groningen field this will become available [80]. Just like that the hydrogen backbone will be developed is certain. To speed up the use of the backbone for a hydrogen refueling station, it could be technically possible to build a pipeline from the HRS to the hydrogen backbone when the 8 bar gas network is not yet available. However, this would increase the investment costs and whether Gasunie would be cooperative to create a connection to their infrastructure for a single refueling station is also uncertain [interview].

Lastly, a tracé study should be performed for supply chain B if a new pipeline would be placed. It is relevant to know where the bifurcation of the pipeline will be located and what route it will pass for the costs of the project. Especially the need to pass the water boards could be a barrier for the network [interview]. If somewhere there is a small dyke, it may be a barrier to place your pipeline there. A tracé study can show whether or not a pipeline network could become a factor X more expensive and could thus indicate the need for an alternative supply chain.

5.6. Reflection on the identified uncertainties

From the identified uncertainties there are some remarkable and frequent recurring notifications. A distinction can be made between intrinsic uncertainties and decision-dependable uncertainties. With intrinsic uncertainties is meant the uncertainties that cannot be taken away. Among these are the uncertainties of events that will happen in the future, the environmental impact and whether or not it will be possible to develop adequate measuring equipment which are needed at the physical layer. But also the public acceptance, which is an intrinsic uncertainty, should be taken into account before investment plans will be created. Important for gauging the public acceptance, is that this differs per location. This parameter is one of the situational specific conditions that need to be taken into account during the design of the hydrogen refueling station. The public acceptance however, towards hydrogen refueling stations and their supply chain does not seem to be a major bottleneck for the roll-out of hydrogen in the mobility sector. Especially with enterprises is the acceptance rather high [interview].

With decision-dependable uncertainties is meant the uncertainties that will be taken away by the decision to take a certain approach.
These start with the business case on which both sides of the market, supply and demand, base their decisions. The lack of a feasible business case is the main bottleneck for the roll-out of hydrogen in the mobility sector. Both sides, supply and demand, postpone their investments and have a wait-and-see attitude due to the high risks for investments. This shows that allocating the risks differently would benefit the progress of making the mobility sector more sustainable. The underlying factor of these high risks is besides the current lack of demand, caused by the high costs of the infrastructure, the hydrogen itself and lack of clear long-term policy.
European harmonization is also a recurring aspect of the system and a decision-dependable uncertainty. Due to lack of harmony in European law and legislation, norms and financial incentives the barrier exists to achieve an economically competing business case. For example, CO_2 taxes, origin certificates for various categories of hydrogen and electricity should be implemented on a European scale and the maximum amount of subsidies that could be allocated towards projects should be raised which is currently held back because of European guidelines.
Also the Emissions Trading System is a relevant factor for the business case and should therefore be made operational, and sooner the better. The German government has backed this by making a

similar statement.

It was also made explicit from the interviews that the power that zero-emission municipalities can enforce at companies and therefore create a business case by giving out tenders with the monopoly for a certain service is an impactful factor for the acceleration towards a sustainable mobility sector. This is paired with the conclusion that the sector requires long-term policy guarantees in order for the market to accept hydrogen in the growing phase. One of these long-term policies can be the cooperation and financial support of the Dutch government to develop the hydrogen backbone in the Netherlands.

5.7. Two potential scenarios

In this section two potential scenarios will be discussed. The first scenario will discuss the effect of creating a consortium with relevant stakeholders for hydrogen in the mobility sector and to look at the influence of this consortium on the uncertainties in the system. The second scenario will look into the effect of implementing a multiplication factor for REUs and how this affects the uncertainties in the system.

5.7.1. Consortium scenario

The hydrogen refueling infrastructure could be looked at as a network externality. This suggests that the value of a hydrogen refueling station increases by the amount of refueling stations in the system [116][117]. The network effects cause a barrier for a new fuel to compete with existing fuels, even when the new fuel is superior in costs and performance [118]. The network effect is noticeable at both the supply side and the demand side.
At the supply side, an increase in the national amount of refueling stations with a hydrogen filling point will for a supply chain with hydrogen transport through the hydrogen backbone lower the variable distribution costs as more stakeholders make use of the infrastructure.
At the demand side, an increase in the national amount of refueling stations with a hydrogen filling point will make it more interesting for consumers to buy a fuel-cell electric vehicle as they have an increase in locations to refuel.
A common characteristic of a network externality is that it has high fixed costs, but relatively low variable costs. Because of the high investment costs adding a hydrogen filling point is a risky investment for a single investor. However, as more investors would simultaneously make an investment in hydrogen refueling stations, the value of the investment would rise due to the network effect. By also including transport companies in the consortium price agreements can be made. This is beneficial for both the refueling station operator as well as the transport company. The company will receive a better price for the fuel than without an agreement and the station operator will in return for the lower profit margin on the hydrogen receive certainty of an agreed upon volume over a longer period of time. Therefore the profit margin on hydrogen can be lower as the operator has more certainty.

As stated previously, when more investors invest simultaneously in hydrogen refueling stations and these would all be supplied via the hydrogen backbone which is the cost-efficient transport mode for hydrogen, the variable costs for hydrogen distribution would decrease even more adding more certainty to the investment. Therefore, by creating a consortium with all relevant stakeholders, the investment risk on both the supply and demand side will be more evenly allocated improving the business case. Thus a coordinated policy approach, like a consortium, that simultaneously stimulates the supply and the demand of hydrogen in the mobility sector is for rapid adoption the most effective approach [119].

The effect of network externalities can even be extrapolated to an international hydrogen refueling station network instead of a national hydrogen network. As the advantage of hydrogen as energy carrier among others is that FCEVs have a longer driving range than most BEVs and have a similar refueling time to conventional fuels, hydrogen is likely to be mainly applied by users that travel relatively large distances where the currently cheaper alternative BEVs are inadequate. Therefore would the value of an FCEV rise as more hydrogen refueling stations would be built internationally.

5.7.2. Renewable Energy Units multiplication factor

The multiplication factor for Renewable Energy Units (REUs) is brought up for discussion due to the guideline 'Renewable energies' which states that a minimum fraction of 14% of fuels should be renewable. This fraction is measured by the energy volume of renewable fuels that is consumed in a year divided by the total energy volume of consumed fuels in that year [120]. Because of the multiplication factor the target would be reached sooner. Whether or not the multiplication factor will be implemented for renewable hydrogen is uncertain, but some consequences of the decision to implement a multiplication factor of 2 will be discussed as follows.

A Renewable Energy Unit represents one gigajoule (GJ) of renewable energy for the Dutch mobility sector. The higher heating value (HHV) of hydrogen is 142 MJ/kg hydrogen. Thus 1 GJ or 1 REU represents approximately 7 kg of hydrogen [120]. This means that for every 7 kg renewable hydrogen that is produced, the producer would receive 1 REU. If for example the price of an REU is €14,- that means that for every kg of renewable hydrogen the producer would receive €2,-. If the multiplication factor for renewable hydrogen would be 2, every gigajoule of renewable hydrogen that is produced would be counted as 2 GJ or 2 REU thus the producer would receive €4,- for every kg renewable hydrogen instead of €2,-. The levelized cost of hydrogen from wind energy in the Netherlands is approximately 6 €/kg as can be found in Appendix B. When the producer uses wind energy to produce renewable hydrogen, the producer would receive 4 €/kg from the REUs market and could therefore supply the renewable hydrogen for 2 €/kg which is competitive with hydrogen produced through SMR. That would accelerate the renewable hydrogen production relative to hydrogen production from fossil fuels.
If the multiplication factor would be lower than 2, the levelized cost of renewable hydrogen would not be similar to that of hydrogen from SMR and thus the transition from non-renewable to renewable hydrogen would take longer due to market forces. Thus the multiplication factor affects the pace of the transition towards sustainable hydrogen.

The Netherlands has less potential for cheap hydrogen production from renewable energy sources relative to European countries like Spain and Portugal [121]. However, the Netherlands does have a competitive advantage on low carbon hydrogen that is produced through SMR combined with CCS [121]. For the production of low carbon hydrogen, no REUs will be received, but the price of SMR with CCS will be competitive with conventional fuels due to the rising carbon dioxide price in the Emissions Trading System. Carbon capture and storage has the potential to reduce the emissions from hydrogen production up to 90% which is an interesting alternative to more expensive renewable hydrogen in the Netherlands for the short and medium term.

Whether or not to implement the multiplication factor for renewable hydrogen can be decided per member state [120]. But when the multiplication factor would be applied on a European scale it would mostly benefit countries where renewable energy sources can be exploited for relatively low

costs. In the same example as above with an REU price of 2 €/kg, a multiplication factor of 2 and a renewable hydrogen production cost of 5.2 €/kg (5.96 $/kg converted with the exchange rate of 1 US$ = 0.877 € [122]), which could occur in countries with a high Equivalent Sun Hours (ESH) like Spain, renewable hydrogen production would cost net 1.2 €/kg while hydrogen production from fossil fuels would cost the producer €2,- per kg. Then the production of renewable hydrogen would substitute hydrogen production from fossil fuels in the market. Simultaneously, this would mean that the hydrogen production in Spain would grow, but that hydrogen producers in the Netherlands are not able to compete with the hydrogen prices and will therefore not produce renewable hydrogen. Thus the hydrogen production in the Netherlands would not be stimulated if the multiplication factor is applied on a European scale.
Whether this is desired or problematic could be discussed, but the author of this research does not share the opinion that it would be problematic. When hydrogen is cheaper to import than produce nationally, this should have the focus for the hydrogen supply in the Netherlands.

A disadvantage of importing energy carriers is dependency on other countries. However, this is currently also the case for natural gas which is imported from Russia. Therefore the dependency on other countries is not considered a bottleneck.
For countries like Spain to develop enough capacity to produce an abundance of renewable hydrogen that their own demand is met and the excessive hydrogen could be exported are long-term plans. Whereas the production of low carbon hydrogen through CCS in the Netherlands can be achieved on the short and medium term. Therefore, the Netherlands would on the short and medium term not lose competitiveness to other countries caused by the multiplication factor. In the long-term it is plausible that the Netherlands would have to import renewable hydrogen. Then it is relevant that in other countries the infrastructure is developed on large scale. The multiplication factor could support these developments.

Especially for renewable hydrogen production in the Netherlands which is relatively expensive compared to low carbon hydrogen alternatives, the multiplication factor would be relevant for the business case. The Dutch government should express that the multiplication factor would be applied for a certain period in order for investors to base their business case on. If this is not the case, investing in renewable hydrogen production plants assuming that the multiplication factor will be applied for a long period increases the risk of the investment. When the factor will be repealed, the plant is unlikely to be able to compete with low carbon hydrogen that is produced nationally and renewable hydrogen that will be imported. Therefore, for the Netherlands the implementation of the multiplication factor may not have the desired impact that it would have in southern European countries.

6

Conclusion and recommendations

Based on the analyses and data from this research it is advisable to adjust current policies in order to achieve the intended reduction of greenhouse gas emissions in the mobility sector. In this chapter the answers to the sub-questions and the main research question will be comprehensively discussed.

6.1. Sub-questions

What are the relevant Dutch policies regarding the supply chain of hydrogen for the mobility sector and how do these compare to the policies in Germany and Japan?

Relevant Dutch policies for decarbonizing the mobility sector involve dominantly price-mechanisms which are statically efficient. In the Netherlands, policy is primarily focused on the production and consumption of hydrogen, and to a lesser extent on the distribution of hydrogen between these processes.

The Emissions Trading System (ETS) and the allocation of Renewable Energy Units (REU) are complementary policies that provide financial incentives for decarbonizing the mobility sector and are expected to make significant impact in decarbonizing the mobility sector. Together with the implementation of a kilometer charge, these policies aim to discourage the use of conventional heavy duty vehicles and to stimulate sustainable alternatives for transport purposes.

