HYDROGEN APPLICATIONS IN HEAVY-DUTY TRANSPORTATION

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Hydrogen Applications in Heavy-Duty Transportation

A study on the potential benefits and barriers of hydrogen applications in inland cargo ships, trains, and heavy-duty trucks.

Realised by Msc Supply Chain Management and Technology & Operations Management Students from the RUG, in cooperation with Green Planet Pesse.

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INHOUDSOPGAVE

1. GENERAL INTRODUCTION

In this report the potential for hydrogen in heavy-duty transport is explored. The transport sector is responsible for 25% of the emissions in Europe. Within this transport sector, the transition towards more sustainable fuel types has started. For light duty vehicles this transition has less barriers to overcome due to heavy-duty transport having more technical constraints and commercial motives. Hydrogen, as a high potential energy carrier, can play a significant role in reducing emissions in the heavy duty sector. In this report the role of hydrogen in three different transport modalities in the Northern Netherlands is explored, being heavy duty trucks, inland cargo shipping and trains. For every modality simulations have been run to optimally place refueling locations. Practical implications for managers are given for every transport modality. The results of the three transport modalities will be combined into one roadmap to 2050 with milestones. This study is part of the HEAVENN project. For this study the master theses of Hidde Scholten, Frank Hagedoorn and Feiko Smid have been used as input.

1.1 General barriers

For the three different transport modalities explored in this study, some general barriers are present.

1.1.1 Lack of funding

Currently, most hydrogen projects are financed by subsidies from governmental authorities. For hydrogen refueling stations this is necessary at this point in time to compensate for both high initial capital costs and high recurring operation and maintenance costs. Opposed to that, banks are reluctant to finance hydrogen-themed projects due to existing insecurities on the future of hydrogen. Another reason hydrogen usage in the transport sector is negligible at this point in time is the high prices for the few options in hydrogen-based transport. At this moment fuel cell vehicles are significantly more expensive in current capital costs, fuel costs, and infrastructure costs compared to fossil fuel vehicles and electric vehicles. However, due to technological innovations, these prices are expected to drop significantly.

1.1.2 Scarcity green hydrogen

An additional barrier for hydrogen is that hydrogen can come as grey, blue or green hydrogen, which have different prices. Grey hydrogen is made by reforming natural gas. Hydrogen can be called blue hydrogen when 80-90% of the carbon dioxide is captured in the production process. Hydrogen is named green hydrogen when it is extracted from renewable energy sources, such as wind or solar energy. Green hydrogen is scarce and substantially more expensive compared to grey and blue hydrogen. An important reason for this is that it is expensive to mass-produce green hydrogen. Due to the higher production costs, the costs for customers are higher. However, in some industries, potential customers are willing to pay more for a more sustainable fuel source.

NOMENCLATURE

AFID	Alternative Fuel Infrastructure Directive
BET	Battery Electric Truck
CCS	Carbon Capture & Storage
CSD	Compression, Storage & Dispensing
FCET	Fuel Cell Electric Truck
GoO	Guarantee of Origin
HDT	Heavy-Duty Truck
HEAVENN	H2 Energy Applications (for) Valley Environments (in) Northern Netherlands
HRS	Hydrogen Refueling Station
LAP	Legal & Administrative Processes
LNG	Liquefied Natural Gas
REDII	Renewable Energy Directive II
RES	Renewable Energy Sources
TCO	Total Cost of Ownership
WTW	Well-to-Wheel
ZE	Zero Emission
HRS	Hydrogen refueling station
TCO	Total cost of ownership
LDV	Light-duty vehicle
HDV	Heavy-duty vehicle
PGS 35	Publication series Dangerous Substances; a document on activities involving hazardous substances
ADR	European Agreement for the International Carriage of Dangerous Goods by Road (Accord européen relatif au transport international des marchandises Dangereuses par Route)

2. HEAVY DUTY ROAD TRANSPORTATION

2.1 Introduction

Fuel Cell Electric Trucks (FCET) are a promising zero-emission alternative in decarbonizing the heavy-duty transportation sector by using hydrogen as a transportation fuel. FCETs have short refuelling times and a long vehicle range when compared to Battery Electric Trucks (BET). Using green hydrogen from renewable energy sources significantly reduces Well-to-Wheel (WTW) emissions for heavy-duty trucks (HDT). However, for a large FCET market to become reality, enormous efforts are yet to be taken. Investors in hydrogen refuelling infrastructure (HRS) are waiting for more FCETs to enter the road. On the other end of the spectrum, companies are not inclined to invest in FCETs as long as there is no widespread refuelling infrastructure. This "chicken-and-egg" problem is well known in the transportation sector and poses one of the most constraining barriers to the wide-scale adoption of hydrogen in heavy-duty road transportation. This part of the study has been researched by Scholten (2021).