However, current Dutch policy is not always sufficiently adequate in practice. This issue is exemplified by the Dutch DKTI regulation that does not cover tractors even though there is a demand for inclusion of this type of vehicle. Therefore, it is recommended to increase the flexibility of current policy regarding permit grants and subsidy application. For similar practical reasons, Germany has decided to increase the available subsidy limits of their DKTI regulation to 80% although this is currently limited to 60% by European guidelines.

The comparison with Germany and Japan provided insights in potential effective changes in current Dutch policy to accelerate the fuel transition in the mobility sector. The main take-aways are the constitution of a consortium to assemble relevant stakeholders to create a nationwide refueling infrastructure, and simultaneously stimulating the supply and demand of hydrogen, while, as a government, committing to long-term policies.

Creating a consortium for hydrogen in the mobility sector allows for a significant cost reduction and a more equal allocation of the investment risks which prevents a wait-and-see attitude by relevant stakeholders.

Currently incentivizing the supply as well as the demand for hydrogen aids in market creation. However, this is only effective policy when supported by long-term commitment as the investments are risky and depreciate over a relatively long period of time.

Similar to Germany and Japan, the Dutch government should take a proactive role in the transition for the mobility sector. The Dutch authorities should act as a 'launching customer' by only buying sustainable vehicles and the decentralized governments should take a role as consumer-pusher as is done in Japan. Practically, the 30 to 40 largest municipalities in the Netherlands could implement zero-emission zones and have renewable bus transport and inland shipping.

Advantages of the Netherlands compared to Germany and Japan include the possibility to import hydrogen through the Port of Rotterdam and the hydrogen backbone, the potential to produce hydrogen at the North Sea and the possibility to use the existing pipeline infrastructure for the transport of hydrogen across the country. Since this existing pipeline network is considered cost-efficient and the safest mode of hydrogen transport, it is recommended to focus future policies on stimulating the use of this infrastructure.

How do the supply chains with tube-trailer road delivery and a dedicated hydrogen pipeline infrastructure compare with each other on the equivalent annual costs and institutions?

The situation specific conditions of refueling stations are dominant factors for the investment and operational and maintenance costs that can be expected for a hydrogen supply chain.

The cost-efficient alternative to transport hydrogen to a refueling station is by connecting the refueling station to the hydrogen backbone via a dedicated hydrogen pipeline infrastructure. Hydrogen distribution through a dedicated hydrogen pipeline network can reduce the distribution costs by approximately 23% compared to a tube-trailer road delivery supply chain which is equivalent to a price reduction of 0.90 €/kg hydrogen. The connection to the backbone has the lowest operational and maintenance costs and least institutional barriers of the two supply chains. Therefore, this is considered a no-regret supply chain for long-term policy.

The tube-trailer road delivery supply chain costs are approximately 0.65 million €/year higher than for a pipeline infrastructure, but is able to supply hydrogen on a shorter notice. Consequently, tube-trailer road delivery is convenient as long as the demand is low because it can develop market creation on the short term.

The hydrogen backbone will be operational from 2027 in the Netherlands and first large industries will be connected to this pipeline infrastructure. This suggests that in the proximity of these large industries a hydrogen refueling station can be connected to the hydrogen backbone and, thus, via this route hydrogen would even be available in some outlying locations in the Netherlands.

What uncertainties can be identified that influence the development of these two hydrogen supply chains?

Five levels of uncertainty have been distinguished in this research: the environment, the social layer, the economic layer, the cyber layer and the physical layer. Most uncertainties have been identified in the economic layer including the financial institutional instruments.

As costs are the main driver for hydrogen to be accepted and accelerated into the economy, most of the uncertainties relate to this aspect. The dominant recurring uncertainties are the cost of hydrogen at the pump, the long-term availability of current financial incentives and the lack of market creation.

Local governments have demonstrated the ability to affect market creation by creating additional conditions for city logistics tenders like zero-emission operations. This has been shown to be an effective way of accelerating the hydrogen share in the economy by Japan.

European harmonization is complementary to this market creation and provides long-term policy like the inclusion of the mobility sector in the Emissions Trading System (ETS) and Renewable Energy Units (REU). Additionally, by developing the European hydrogen backbone, a cost-efficient distribution network for import and export is established which marks a long-term investment that will improve the confidence of potential investors to enter the hydrogen market. Further research should analyze to what extent these uncertainties impact the pace of the emission reductions in the mobility sector, the priority these uncertainties should receive and what factors are relevant to increase market development.

6.2. Main research question

What recommendations can be provided to obtain a feasible business case for the supply chain of a hydrogen refueling station with low carbon hydrogen in the Netherlands?

From the analyses performed in this research, the collected data and interviews multiple recommendations for providing a feasible business case for the supply chain of a hydrogen refueling station in the Netherlands can be deducted. The four dominant conclusions will be discussed here.

1. The long-term commitment of the Dutch government should include long-term policy as well as financial incentives and decentives. The business case is the dominant decision factor for companies and without the financial motive, they will not make sufficient investments for the transition. If clearly demonstrated that transport costs per kilometer will be less when using hydrogen as fuel compared to non-renewable energy sources, the mobility sector will quickly shift towards the former fuel type. Therefore, a kilometer tax should be introduced on conventional vehicles to support this transition towards hydrogen.
2. Local governments can make an impact by becoming zero-emission municipalities forcing city logistics companies to abide by the requirements of zero-emission for tenders. As a result of this zero-emission requirement, the financial incentive and urge for these companies to convert their fleet to battery electric, hydrogen or green gas fuel based vehicles becomes relevant. The need to become zero-emission will automatically cause a demand for hydrogen which requires hydrogen refueling stations. Thus, such a policy would in these municipalities originate high potential hydrogen refueling stations by creating a hydrogen market with presence of both supply and demand. In addition, conventional trucks can be charged a fee for entering the inner city within zero-emission urban areas. This environmental tax for conventional vehicles will negatively impact their business case and increase the financial incentive.

3. The cost analysis has clearly demonstrated that hydrogen supply through a pipeline infrastructure is financially favorable with a relative cost difference of 23% compared to a supply chain with tube-trailer road delivery. The difference is approximately 0.65 million €/year for a single refueling station that supplies 2000 kg of hydrogen per day which is equivalent to a price reduction of 0.90 €/kg hydrogen. Therefore, the recommendation is to create policy for and to facilitate the retrofitting of the existing natural gas pipeline infrastructure to be converted to dedicated hydrogen pipelines as soon as possible. Since hydrogen is a multi-sector solution for decarbonization and can be safely and cost-efficiently transported through the existing pipeline network, the Dutch government should facilitate the conversion of this distribution infrastructure.

   In addition to obtaining an adequate hydrogen distribution network that already covers the whole nation, converting the existing gas infrastructure to transport hydrogen shows a long-term commitment from the Dutch government which is highly desired by the market.

   However, during the current Dutch start-up phase in which the hydrogen market and a dedicated hydrogen pipeline network are being developed, it may be advisable to temporarily supply hydrogen via tube-trailers in specific cases. Therefore, Dutch policymakers should focus on high potential hydrogen refueling stations and decide on the necessary supply chain for each location separately during this phase.

4. The establishment of a cooperative consortium of relevant stakeholders that focuses on the development of a national covering hydrogen refueling station network instead of the current single-station focus has two functions. It will result in a more equal investment risk allocation between investors and lead to a significant cost reduction when realizing the nation-wide refueling infrastructure. This cost reduction was estimated to be 10% of the total costs of developing a hydrogen refueling infrastructure in Germany.

It is important to note and to explicitly emphasize that these recommendations are based on the data incorporated in this research and the two supply chains that have been discussed. Alternatives of supplying hydrogen that are not taken into account are out of the scope of these recommendations.

7 Reflection

This chapter reflects the approach taken to answer the main research question, the research method including the position of this research in respect of the literature, and lastly the scientific and societal contribution.

7.1. The research approach

This thesis aims to provide a well-founded recommendation of how the business case of a hydrogen supply chain for the mobility sector can be improved. To establish a defined answer in reaching this goal three sub-questions were drafted.

To answer the first sub-question, a base knowledge about hydrogen supply chains was needed. This was established by looking into Dutch and European policies regarding hydrogen, hydrogen supply chains for the mobility sector and by comparing Dutch policies to policies of Germany and Japan which have already committed themselves to hydrogen as a multi-sector solution for decarbonization.

To answer the second sub-question, two supply chains were analytically decomposed to make an estimation of the total equivalent annual costs that would be associated with them. The results could be translated into which the cost-efficient supply chain would be to focus Dutch policy on.

To answer the third sub-question, uncertainties needed to be identified in order to evaluate whether the cost-efficient supply chain is indeed likely to have a better business case and would thus be more suitable. This is done since any future cost analysis will contain a degree of uncertainty.

After having answered these three sub-questions, Dutch and European policies are understood and the comparison with Germany and Japan yielded the relevant focuses that Dutch policy should entail for the successful rollout of hydrogen in the mobility sector. It was evaluated whether these two aspects are aligned and thus whether additional focus is necessary on certain aspects. Additionally, the cost-efficient supply chain between tube-trailer road delivery and a pipeline infrastructure is investigated and whether the cost-efficient supply chain is indeed more suitable to focus Dutch policy on due to uncertainties in both supply chains. After these aspects have been investigated, the main research question can be answered and indeed a well-founded recommendation was established.

The research approach could have been improved by considering more potential cost-efficient supply chains like liquefied hydrogen road transport and on-site hydrogen production. Also, it would be interesting to quantify the identified uncertainties to risks and subsequently combining the risks with the results of the cost analysis. This would allow for a mathematical validation of whether the conclusions that have been drawn and the recommendations that have been stated are valid.

Furthermore, validation of this research could have been enhanced if the results could have been verified by the operators of two existing hydrogen refueling stations that are supplied via tube-trailer road delivery and a pipeline infrastructure. The company Ekinetix was contacted but unfortunately no response was supplied and Avia-Marees was not able to verify the exact costs. However, as the refueling station in Rhoon receives their hydrogen through a pipeline infrastructure and seven other hydrogen refueling stations in the Netherlands receive their hydrogen by tube-trailer road delivery this enables getting confirmation of the costs.

7.2. The research method

This research has combined a quantitative study (the cost analysis) with a qualitative study (interviews for data gathering). The research method is discussed and reflected on in the following section.

7.2.1. The research method reflection

Combining quantitative and qualitative analysis techniques in a research has advantages as well as disadvantages in providing an accurate and precise answer to the main research question. Advantages of the quantitative aspect of this research are the establishment of the comparison between the two considered supply chains on a ratio data level instead of an ordinal level and that changes in parameters are relatively easy to incorporate when necessary which is beneficial in a dynamic sector. A disadvantage of using a quantitative method is that assumptions have to be made for parameters that are hard-to-quantify which may influence the results.

The main advantage of conducting interviews is the ability to emphasize the intrinsic motivation of stakeholders which cannot always be obtained from literature. The nuance that people can provide in a dialogue may therefore supersede the information that can be read. This was especially useful in this research as many stakeholders are included in the complex system that is the energy transition in the mobility sector and are interdependent of each other. This translates itself into that results from interviews may have a higher precision than quantitative analysis techniques.

Disadvantages of conducting interviews as data sources are that the information could be biased by the interviewee and that the research is limited to the experts available and willing to be interviewed. Because of this limitation, the results may lack accuracy. All stakeholders interviewed have their own perspective towards the energy transition and what role hydrogen should or could play in it, which should be averaged out by increasing the sample size and thus interviewing more experts. For example, it turned out that on the topic of this research experts disagree as to whether the focus should be directly on zero-emission hydrogen or first on low carbon hydrogen for the transition phase and whether it should be produced in the Netherlands or imported.

Another disadvantage of conducting interviews is caused by the rapid dynamic characteristic of hydrogen innovations. Due to the fast changes in (inter)national policy, state-of-the-art technologies and societal opinions towards the energy transition, data from literature as well as from interviews have an expiration date. This is a limiting factor for a qualitative research method as performed in this research. In a quantitative model where causality effects are included, changes in data are less problematic as the parameters can be more easily adapted, whereas with interviews a new dialogue should be held. Three examples of changes that have occurred in the past semester during this research and that have changed the scope and relevance of this research are:

- The functional unit of this research was initially set at 200 kg hydrogen per day. During the project this changed to 2000 kg per day in order to include the expected increase in share of fuel-cell heavy duty vehicles;

- During 'Prinsjesdag' in the Netherlands, the Dutch budget presented on September 21st, 2021, showed that the Dutch government will invest €750 million in the hydrogen backbone infrastructure. During this research, this was not yet public information and therefore not included in the analyses. However, it does confirm the results of this research as it is in line with the recommendations and answer to the main research question;

- In July 2021, the 'Fit for 55' package was presented with actions to reach the 55% emissions reduction in 2030. This package is, as was discussed in Chapter 2, not yet definite, but shows an international commitment towards hydrogen as a multi-sector solution and harmonization.

Creating a parametric model would be interesting as it can cope with the dynamic behavior of hydrogen applications. However, a limitation of a parametric model lies in the fact that the reality has to be simplified. As the energy transition is a rather complex system it must be safeguarded not to over-simplify if for that model.

7.2.2. Discussion of the results

The results of the research show that the more suitable supply chain for hydrogen in the mobility sector is through a dedicated hydrogen pipeline infrastructure. Furthermore, the research demonstrates what is needed for policy to comply with and stimulate this supply chain. The results can however not be interpreted as the exact right answer to the decarbonization of the mobility sector as there are uncertainties present and decision choices impacted the results of this thesis. Therefore the results should be interpreted as a substantiated estimation that an infrastructure with dedicated hydrogen pipelines would significantly reduce the system costs and is less limited by safety measures when compared to tube-trailer road delivery.
Besides the cost disadvantage of tube-trailers, it was also concluded that in the future tube-trailers would have to make two round trips per day to be able to supply 2000 kg of hydrogen to refueling stations. As this would lead to a logistical issue in the long-term, this is an undesired scenario for the supply of a nationwide hydrogen refueling infrastructure.

7.2.3. Reflection on the limitations

Even though the results from this research seem to be in line with the latest developments in Europe and the Dutch government with respect to hydrogen and the results from similar researches, the research has certain limitations due to assumptions and choices that were made in the process. These limitations will be discussed as follows.

Firstly, the costs in the quantitative analysis of the research are rigid over time as they do not deviate. This is unlikely to be true in reality. Therefore it would have been interesting to perform a sensitivity analysis with respect to the costs, but also on the effect a different functional unit has to the equivalent annual costs. This would provide insights into the margin of error of the results and therefore the resilience of the supply chains since the demand will increase gradually over time.

Secondly, only two supply chains have been considered in this research. It would have been interesting to make the comparison with additional interesting supply chains for the Netherlands like liquefied hydrogen road transport and on-site hydrogen production.

Thirdly, more experts could have been interviewed to average out the preconceptions of the interviewees and to obtain more input for the validation of the considered system analyses. Another consideration would be developing a game which creates a functioning consortium with all relevant stakeholders as alternative for conducting interviews. Such a game could reflect on whether or not it is possible to reach agreements and what commitments are required from which stakeholders to initialize a transition.

7.2.4. Position of the research in the literature

Each member state of the United Nations has to meet the climate goals through their nationally determined contribution (NDC) due to climate change. The mobility sector in the Netherlands was responsible for 19% of the GHG emissions in 2019. It is clear that decarbonization in this sector is required, but how this will be established is not yet clear. These starting points formed the basis of this research. In Chapter 1 it was pointed out that currently the dominant alternatives are battery electric vehicles, bio-fuels, synthetic fuels and hydrogen. This research has looked into one of these four alternatives and did not focus on the production of hydrogen nor the technical usage in the mobility sector. This research focused on the cost-efficient distribution by making a comparison between two alternatives out of many more conceivable supply chains. Thus this research has focused on a rather specific aspect of the decarbonization of the mobility sector. Therefore it is essential to collect similar researches that focus on different hydrogen supply chains. Then all these hydrogen supply chain studies should be compared to the results from similar studies concerning supply chains using the other three potential sustainable fuels. This bottom-up research approach is required to obtain the bigger picture of decarbonizing the mobility sector.

Due to the dynamic behavior of technical innovations of all four potential sustainable fuels, the bottom-up research approach has an expiration date. Therefore it is advised to periodically evaluate the results from all bottom-up researches, including this research, and reflect upon.

To recap, climate change is a multi-sector issue and due to the multiple stakeholders included it is a complex issue which is continuously subjected to change. As hydrogen has the potential to be a multi-sector solution for reducing GHG emissions, it should be considered as such. Limiting the comparison of the four potentially sustainable fuels to the mobility sector would be a too limited scope. Hydrogen and the other fuels should be taken into account for all applications they could have in a multi-sector scope. Thus after the comparisons for the mobility sector, the results should be tested and evaluated on an even higher level of scope.

This concludes how this research is positioned in the literature. The results and recommendations are in line with the literature as well as with the opinions of the experts that have been interviewed during this research.

7.3. The scientific and societal contribution

The scientific contribution of this research translates into the combination of a techno-economic approach with current Dutch and European policy for the comparison of two state-of-the-art technologies in order to decarbonize the mobility sector in the Netherlands. Some results that were found interesting were:

- In the future tube-trailers are required to make two round trips per day in order to supply a sufficient amount of hydrogen to refueling stations. This will result in additional traffic pressure on the road network in the Netherlands which is an unwanted side-effect;

- Hydrogen distribution through pipelines is safer as it occurs underground and requires less on-site storage than tube-trailer road delivery. By using a pipeline infrastructure not only the mobility sector would benefit from the infrastructure, but also other sectors could be connected to such network resulting in lower marginal costs and multi-sector decarbonization which is desired for reaching the climate goals;
- Cost minimization is the dominant factor in hydrogen strategies and policies. Supply chain efficiencies are irrelevant for the acceptance of hydrogen in the mobility sector while this was included in multiple academic studies as a relevant factor.

For both the scientific and the societal contribution it is required that all included stakeholders are informed of changes in the system. This refers to policy changes as well as technological changes.

This research was performed in collaboration with the Ministry of Infrastructure and Water Management and the Netherlands Enterprise Agency. The dialogues that have been held between the supervisors are a relevant product of this research next to the results and recommendations that have been stated in this report. A topic as dynamic as hydrogen innovations and applications demands the academic and policy-making worlds to keep communicating and learning from one another. This research has contributed to the dialogue between stakeholders and has brought together their insights from various aspects of the system in a single report.

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8
Further Research

8.1. Market creation

Further research should investigate what the conditions are for hydrogen market creation in the mobility sector in the Netherlands and how could this be affected by Dutch policy. Existing hydrogen refueling stations could in further research be compared on their situational specific characteristics and from that starting point generic conditions could be developed. The added value of such research would be that not every individual municipality or energy company would have to perform their own analyses but that a more transparent system could exist enabling lower barriers for entry of investors in hydrogen refueling stations. Based on such research risk and cost analyses could be executed which are a solid base for investors to base their decisions on.
The research could also go in on the effect that certain policies and supply chain decisions have on the competitiveness in the hydrogen refueling market. For example, in Germany the decision was made to have a uniform dispensing price for hydrogen, independent of the refueling station's location. How would such a decision for the Netherlands have influence on the market and who would have to make such decision? Also an interesting question would be "What would the effect of such price mechanism be on the pace of adoption of a national covering hydrogen refueling infrastructure in the Netherlands?".

8.2. Hydrogen storage in a pipeline

As was noticed in this research, it would be possible to store hydrogen in a dedicated newly designed hydrogen pipeline. This could make on-site storage an obsolete need. Because the volume is proportional to the pressure of the hydrogen inside the pipeline, it is possible to design this pipeline for a pressure of for example 200 bar (compared to a standard pressure of 30 - 50 bar). This would have the result that less on-site storage capacity would be required which is generally space inefficient. Storing hydrogen in underground pipelines would also influence the institutional framework of the system as underground storage has less safety constraints than above-ground storage.
In this further research the technical possibilities as well as the financial and institutional effects would have to be analyzed.
Hydrogen storage in a pipeline is not exclusively relevant for supply chains in the mobility sector, but for the entire hydrogen system. Storage in a pipeline by increasing the pressure is a characteristic that electricity lacks. Electricity cannot be stored in an electricity cable. The electricity cable has a certain limit that in most electricity networks in the Netherlands is almost reached. Storage in pipelines could for example be useful in hydrogen production at the North Sea with intermittent hydrogen production.

8.3. HyET: An integrated purification unit and compressor for the backbone supply chain

As was noticed in chapter 4 HyET Group is developing a unit that is able to separate the hydrogen from a gas mix in a pipeline and simultaneously compress this hydrogen. This would have a major impact on the economic feasibility of the backbone supply chain as it would not anymore be a requirement to make a connection to the backbone supply chain. It could then be possible to mix hydrogen in with parts of the existing and operating gas infrastructure and separate the hydrogen locally at the refueling station. In further research it should be incorporated what the new agreements would be with regulated energy suppliers and whether this is indeed a feasible and safe alternative for hydrogen distribution to a hydrogen refueling station.

8.4. Hydrogen separation unit design for the backbone supply chain

For the separation unit of the hydrogen backbone system, recent research (July, 2021) found that a combination of a Pd-Ag membrane that is connected in series has the potential to supply a higher hydrogen purity, but also be a cheaper system than known alternatives [100]. The results of this research show that with the series connected membranes a separation cost of 5.05 €/kg H_2 can be achieved in a high pressure (40 bar) gas grid compared to a PSA separation cost of 8.3 US$/kg H_2 or 9.80 €/kg H_2 using a single metallic membrane [100]. The reason that this series connected membranes system is not applied in this research is that the proposed system was only tested for a daily hydrogen production of 25 kg, whereas this research considers a factor 80 higher output. Therefore this system is noted in further research to investigate whether it could be applied in a larger scale system and still be financially competitive with the alternative separation processes and achieve the required hydrogen purity for the use by vehicular fuel-cells.

8.5. Methanol as a hydrogen carrier

Methanol as a hydrogen carrier has the potential like ammonia to be produced sustainably and could also be decomposed locally [interview]. Methanol can be produced sustainably from carbon dioxide and water.
What the exact institutional aspects and safety measures are of distributing, storing and decomposing methanol to hydrogen with respect of distributing and storing pure hydrogen should be analyzed in this further research. Also a cost analysis should be performed as the costs are the main driver that could accelerate the rollout of a technology. Due to time limitations a supply chain that uses methanol as hydrogen carrier was not incorporated in this research.

8.6. Energy import

As other locations like Oman, Australia and the Sahara dessert have the potential to produce hydrogen from renewable energy for a lower levelized cost of hydrogen than the Netherlands the supply chain costs of hydrogen import should be researched. Because the dominant factor for the transition towards hydrogen applications in the Netherlands are the costs, low cost hydrogen production in other countries and transporting it to the Netherlands has the potential to improve the business case of supply chains. By producing hydrogen in these more suitable locations the uncertainty of the environmental influences like equivalent sun hours (ESH) are limiting to a lesser extent. Further research concerning production at these more suitable locations and transport should look at the costs as well as political and energetic dependency.

9
Data gathering

The data that has been applied in this research finds its origin in interviews that have been conducted with the experts below, the graduation committee, governmental reports and literature.