2.2 Barriers

Next to the chicken-and-egg problem, there are several other barriers that require attention and should be removed as soon as possible. The barriers have been split up into economic, regulatory, technical and safety barriers.

2.2.1 Economic Barriers

One of the main economic burdens is the high price of constructing an HRS. The costs of building an HRS are significantly higher than building a conventional gas station. The costs of a compressor that is needed to pressurise hydrogen to the required level (700 bar for passenger vehicles, and 350 bar for heavy-duty vehicles) is by far the largest cost component. The Capital Expenditure (Capex) of a compressor was estimated to be between 1 and 1.5 million dollars (roughly 800,000 - 1M euros). Moreover, the storage costs of hydrogen at an HRS facility make up a large portion of the total costs. Compressed hydrogen needs to be temporarily stored with high pressure to account for fluctuation in demand and therefore act as a buffer. These costs range between 150,000 and 250,000 dollars (roughly 125,000-200,000 euros). In a project called 'Hyspeed for H2 trucks' initiated by Green Planet and supported by New Energy Coalition, a fixed investment cost for Compressor, Storage, and Dispensing (CSD) costs of an HRS facility for FCETs was found to be 1.376 million euros. It concerns the extension of an existing light-duty vehicle HRS installation, and through consultation with the company it turned out that roughly an additional 1 million euros of Capex should be added to this amount. In conclusion, potential HRS investors for FCETs should take into account that the investment costs amount to roughly 2M and 2.5 M euros. To put this in perspective, the costs of building a conventional gas station are roughly between 100,000 and 300,000 euros. Without financial government support, most companies are not able to make an investment of 2M or more from their own funds.

Another main economic barrier is the high supply costs of green hydrogen. The Dutch Environmental Assessment Agency (PBL) conducted a study in 2020 to calculate the production costs including storage and transportation of blue and green hydrogen in 2030. They use a low, middle, and high scenario. The results showed a green hydrogen price ranging from €2,56 to €5,33 per kg in 2030[1] for green hydrogen produced from renewable energy sources (RES) at the North Sea. Nevertheless, they acknowledge that this is based on optimistic assumptions, in which for instance electrolyzer costs should halve in 10 years. They argue that in the short term, blue hydrogen with CCS storage is cheaper, however the price difference will diminish moving towards 2040. To speed up the cost reductions of green hydrogen in the Netherlands, large wind parks are needed to produce enough RES to produce the hydrogen.

2.2.2 Regulatory Barriers

An independent organization called HyLAW, funded by the Fuel Cell Hydrogen Joint Undertaking (FCH JU), has created an extensive database with reports on legal and administrative processes (LAPs) around hydrogen in Europe (HyLaw, 2021). In the report specifically devoted to LAPs in the Netherlands, two LAP barriers were identified (van der Meer et al., 2018). Fuel origin and certification is the first, in which they argue that the absence of a common definition (Guarantee of Origin, GoO) for green hydrogen hinders the development of a widespread hydrogen market. They add that the Renewable Energy Directive II (REDII) does not provide sufficient room to label all renewable hydrogen 'green'. The REDII is a legally binding directive first established in 2009, and in 2018 it has been revised, setting the binding renewable energy target for all member states to 32% in 2030 (Renewable Energy Directive | Energy, 2014).