9.1. Experts

The stakeholders that have contributed to this research by providing data and the validation of data are as follows:

Ibren Feijen Msc.
Project manager at New Energy Coalition

Dr. Ir. Rob Stikkelman
Tu Delft

Harry Smit
Project manager for the development of the hydrogen backbone at Gasunie

Ir. Daan Geerdink
Chemical engineer at Hygro

Dick-Jan Marees
Director of Avia Marees

Albert van der Molen
Stedin

Jörg Gigler
Director at TKI Nieuw Gas Topsector Energie

9.2. Graduation committee

Prof. Dr. Ir. Z. Lukszo
Dr. A. F. Correljé
Prof. Dr. A.J.M. van Wijk
D. Schaap Msc.
R. Dwars Msc.

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A

Currently available financial incentives

The section will be divided into three different categories: National subsidies; National tax reductions; European subsidies. The European Union does not collect taxes from individual projects and therefore only subsidies will be discussed from the EU.

A.1. National incentives (subsidies)

The Netherlands has implemented various subsidies for hydrogen projects, each focussing on a different aspect and with different requirements for the application. The following subsidies will be discussed in this paragraph [123]:

- DEI+ (Demonstratie Energie- en Klimaatinnovatie)
- MOOI (Missiegedreven Onderzoek, Ontwikkeling en Innovatie)
- DKTI (Demonstratie Klimaattechnologieën en Innovaties in Transport)
- SDE++ (Stimulering Duurzame Energie)
- TSE (Topsector Energie)
- HER+ (Hernieuwbare Energie)

DEI+
The DEI+ subsidy is made available for investors in renewable energy sources, like wind and solar energy, that is used in an innovative manner to reduce CO2 emissions. The size of this subsidy is €126.6 million [124]. The DEI+ has a focus on reducing the carbon emissions in the industry, built environment and electricity sector [125]. The regulation covers eight themes: natural gas-free housing; Circular Economy; Carbon Capture, Utilisation and Storage; Energy-efficiency; Renewable energy including spatial integration; Increasing flexibility in the energy system (including hydrogen); Local infrastructure; Other CO_2-reducing measures in the industry or electricity sector. An example where this regulation was applied is at a data center that supplies currently its residual heat to a nearby swimming pool and in return, the swimming pool provides a cold stream back to the data center.

MOOI
The MOOI regulation was meant for projects that were focused on the categories: Wind at sea; Renewable electricity on land; Built environment; Industry. The full budget for the MOOI regulation was €95 million but this was split into the four categories with respectively a budget of €10.1 million; €10.9 million; €57 million; €17 million [126]. The MOOI regulation had a preference for 'green' hydrogen production through the process of electrolysis because it was mainly focused on producing

large scale and with the current state of technology electrolysis was assumed (by the Dutch government) to be the most obvious technology to achieve large scale 'green hydrogen' production [125]. In 2021 the MOOI regulation consists out of one theme: System solutions for integrating large scale renewable electricity generation and is only aimed at projects located in the Netherlands. For 2021 the budget of this regulation is €13.8 million and can give grants for 40% of the CAPEX costs when the applicant is a large enterprise, 50% when the applicant is a middle-large applicant and 60% when the applicant is a small enterprise [127][128]. Knowledge institutions are eligible to receive up to 80% compensation. The minimum size of a project is €2 million and the maximum is €4 million. The MOOI regulation is currently closed, but will be open for applications from July 6th until September 7th in 2021.

DKTI

The DKTI regulation is meant for companies that have the desire to decarbonize the mobility sector and to learn by doing. The DKTI regulation helps projects (that have not yet started) to gather knowledge and innovate in technologies (like hydrogen traffic) that are not yet on the market or have not been on the market for a long time [129]. The total budget for this regulation was €36.62 million. Through the DKTI regulation, the government aims to financially assist companies that have the desire to increase the sustainability in their company but are limited to the heavy batteries for BEVs and the long charging time that it takes to refuel BEVs. To assist these companies in the purchase of more expensive vehicles (FCEVs) in comparison with the alternative (conventional vehicles) the DKTI regulation can be granted [125]. An important note for this regulation is among others that it is aimed at developing the amount of compatible vehicles as well as the complementary infrastructure in order to refuel these vehicles. This applies to private vehicles as well as to heavy duty vehicles (HDVs) [125]. Currently the application for this regulation is closed, it was in 2021 open from March 23rd to April 6th. The maximum subsidy used to go up to 90% of the projects CAPEX and had a maximum absolute cap of €1 million, which is effectively in practice around 60% of the projects CAPEX [interview].

SDE++

The SDE++ regulation provides subsidies for projects in five categories: Renewable electricity (through osmosis, hydro-energy, wind or solar); Renewable heat (through using biomass in the process, using compost, deeply oriented geothermal heat, solar thermal systems); Renewable gas (from biomass); low-CO_2 heat (through aquathermal systems, daylight greenhouses, electrical boilers, shallow geothermal heat, residual heat, heatpumps); low-CO_2 hydrogen production (through electrolysis or by applying CCS technologies). The total budget for this regulation is €5 billion and applying is in the year 2021 limited from October 5th until November 11th [130].

Thus for projects that create hydrogen via electrolysis with additional renewable electricity or produce low carbon hydrogen via CCS technology the SDE++ regulation is applicable [131]. The regulation is however only available for projects that produce 'green' hydrogen, when this hydrogen is produced through the process of electrolysis and has a minimum hydrogen production capacity of 0.5 MW [125][131]. For the hydrogen production through electrolysis a maximum of 2000 full load hours can be subsidized. Hydrogen production complemented with CCS technologies is a carbon-reducing solution for processes that are unable to adapt their processes to become CO_2-neutral. The SDE++ regulation is also applicable for these projects and dependent whether the capture installation is newly purchased or if an existing installation is used, the size of the subsidy will be determined [131].

TSE

The TSE (Topsector Energiestudies Industrie) is a regulation that focuses on the feasibility of a pilot or demonstration project that aims at CO2 reduction. Producing hydrogen and other renewable fuels is one of the ways to establish that [123]. The budget for 2021 is €8 million and covers five themes: 1) Closing industrial chains; 2) CO_2-free energy and heat systems for the industry; 3) Electrification and innovations for climate neutral production processes; 4) Carbon Capture, Utilization and Storage; 5) Residual CO_2 reducing measures.
For themes 1, 2, 3 and 5 it is possible for large enterprises to receive up to 50% compensation for their project with a cap of €500,000 and for medium or small businesses this can be increased with respectively 10% and 20%. FOr projects that cover theme 4 also large enterprises can receive up to 50% compensation for their project and medium or small businesses this can be increased with respectively 10% and 20%, with a cap of €2 million per project [132]. Applications for this regulation are open until September 7th.

HER+

The HER+ (Hernieuwbare Energietransitie) regulation focuses on CO2 reduction as a broad concept, not specifically at renewable energy production. Projects that can make use of the HER+ regulation need to have the aim of CO2 reduction in the year 2030 and therefore aid in reaching the Dutch emission targets. The total budget of this regulation is €50 million [123][133]. This regulation is open for applicants until March 31st, 2022.

A.2. National incentives (tax reduction)

Besides the possibility of stimulating hydrogen projects by providing subsidies, the Netherlands has implemented tax reductions. An important note for this incentive to make use of is that the project has to make a profit in order to be able to pay taxes and thus to use the tax reductions. The following tax reductions will be discussed in this paragraph:

- MIA & Vamil
- EIA
- BPM & MRB

MIA & VAMIL

The MIA and VAMIL regulations are two tax reduction incentives to assist investors in reducing part of the costs in order to create a better business case for the desired projects. The MIA (Milieuinvesteringsaftrek) could go as far as reducing 36% of the investment costs of the project. That is above the ordinary investment cost tax reduction [134][54]. With the VAMIL (Willekeurige afschrijving milieu-investeringen) it is possible to depreciate up to 75% of the investment costs at a moment in time that is most opportune for the investor to gain the most out of a liquidity and interest benefit. The tax benefits could be as much as 12% when the MIA and VAMIL are combined [134]. But on the entire lifetime of a vehicle, the Vamil has practically no effect [54]. The budget of the MIA regulation in 2021 is €114 million and for the VAMIL is €25 million [134].
Similar to the DKTI regulation, the MIA can be especially useful for companies who have the desire to improve their sustainability by altering their conventional vehicles to electric vehicles, but the BEVs cannot meet their requirements. To lower the purchase costs of FCEVs these companies can be eligible for the MIA regulation [125].

EIA
When someone invests in sustainable energy and energy efficient technology, they can make use of the EIA (Energie-investeringsaftrek) regulation. This regulation enables that up to 45.5% of the investment costs can be deducted from the fiscal [123]. This regulation is also applicable for investors who focus on balancing the energy balance which is becoming a larger issue with the growth of renewable energy sources in the energy mix [135]. Decentralized hydrogen production for the mobility sector could play a proper role in this balancing. Therefore is the EIA sincerely relevant. The budget for 2020 was €147 million and for 2021 this is €149 million and on average the regulation provides a compensation of 11% [136] [123].

BPM & MRB
Fuel-Cell Electric Vehicles (FCEVs) are fiscally stimulated in the Netherlands (similar to BEVs) at least until 2025. FCEV- and BEV-owners do not pay the 'tax on passenger cars and motor vhicles' (BPM) nor the 'vehicle tax' (MRB) and get a (unlimited) discount on the additional tax liability [125][137]. From 2025 a BPM will have to be paid of €360 at the purchase of an FCEV or BEV. During 2025 the discount for the MRB is 75%, the residual 25% has to be paid of the regular tariff and from 2026 FCEV- and BEV-owners have to pay the regular tariff of the motor vehicle tax [137].

A.3. European incentives

- EFRO (Europees Fonds voor Regionale Ontwikkeling)
- CEF (Connecting Europe Facility Transport)
- IPCEI (Important Projects of Common European Interest)
- Interreg
- RED2 (Renewable Energy Directive 2)
- Horizon
- JTI Fuel Cells and Hydrogen

EFRO
The 'Europees Fonds voor Regionale Ontwikkeling' (EFRO) is a regulation that helps to converge the economic growth between various regions. It focuses on projects that increase the regional competition, increase the employment opportunities and projects that aim to reach a low carbon economy by improving the energy-efficiency and innovate in this sector. An example of a project in the Netherlands that makes use of the EFRO regulation is a hydrogen production unit that uses a biomass unit to produce hydrogen on large scale [138].

CEF
The Connecting Europe Facility (CEF) regulation is a financing instrument from the European Union focused on aiding projects financially that aim at the development of trans-European transportation and energy networks. Over the period of 2014 to 2020 the CEF Transport has a total budget of €24 billion and the CEF Energy regulation has a budget of €4.7 billion. CEF Transport projects are eligible for the financial support when they aim at improving the TEN-T network through Europe by innovative means. Hydrogen as a fuel for the mobility sector is part of this. In order to be eligible for the CEF Energy regulation the project has to be on the European list of Projects of Common Interest (PCI) and thus needs to affect at least two European countries [138].
In March 2021 the European Council reached a provisional agreement on the CEF regulation for the

period of 2021 - 2027. The budget for this period will be raised to €33.71 billion. Projects in the transport, digital and energy sector are still eligible for the application of the CEF 2.0 funding and can apply retroactively from 1 January 2021 [37].

IPCEI

The Integrated Projects of Common European Interest (IPCEI) regulation affects all kinds of projects under the name of 'Hydrogen for Climate Action'. This includes projects that are not feasible and could be anywhere in the hydrogen supply chain from 'green' production to the application and dispensing into vehicles [138].

Interreg

The Interreg regulation is part of the EFRO because it is also for the coupling of regions but then cross-border specific. Hydrogen fits the requirements of innovation and low carbon economy in order to be eligible for the Interreg regulation. The budget for 2014 to 2020 was €309 million. There is supposed to be a renewed regulation that is similar to the Interreg for the period 2021-2027, but this was delayed due to the uncertainties with respect to Brexit [138].

RED2

The Renewable Energy Directive 2 (RED2) regulation has the purpose to provide incentives for the increase in sustainable alternatives for (among other sectors) the mobility. It aims to stimulate the increase of renewable fuels for transportation and the required network to achieve this goal. The RED2 provides a system where a market is created for renewable energy sources. The RED2 has set a target that 32% of the final consumption in the energy mix has to come from renewable sources by 2030 [139].

Horizon

Horizon Europe is the key funding programme of the European Union with the purpose to fund innovations and research with a total budget of €95.5 billion. The Horizon regulation strengthens research and innovation in developing, supporting and implementing European policies. In order to do so, all legal entities from the EU can apply for funds from this regulation [140].

JTI Fuel Cells and Hydrogen

The JTI Fuel Cells and Hydrogen (FCH-JU - Fuel-Cell and Hydrogen Joint Undertaking) was a public-private cooperation that worked together on the matters of hydrogen. The goal of the FCH-JU was to commercialize hydrogen as fuel and fuel-cells by enabling and financing innovative projects in this sector [141]. The total budget of this public-private cooperation was €700 million between 2014 and 2020 and for 2021 there will be a new budget. From 2021 on forward the name will also be changed to Clean Hydrogen for Europe (CHE). This regulation received its financial capital from the European regulation 'Horizon'.

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B
List of costs per hydrogen production method

The cost of hydrogen per prdouction method that have been found in the literature are presented in table B.1 and have been sorted by year. The evolution of these hydrogen prices have also been visualized per production method over time in the figures beneath the table. For the prices that were only found for a single year the figures are not shown. As various data was found in $/kg while in this research the unit €/kg is applied following conversion rate has been used:
1 US$ = 0.8931 €

Table B.1: Overview of hydrogen prices per production method as stated in the literature

H_2 production method	H_2 price (range)	Unit	Year	Reference
Ammonia	14.91	€/kg	2019	[142]
Ammonia	7.35	€/kg	2020	[143]
Ammonia	6 - 10	€/kg	2021	[77]
Biomass (with CCS)	3.75	$/kg	2021	[144]
Biomass (without CCS)	4.63	$/kg	2016	[89]
Biomass (without CCS)	2.20 - 7.50	€/kg	2017	[145]
Biomass (without CCS)	11.23	€/kg	2019	[142]
Biomass (without CCS)	1.77 - 2.05	$/kg	2019	[146]
Biomass (without CCS)	2.3	$/kg	2021	[144]
Coal (with CCS)	1.03	$/kg	2016	[89]
Coal (with CCS)	1.63	$/kg	2019	[146]
Coal (with CCS)	1.60 - 3.30	$/kg	2020	[101]
Coal (with CCS)	2.5	$/kg	2021	[144]
Coal (without CCS)	0.96	$/kg	2016	[89]
Coal (without CCS)	1.34	$/kg	2019	[146]
Coal (without CCS)	1.95	$/kg	2020	[147]
Coal (without CCS)	1.4	$/kg	2021	[144]
Electrolysis (Wind)	6.64	$/kg	2016	[89]
Electrolysis (wind)	6.1	€/kg	2017	[145]
Electrolysis (wind + PEM)	4 - 12	€/kg	2017	[145]
Electrolysis (wind + PEM)	10.9	€/kg	2018	[105]
Electrolysis (wind + PEM)	4 - 6	€/kg	2019	[62]
Electrolysis (Wind)	5.89 - 6.03	$/kg	2019	[146]
Electrolysis (wind)	5.5	$/kg	2021	[144]
Electrolysis (wind)	6 - 7.4	$/kg	2021	[77]
Electrolysis (PV + grid + Alkaline)	9.29 - 12.48	€/kg	2020	[11]
Electrolysis (PV + Alkaline)	6.85	$/kg	2020	[147]
Electrolysis (PV)	12.1	$/kg	2020	[101]
Electrolysis (PV)	9.4	$/kg	2021	[144]
SMR (with CCS)	1.22	$/kg	2016	[89]
SMR (with CCS)	2.27	$/kg	2019	[146]
SMR (with CCS)	1.50 - 3.16	$/kg	2020	[101]
SMR (with CCS)	1.4	$/kg	2021	[144]
SMR (with CCS)	2	$/kg	2021	[144]
SMR (without CCS)	1.03	$/kg	2016	[89]
SMR (without CCS)	2 - 7	€/kg	2017	[145]
SMR (without CCS)	2.08	$/kg	2019	[146]
SMR (without CCS)	1.43	$/kg	2020	[101]
SMR (without CCS)	1.13	$/kg	2020	[147]
SMR (without CCS)	2.08	$/kg	2021	[77]

C
Joint costs for both supply chains

C.1. High pressure compressor

All compressors that are incorporated in the supply chains have to meet the standards of NEN-EN 1012-3 [21].

CAPEX
16,000 €/kg/hour (2017) [145]
20,800 €/kg/hour (2018) [105]
9,600 €/kg/hour (future) [105]
The average of the CAPEX is 18,400 €. The CAPEX of the future is not considered as no year indication was given for 'future'.

In the research of Chrysochoidis-Antsos et al. a hydrogen output of 330 kg/day was considered. For this output a high-pressure compressor flow rate of 33.6 kg/hour was required. The flow rate for the supply chain conditions in this research is calculated as follows:
2000 [kg/day] / 330 [kg/day] = 6.1
6.1 · 33.6 [kg/hour] = 204 [kg/hour]

As the average investment costs for the high-pressure compressor is 18,400 €/kg/hour, the total CAPEX can be calculated as follows:
18,400 [€/kg/hour] · 204 [kg/hour] = 3,746,910 €.
Thus the CAPEX of the high-pressure compressor is estimated at 3,746,910 €, which is rounded to 3,747,000 €.

$$C_{high-pressure\,compressor_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 3,747,000 = 251,857$$

This is rounded to 252,000 €/year.

OPEX
4% of the CAPEX (2017) [145]
4% of the CAPEX (2018) [105]
2% of the CAPEX (future) [145]
2.5% of the CAPEX (future) [105]
For the OPEX 4% of the CAPEX is considered as for 'future' no year indication was given in the researches.
OPEX = 0.04 · 3,746,910 = 149,877 €/year.
This is rounded to 150,000 €/year.

REPLEX

For the replacement of the high-pressure compressors one replacement is considered [105]. Therefore the REPLEX equals the CAPEX. It is likely that the costs for compressors will decrease in the future, however due to lack of data no estimation is considered in this research. Therefore a similar cost as the CAPEX is applied which is 3,746,910 €.

$$C_{high-pressure\,compressor_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{3,747,000}{(1+0.03)^{10}} = 187,406$$

This is rounded to 187,500 €/year.

C.2. High pressure storage

CAPEX

The CAPEX is 1180 €/kg (2018) [105].

In a different study for a hydrogen demand of 1875 kg/day, a low pressure storage of 1875 kg and a high pressure storage of 225 kg was used [51]. This study especially focused at the hydrogen demand of heavy duty vehicles and therefore this data will be extrapolated to fit the supply chain requirements in the functional unit of 2000 kg/day demand in this research. Extrapolated this would result in a medium pressure storage of 2000 kg and a high pressure storage of 240 kg. Therefore a high pressure storage capacity of 240 kg is considered.

1180 [€/kg] · 240 [kg] = 283,200 €.

$$C_{high\,pressure\,storage_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 283,200 = 19,000$$

OPEX

The OPEX is 1% of the CAPEX [105].

283,200 · 0.01 = 2,832.

This is rounded to 3,000 €/year.

REPLEX

The lifetime of a high pressure storage is estimated at 30 years [73].

$$C_{high\,pressure\,storage_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{283,200}{(1+0.03)^{30}} = 7,800$$

This is rounded to 8,000 €/year.

C.3. Refrigeration unit

CAPEX

The CAPEX is 143,880 €/kg/min [82].

As was discussed a flow rate of 7.2 kg hydrogen per minute is required for the refrigeration unit.

CAPEX = 143,880 · 7.2 = 1,035,936 €, which is rounded to 1,036,000 €.

Four refrigeration units are required, thus the CAPEX are four times as large, which is 4,144,000 €.

$$C_{refrigeration\,unit_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 4,144,000 = 278,542$$

This is rounded to 280,000 €/year.

OPEX
The OPEX is approximately 2.0% of the CAPEX per year, which denotes €22,283 per year [105]. This is rounded to 22,000 €/year.

REPLEX
For the refrigeration unit no replacement expenditures are considered in the research of Perna et al. [143]. However, the research of Chrysochoidis-Antsos et al. does consider one replacement [105]. In this research also one replacement is considered. Therefore the REPLEX is as follows:

$$C_{refrigeration\,unit_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{4,144,000}{(1+0.03)^{10}} = 207,261$$

This is rounded to 210,000 €/year.

C.4. Dispensing unit

CAPEX
CAPEX is 130,000 € [77][143][105].
Four dispensing units are required, thus the CAPEX are four times as large, which is 520,000 €.

$$C_{dispensing\,unit_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 520,000 = 34,952$$

This is rounded to 35,000 €/year.

OPEX
The OPEX is €4000 per year per dispensing unit [77][143][105]. Therefore the OPEX is €16,000 per year.

REPLEX
For the dispensing unit one replacement is considered resulting in a REPLEX of €130.000 per dispensing unit [143].

$$C_{dispensing\,unit_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{520,000}{(1+0.03)^{10}} = 26,008$$

This is rounded to 26,000 €/year.

C.5. Energy consumption

C.5.1. Compression, cooling and dispensing

The energy requirement for the compression of hydrogen up to 500 bar (including cooling) is approximately 2.6 kWh/kg hydrogen [8]. And to further compress the hydrogen to 900 bar the energy requirement is approximately 3.5 kWh/kg hydrogen [8].
For the compression up to 500 bar 2.6 [kWh/kg] · 2000 [kg/day] · 365.25 [days/year] = 1,899,300 [kWh/year] is needed.
For the compression up to 900 bar 3.5 [kWh/kg] · 2000 [kg/day] · 365.25 [days/year] = 2,556,750 [kWh/year] is needed.
In total 1,899,300 [kWh/year] + 2,556,750 [kWh/year] = 4,456,050 [kWh/year] is needed for the compression and cooling of the hydrogen.

C.5.2. Pressure Swing Adsorption unit

The energy penalty of a PSA unit is 0.8 - 1.5 kWh/m^3 (at 25.81 bar) [148]
The density of hydrogen at 20 °C and 1 atm (1.01325 bar) is 0.08376 kg/m^3
25.82 [bar] / 1.01325 [bar] = 25.4725 (this is the factor that will be multiplied by the density)
$25.4725 \cdot 0.08376 = 2.1335$ kg/m^3
So the energy penalty of a PSA unit is 0.8 - 1.5 kWh per 2.1335 kg.
0.8 / 2.1335 = 0.374957
1.5 / 2.1335 = 0.703045
The energy penalty of a PSA unit is thus 0.375 - 0.70 kWh/kg.
Thus per year that is:
$2000 \cdot 365.25 \cdot 0.375 = 273{,}906$ kWh
$2000 \cdot 365.25 \cdot 0.70 = 513{,}574$ kWh
The energy penalty of a PSA unit ranges approximately between 274,000 - 514,000 kWh per year.

The electricity price in the Netherlands in 2020 was 0,0707 €/kWh.
Assuming for the PSA unit energy penalty a pessimistic scenario the total energy consumption costs are as follows:
$(4{,}456{,}050 + 514{,}000) \cdot 0{,}0707 = 351{,}382.5$
The costs for the energy consumption of the supply chain are approximately 351,500 €/year.