REDII states that green hydrogen can only be supplied through newly developed RES stations, and not from currently existing renewable power sources. However, because

[1] *https://www.pbl.nl/publicaties/waterstof-voor-de-gebouwde-omgeving-operationalisering-in-de-startanalyse-2020*

green hydrogen production currently has no significant economies of scale to be widely economically attractive, the REDII requirement hinders the process of scaling up significantly. Therefore, the New Energy Coalition (2020) also calls for immediate and temporary exemption during the scale and mature phase until 2025, to facilitate the scale-up phase. Secondly, quality control and measurement are an issue, which is present in the Netherlands on a low scale. The Netherlands follows International Organization for Standardization (ISO) guidelines for the quality check and frequency of checks. However, there is no regulated authority in place to perform the checks. This leads to the fact that HRS owners have the responsibility to ensure the ISO-required quality of fuel, and this is a very difficult, costly, and technically complicated process.

All in all, these barriers need to be removed by direct exemption from REDII and installing a well-organized local authority body to ensure the frequency and quality of the fuel checks. This might take time, however removing these barriers will lead to faster growth in the FCET market.

2.2.3 Technical Barriers

The energy efficiency of a FCET is a serious problem. Using renewable electricity to produce green hydrogen for FCETs is highly inefficient because between 57% and 73% of the energy is wasted compared to the pathway with BETs[2]. Groundbreaking innovative technologies might be needed to either find a way to reuse that 'lost' energy or to improve the energy efficiency in the engine of a FCET. However, there are technical thermodynamic limitations on the extent to which a FCET can improve its energy efficiency compared to the BET alternative. Removing this barrier should thus be accomplished by both minimizing energy waste and increasing RES generation. Another important barrier is that for the production of fuel cells, platinum is needed which has a negative environmental impact. If demand for FCETs significantly increases, more platinum will need to be produced, which implies that the total environmental impact of FCETs is negatively affected. Therefore, the use of platinum in fuel cell production should be minimized, along with achieving a high recycling rate of the platinum.

2.2.4 Safety Barriers

Another important barrier to hydrogen application is the safety procedures that come with delivering the fuel to the vehicles. In the Netherlands, a publication regarding hazardous materials[3] has been established specifically for hydrogen delivery to vehicles. Some general dangers of gaseous hydrogen are; hydrogen has a very thin substance allowing it to penetrate through objects relatively easily, it has a high diffusion coefficient, very little energy is needed for ignition, and the flame of hydrogen is barely visible. Several components in HRSs are thus necessary to preserve the safety of using hydrogen. This includes a cooling system, a cascade system to control the difference in pressure between the tank and the vehicle, the dispenser must adhere to ISO standards, a purifier is needed to ensure a required percentage of purity of the hydrogen, and different measurement instruments must be in place (Parks et al., 2014). In PGS35 (2020), all these components are extensively discussed and HRS constructors must adhere to these regulations to minimize the risk of an explosion that might not only be harmful to the station itself, but also to the society living around it. Moreover, all this equipment requires serious financial investments and comes with risks that might disincentivize potential HRS builders.

[2] *https://linkinghub.elsevier.com/retrieve/pii/S0306261920316810*
[3] *https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS35.html*

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2.3 Case Study Northern Netherlands

For the hydrogen applications in the heavy-duty road transportation sector, a case study was performed in the Northern Netherlands. The main aim in the case study was to optimally determine a HRS structure that can accommodate FCETs under different scenarios. The scope of the study is to locate HRS facilities along the highway network. A model has been developed that takes into account the HDT flow on the main highways and accordingly minimizes the total costs of building these facilities. This approach is specifically relevant in early adoption stages of the FCET market, given the extremely high costs at this point.

2.3.1 Scope of the study

The main highways in the Northern Netherlands have been selected as a unit of analysis, along with a set of Origins and Destinations, between which HDTs move to deliver and pick up orders. The highway network of interest can be found in figure 1. The red points indicate origin and destination cities, the blue points are potential HRS sites and the green lines indicate the chosen highways.

Figure 1: Highway network of interest

Only taking into account HDT flows that originate and depart from within the Northern-Netherlands would lead to an unrealistic amount of HDT flow that could potentially demand hydrogen. Therefore, additional regions outside of the Northern Netherlands have been selected. FCETs that depart from those regions and drive to the Northern Netherlands would be needing hydrogen to refuel their round trip. The selected regions can be found in figure 2.