C.6. Cost overview

Table C.1: For both supply chains the annual costs overview for joint components

Plant section	**CAPEX,a [€/year]**	**OPEX [€/year]**	**REPLEX,a [€/year]**
High pressure compressor	252,000	150,000	187,500
High pressure storage	19,000	3,000	8,000
Refrigeration unit	280,000	22,000	210,000
Dispensing unit	35,000	16,000	26,000
Energy consumption	N/A	351,500	N/A

D

Costs of supply chain A

D.1. Pressure Swing Adsorption unit

The price of renewable hydrogen in 2017 was 5.24 €/kg +-5% [79]. This price is expected to decrease to €2.92 per kg hydrogen ±25% in 2025 and decrease even further towards 2030 [79].
In this research the hydrogen price of €2 per kilogram for low carbon hydrogen is applied (based on the average of the LCOH through SMR with CCS from 2019 to 2021) and this price is assumed to be constant through the 20 year timespan.
This hydrogen is low carbon hydrogen instead of renewable, therefore a purification step is required. A Pressure Swing Adsorption unit (PSA) for the purification step is estimated to have added approximately 0.70 US$/kg to the hydrogen price in 2019 and is expected to add approximately 0.40 US$/kg to the hydrogen price in 2025.
Applying the conversion rate of 1 US$ = 0.8931 € the costs in 2025 are approximately (0.35724) 0.36 €/kg.
As 2000 kg of hydrogen per day is demanded and on average there are 365.25 days in a year, the total yearly costs for the purification of the low carbon hydrogen are:
0.36 [€/kg] · 2000 [kg/day] · 365.25 [days/year] = 262,980 [€/year]
The yearly costs for the low carbon hydrogen are estimated at €263,000.

D.2. Storage (off-site at low pressure)

CAPEX
2017:
The costs for hydrogen storage were for a 50 bar pressure, 200 bar pressure and 350 bar pressure storage 470 €/kg [73].

2019:
For 22 hydrogen storage containers of each 800 kg of hydrogen at 300 bar an investment of 6.6 million € is required [149].
Thus for 1 container that would require an investment of 300,000 €. However, this is for 800 kg of hydrogen and 1000 kg of hydrogen is needed. Extrapolating these costs the resulting CAPEX is 375,000 €.

The costs for the most recent research will be applied, thus the CAPEX for the low-pressure off-site storage equals 375,000 €.

$$C_{off-site storage_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 375,000 = 25,206$$

This is rounded to 25,000 €/year.

OPEX
Every 10-15 years an inspection and maintenance is required which results in an OPEX of 2% of the CAPEX [73].
Assumed is that this inspection will take place every 10 years. The OPEX will be calculated as follows:
375,000 [€] · 0.02 / 10 [years] = 750 [€/year]
Thus the OPEX is 750 €/year.

REPLEX
The lifetime of stationary storages are 30-40 years [73]. It is assumed that the storage will be depreciated over a period of 30 years. Therefore the REPLEX is as follows:

$$C_{off-site storage_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{375,000}{(1+0.03)^{30}} = 10,385$$

This is rounded to 10,500 €/year.

D.3. Compressor (low pressure)

CAPEX
5000 €/kg H_2 per hour (2017) [145]
6500 €/kg H_2 per hour (2018) [105]
The average equals 5750 €/kg H_2 per hour
The tank should be able to be filled in 1,5 hours [150], thus a flow rate of 666.67 kg H_2/h is needed. This results in a CAPEX of 3,833,334 € which will be rounded to 3,833,000 €.

$$C_{low-pressure compressor_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 3,833,000 = 257,638$$

This is rounded to 258,000 €/year.

OPEX
4% of the CAPEX (2017) [145]
4% of the CAPEX (2018) [105]
The average equals 4% of the CAPEX
The OPEX is 153,334 €/year which will be rounded to 153,000.

REPLEX
The lifetime of a compressor is 10 years, thus the compressors require 1 replacement and need to be depreciated in a period of 10 years [77][145][105].
The replacement costs are assumed to equal the investment costs. Thus the REPLEX is as follows:

$$C_{low-pressure compressor_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{3,833,000}{(1+0.03)^{10}} = 191,707$$

This is rounded to 192,000 €/year.

D.4. Tube-trailer

CAPEX

To get a feeling of the investment costs for a tube-trailer these numbers were found in the literature:

- 550,000 € for net capacity of 670 kg and O&M of 2% (2017). This is 820 €/kg for the CAPEX [150].
- 724,000 US$ (= 646,605 €) for 690 kg (2018). This is 937 €/kg for the CAPEX [151].
- 646,050 € for 885 kg and O&M of 2% (2019). This is 730 €/kg for the CAPEX [62].
- 176,470 US$ (= 157,605 €) for 350 kg (2020). This is 450 €/kg for the CAPEX [63].
- 830 €/kg for 1000 kg at 500 bar (2017) [73]
- 605 €/kg for 1000 kg at 500 bar (2025) [73]

In an interview it was noted by the interviewee that the costs of 830 €/kg (2017) and 605 €/kg (2025) are commonly used by stakeholders. Therefore the decision was made to apply 605 €/kg in the calculations.
Thus the assumed CAPEX of the tube-trailer is 605,000.

$$C_{tube-trailer_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 605,000 = 40,665$$

This is rounded to 41,000 €/year.

OPEX

The OPEX is 2% of the CAPEX (2017, 2019) [150][62].
The OPEX is 4% of the CAPEX (2019) [149].
The average of the OPEX percentages is 2.67% which is approximately 16,150 €/year.
This is rounded to 16,000 €/year.

REPLEX

The lifetime of these tube-trailers are 20-30 years, thus the tube-trailer does not need a replacement. But it will be depreciated over a period of 20 years [73][149].

$$C_{tube-trailer_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{605,000}{(1+0.03)^{20}} = 22,515$$

This is rounded to 22,500 €/year.

D.5. Truck

CAPEX

The CAPEX of the truck is 160,000 € (2017, 2019) [62][150].

$$C_{truck_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 160,000 = 10,755$$

This is rounded to 11,000 €/year.

OPEX
The OPEX is 12% of the CAPEX (2017, 2019) [62][150]
Thus the OPEX is 19,200 €/year.

REPLEX
The depreciation period of a truck is 8 years [150]. Thus the truck would need to be replaced 2.5 times in a timespan of 20 years.

$$C_{truck_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{160,000}{(1+0.03)^{8}} = 8,490$$

The REPLEX is rounded to 8,500 €/year.

D.6. Transport costs

The transport costs consist of the variable costs due to the driving distance. The transportation costs for hydrogen by tube-trailer are estimated at approximately 1.78 €/km [92]. The tube-trailer has a maximum capacity of 1000 kg per trip, thus to supply 2000 kg per day, the tube-trailer has to make two round trips. Therefore a transportation cost of 2 · 1.78 = 3.56 €/km is considered. For the cost analysis the transportation cost needs to be converted from daily costs to yearly costs. Therefore the 3.56 €/km will be multiplied by 365.25 days per year which is approximately 1300 €/km. It is plausible that the costs of transporting hydrogen would deviate a bit because the driver might be required to have additional certificates [interview]. But, it is not likely that the costs will be significantly higher or lower. Concluding, the costs for transporting hydrogen by tube-trailer road delivery is €1300 per kilometer for two round trips with a delivery of 2000 kg per day in total.
Assuming a distance of 100 km between the hydrogen production facility and the hydrogen refueling station, this cost is:
1300 [€/km/year] · 100 [km] = 130,000 [€/year]
The transportation costs by tube-trailer are approximately 130,000 €/year.

D.7. Hydrogen storage (on-site and at 500 bar)

This storage unit is similar to the off-site storage, except that it is designed at 2x the capacity, because it cannot be allowed to be completely empty at moments as that would mean that no refueling is possible anymore. Therefore the on-site storage has to be designed at the full hydrogen demand per day. Thus the costs are also twice as high.

CAPEX
The CAPEX is 750,000 €.

$$C_{on-site storage_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 750,000 = 50,411$$

This is rounded to 50,500 €/year.

OPEX
2% of the CAPEX (2017) [150]
1% of the CAPEX (2018) [105]
The most recent storage cost is assumed which is 1% of the CAPEX.

Thus the OPEX is:
0.01 · 750,000 [€] = 7,500 €/year.
The OPEX is 7,500 €/year.

REPLEX
The lifetime of stationary storages are 30-40 years, thus the does not have to be replaced. But it will be depreciated over a period of 30 years. Therefore the REPLEX is as follows:

$$C_{on-site storage_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{750,000}{(1+0.03)^{30}} = 20,769$$

This is rounded to 21,000 €/year.

D.8. Cost overview

Table D.1: Supply chain A annual cost overview per component

Plant section	**CAPEX [€/year]**	**OPEX [€/year]**	**REPLEX [€/year]**
Pressure Swing Adsorption unit	-	263,000	-
Off-site hydrogen storage	25,000	750	10,500
Compressor (low pressure)	258,000	153,000	192,000
Tube-trailer	41,000	16,000	22,500
Truck	11,000	19,200	8,500
Transportation costs (100 km)	N/A	130,000	N/A
On-site medium pressure hydrogen storage	50,500	7,500	21,000
Compressors (high pressure)	252,000	150,000	187,500
On-site high pressure hydrogen storage	19,000	3,000	8,000
Refrigeration unit (4x)	280,000	22,000	210,000
Hydrogen dispenser (4x)	35,000	16,000	26,000
Energy consumption costs	N/A	351,500	N/A
Sum	971,500	1,131,950	686,000
Total	2,789,450		

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E
Costs of supply chain B

E.1. Transportation costs

CAPEX
N/A

OPEX
In a medium scenario the transportation costs through the hydrogen backbone are 0.13 €/kg [80]. It can be assumed that the hydrogen will be transported over a distance less than 1000 km since the total length of the hydrogen backbone in the Netherlands will be 1,100 kilometer.
The transportation costs are as follows:
0.13 [€/kg] · 2000 [kg/day] · 365.25 [days/year] = 94,965 [€/year] The transportation costs are approximately 95,000 €/year.

REPLEX
N/A

E.2. Pressure Swing Adsorption unit

A Pressure Swing Adsorption unit (PSA) is estimated to add approximately 0.70 US$/kg to the hydrogen price in 2019 and is expected to add approximately 0.40 US$/kg to the hydrogen price in 2025. Applying the conversion rate of 1 US$ = 0.8931 € the costs in 2025 are approximately (0.35724) 0.36 €/kg.
Then the yearly costs for applying a PSA unit for the purification step is approximately:
0.36 [€/kg] · 2000 [kg/day] · 365.25 [days/year] = 262,980 [€/year]
The costs for the Pressure Swing adsorption unit are approximately 263,000 €/year.

E.3. Compressor (low pressure)

CAPEX
5000 €/kg H_2 per hour (2017) [145].
6500 €/kg H_2 per hour (2018) [105].

The average equals 5750 €/kg H_2 per hour.
As a flow of 216 kg/hour is sufficient, a CAPEX of 1,242,000 € is estimated.

$$C_{low-pressure\,compressor_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 1,242,000 = 83,482$$

This is rounded to 83,000 €/year.

OPEX
4% of the CAPEX (2017) [145]
4% of the CAPEX (2018) [105]

The average equals 4% of the CAPEX which denotes 49,680 €/year, which is approximately 50,000 €/year.

REPLEX
The lifetime of a compressor is approximately 10 years, thus the compressors require 1 replacement. Thus the REPLEX equals the CAPEX [77].

$$C_{low-pressure\,compressor_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{1,242,000}{(1+0.03)^{10}} = 62,118$$

This is rounded to 62,000 €/year.

E.4. On-site medium pressure hydrogen storage

In a different study for a hydrogen demand of 1875 kg per day, a low pressure storage of 1875 kg and a high pressure storage of 225 kg was used [51]. This study especially focused at the hydrogen demand of heavy duty vehicles and therefore this data will be extrapolated to fit the supply chain requirements in the functional unit of 2000 kg per day demand in this research. Extrapolated this would result in a medium pressure storage of 2000 kg and a high pressure storage of 240 kg. However, as a pipeline infrastructure allows for on-demand supply less on-site storage is needed.
An FCEV refuels approximately 5 kg of hydrogen. This would suggest that 48 FCEVs can refuel. An FCEV could refuel in approximately 5 minutes.
48 [vehicles] · 5 [minutes/vehicle] = 240 [minutes]
An FC-HDV can refuel in approximately 15 minutes.
240 [minutes] / 15 [minutes/vehicle] = 16 [vehicles]
An FC-HDV refuels approximately 40 kg.
16 [vehicles] · 40 [kg/vehicle] = 640 [kg]

CAPEX
500 €/kg (2017) [150].
870 €/kg (2018) [105].
356 €/kg (2019) [152].
375 €/kg (2019) [149].
The value of 375 €/kg is considered as was the case in supply chain A.
The low pressure storage costs are thus:
375 [€/kg] · 640 [kg] = 240,000 [€]
The CAPEX for the on-site medium pressure hydrogen storage unit is 240,000 €.

$$C_{medium\,pressure\,storage_{CAPEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot 240,000 = 16,132$$

This is rounded to 16,000 €/year.

OPEX
2% of the CAPEX (2017) [150]
1% of the CAPEX (2018) [105]
The most recent storage cost is assumed which is 1% of the CAPEX.
Thus the OPEX is:
0.01 · 240,000 [€] = 2,400 €/year.
The OPEX is 2,400 €/year.

REPLEX
No replacement is required for the hydrogen storage because the lifetime of a hydrogen storage is approximately 30-40 years. The medium pressure hydrogen storage will be depreciated in a period of 30 years, therefore the REPLEX is as follows:

$$C_{medium\,pressure\,storage_{REPLEX,a}} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20}-1} \cdot \frac{240,000}{(1+0.03)^{30}} = 6,646$$

This is rounded to 6,500 €/year.

E.5. Cost overview

Table E.1: Supply chain B annual cost overview per component

Plant section	**CAPEX [€/year]**	**OPEX [€/year]**	**REPLEX [€/year]**
Transport costs	N/A	95,000	N/A
Pressure Swing Adsorption unit	-	263,000	-
Compression (low pressure)	83,000	50,000	62,000
On-site medium pressure hydrogen storage	16,000	2,400	6,500
Compressors (high pressure)	252,000	150,000	187,500
On-site high pressure hydrogen storage	19,000	3,000	8,000
Refrigeration unit (4x)	280,000	22,000	210,000
Hydrogen dispenser (4x)	35,000	16,000	26,000
Energy consumption costs	N/A	351,500	N/A
Sum	685,000	952,900	500,000
Total	2,137,900		

E.6. Hydrogen pipeline diameter requirements for pressures of 50, 30 and 8 bar pipelines.

The correlation between the density of hydrogen and the pressure is at lower pressures (between 8 and 50 bar) and at ambient temperatures almost linear [153].

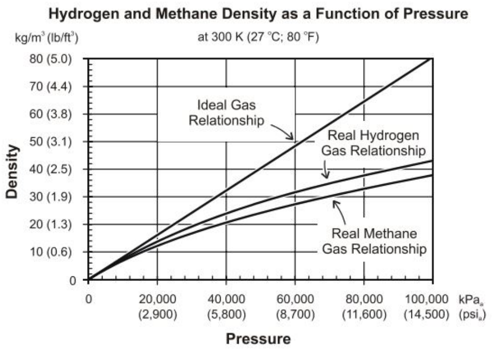

Figure E.1: Hydrogen Density as a Function of Pressure [153]

As can be observed in figure E.1 the slope of the linear line can be calculated as follows:
dy/dx = (80-0)/(1000-0) = 0.08 [(kg/m^3)/bar]
When the pressure inside the pipeline is 50 bar that means that:
0.08 [(kg/m^3)/bar] * 50 [bar] = 4 [kg/m^3] is distributed.
2000 [kg/day] / 4 [kg/m^3] = 500 [m^3/day]
So per hour that is:
500 [m^3/day] / 24 [hours/day] = 20.83 [m^3/hour]
So when the hydrogen in the pipeline has a pressure of 50 bar, a flow rate of 20.83 [m^3/hour] is required to supply 2000 kg per day to the refueling station.

When the pressure inside the pipeline is 30 bar that means that:
0.08 [(kg/m^3)/bar] * 30 [bar] = 2.4 [kg/m^3] is distributed.
2000 [kg/day] / 2.4 [kg/m^3] = 833.333 [m^3/day]
So per hour that is:
833.333 [m^3/day] / 24 [hours/day] = 34.72 [m^3/hour]
So when the hydrogen in the pipeline has a pressure of 30 bar, a flow rate of 34.72 [m^3/hour] is required to supply 2000 kg per day to the refueling station.
That means that at least a G25 pipeline is needed for the hydrogen distribution in order to supply 2000 kg per day at a pressure range of 30 to 50 bar [154].

When the pressure inside the pipeline is 8 bar that means that:
0.08 [(kg/m^3)/bar] * 8 [bar] = 0.64 [kg/m^3] is distributed.
2000 [kg/day] / 0.64 [kg/m^3] = 3,125 [m^3/day]
So per hour that is:
3,125 [m^3/day] / 24 [hours/day] = 130.2 [m^3/hour]
So when the hydrogen in the pipeline has a pressure of 8 bar, a flow rate of 130.2 [m^3/hour] is required to supply 2000 kg per day to the refueling station.
The G25 has a maximum capacity of 40 m^3/hour. Thus a larger pipeline is required to distribute 2000 kg/day of hydrogen through the 8 bar pipeline network [154].

F

Cost distribution per supply chain

In this appendix visualizations of the costs of the two supply chains will be presented.

F.1. Supply chain A: Tube-trailer road delivery

The CAPEX and REPLEX of supply chain A do not vary per scenario as the transportation cost is the only variable.
The OPEX for eight driving distance scenarios is presented in figure F.1. These are the yearly operational & maintenance expenditures.

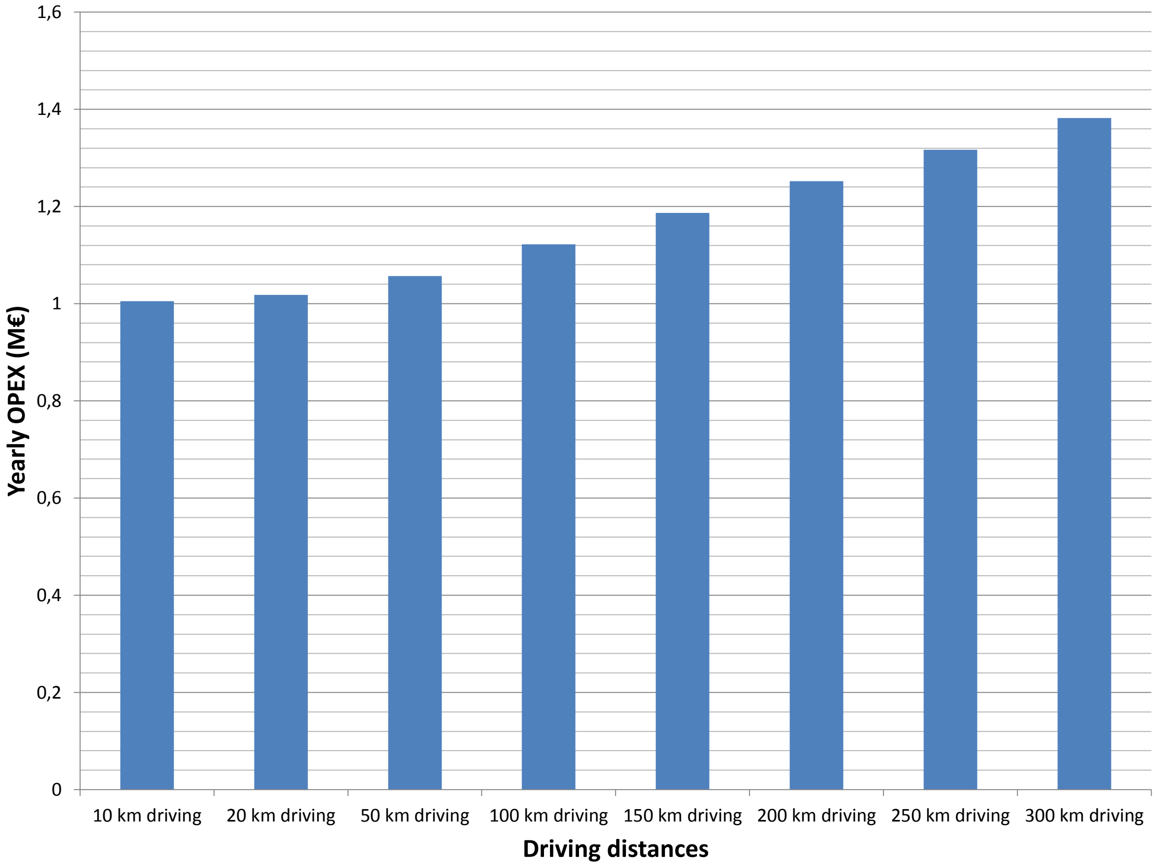

Figure F.1: The OPEX for eight different driving distance scenarios in supply chain A

Because the transportation cost is the only variable in the calculation, the differences in yearly OPEX are caused due to the travel distance.
It can be seen that the difference in costs per year that can be allocated to the driving distance

between 300 km and 10 km is approximately 377,000 €/year.
For figures F.2, F.3 and F.4 a driving distance of 100 km is assumed. Thus similar costs as in table D.1 are considered.

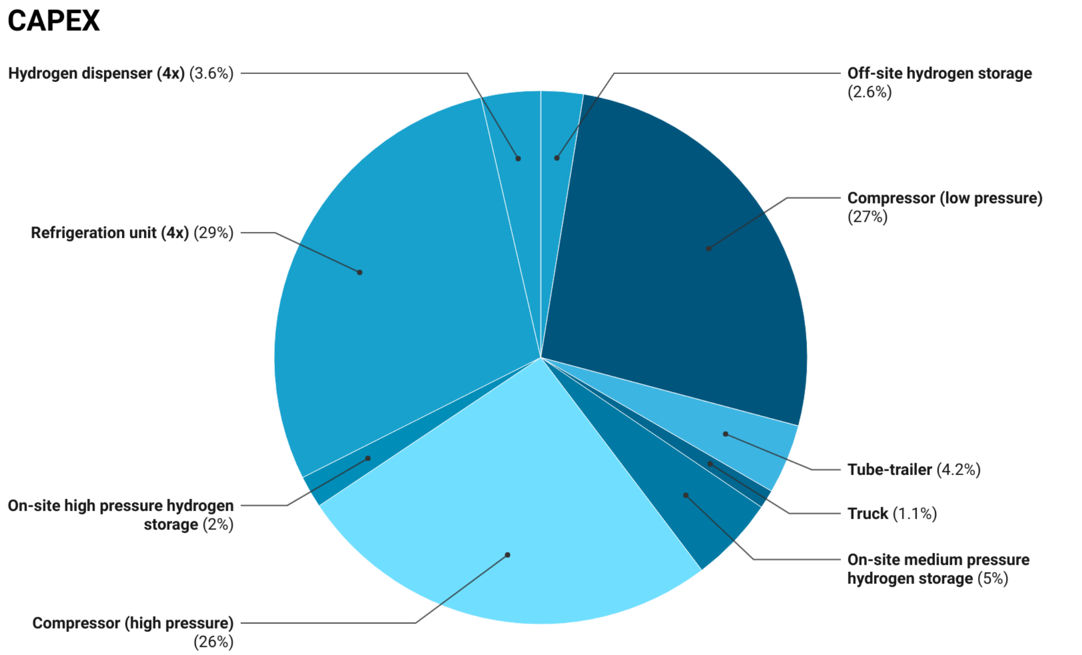

Figure F.2: The CAPEX & REPLEX fraction per component of the scenario with 100 km driving distance in supply chain A

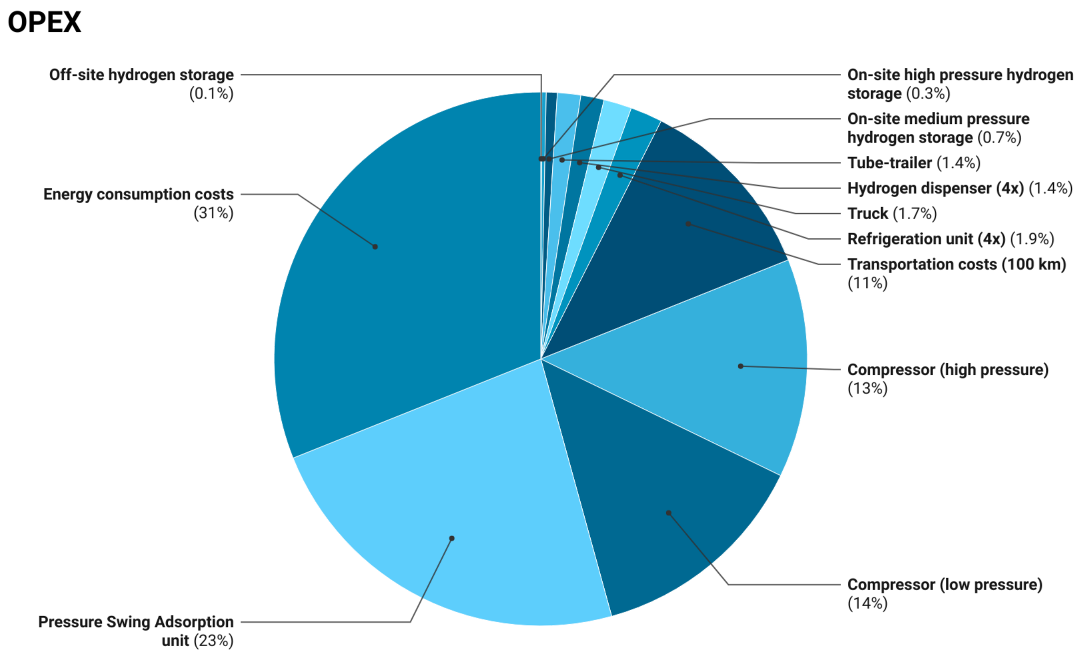

Figure F.3: The OPEX fraction per component of the scenario with 100 km driving distance in supply chain A

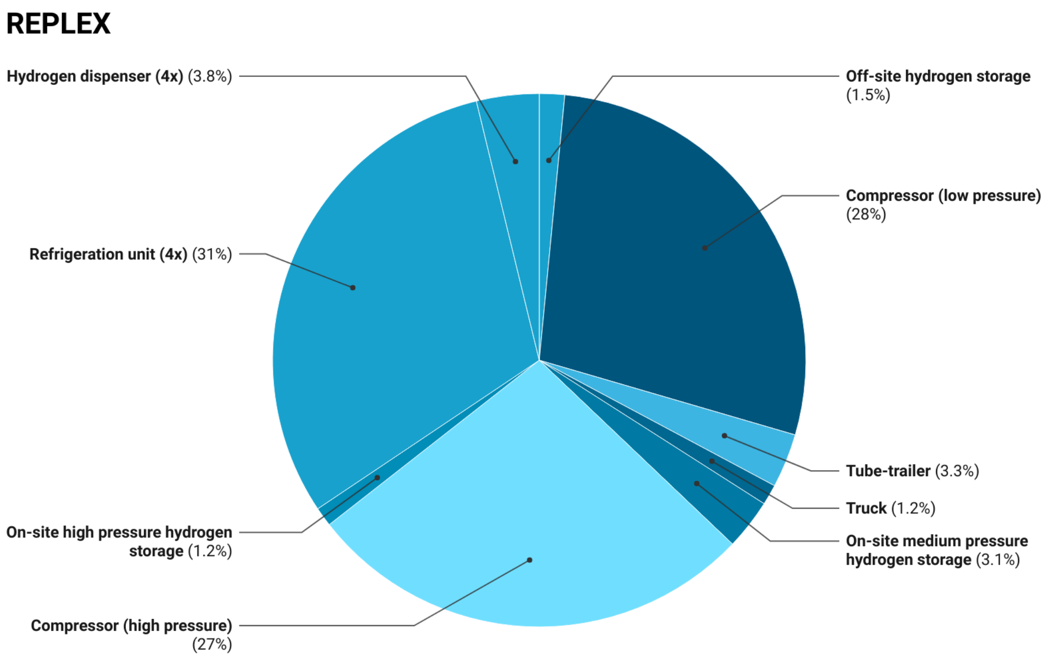

Figure F.4: The OPEX fraction per component of the scenario with 100 km driving distance in supply chain A

F.2. Supply chain B: Backbone

The distribution of the CAPEX, OPEX and REPLEX are presented in figures F.5, F.6 and F.7.

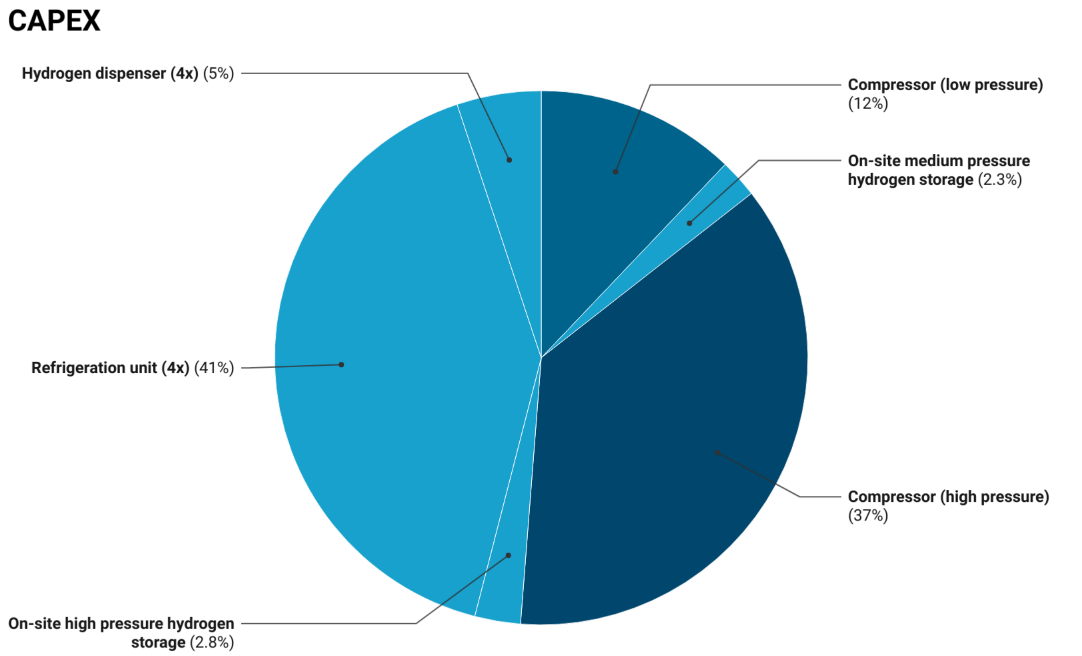

Figure F.5: Cost distribution of the CAPEX of the backbone supply chain

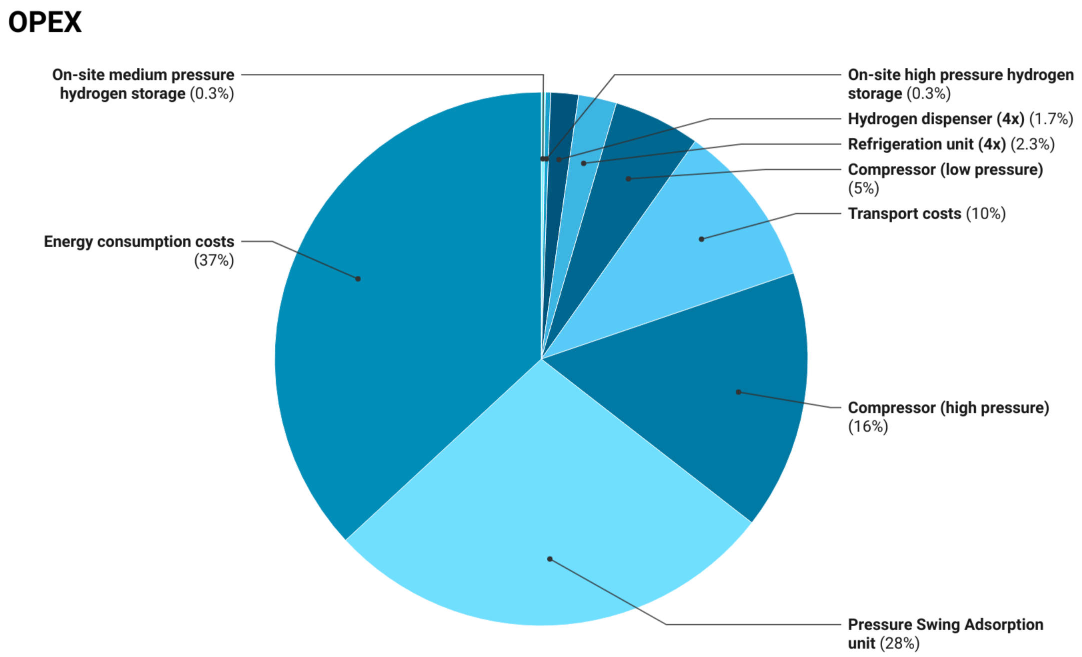

Figure F.6: Cost distribution of the OPEX of the backbone supply chain

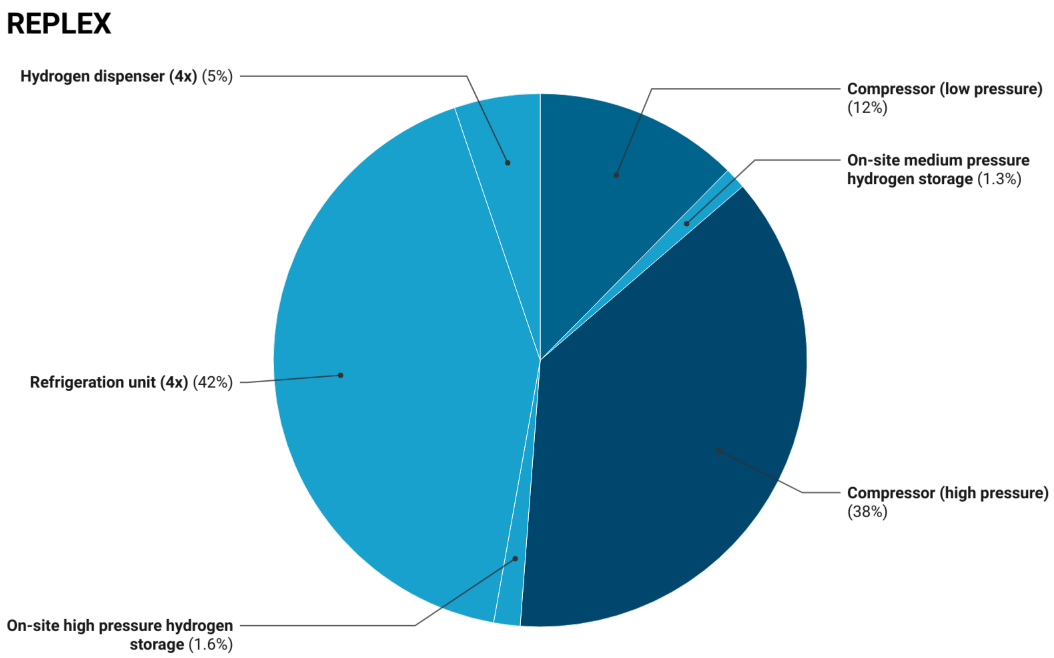

Figure F.7: Cost distribution of the REPLEX of the backbone supply chain