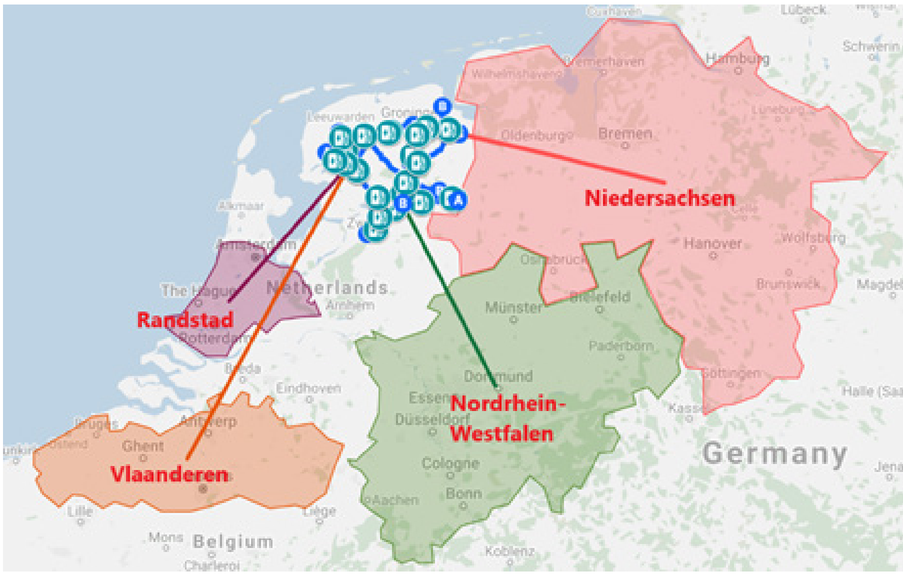

Figure 2:Neighboring regions for hydrogen refueling

After having established the scope and unit of analysis for the case study, the results were generated. For the year 2030, 2040 and 2050 an analysis was run for three scenarios; pessimistic, realistic, and optimistic.

2.3.2 Results

2030	Fixed Conditions	Pessimistic	Realistic	Optimistic
Type of Hydrogen	Blue & Green			
Hydrogen Supply	Tube Trailers			
FCET penetration		5%	10%	15%
Number of stations		4	8	12
Average capacity (kg H2)		750	750	750

Table 1: Roadmap scenarios 2030

Table 1 shows the main results for 2030. The locations of the HRS facilities in the realistic scenario can be seen in Figure 3. Around Groningen, three stations are opened. Groningen is one of the major cities in the NN, and the direct highways next to it are the A7 and A28, which also are the most frequently used highways in the NN. Furthermore, 5 stations are opened, mainly around Meppel, Drachten, and Assen. An important note here is that, especially from a cost-minimising perspective, it is best to place HRS facilities at existing gas stations along the highway. Permits for having a refuelling station along the highway usually last for 8 to 10 years. This means that to accomplish a 10% FCET coverage rate in 2030, existing companies should build an HRS at their premise.

Figure 3: Locations of HRS facilities 2030 scenario

Gas stations that are currently located along the highway should have an interest in working with alternative fuels. An excellent example is Green Planet, who worked together with Shell to realise a publicly accessible HRS next to the highway. If governments indeed provide more subsidies and incentivize the roll-out of HRS stations, it should be the large, existing gas stations that make the first jump. These companies are more likely to have the resources to make the heavy investment, and they can act as role models for other companies considering the jump to hydrogen but do not yet have the financial resources available. The government plays an essential role in incentivizing these companies to make the investment through subsidies and clear guidelines. Transparency and collaboration between the market and the government are also key to ensure that both HRS facilities and FCETs are invested in. Before 2030 it is assumed that there is no widespread pipeline structure yet that can deliver hydrogen directly to the HRS facilities. This means that tube trailers will be needed to transport hydrogen from green hydrogen plants to the HRS. Moreover, green hydrogen is expected to grow significantly in availability, however it will not be at a stage yet that infinite capacities can be assumed. Therefore, the role of blue hydrogen as a complement to green hydrogen is important to assure a balanced growth of the market.

2040	Fixed Conditions	Pessimistic	Realistic	Optimistic
Type of Hydrogen	Green			
Hydrogen Supply	Liquid H2 Trucks & Pipeline			
FCET penetration		20%	30%	40%
Number of stations		8	12	16
Average capacity (kg H2)		1500	1500	1500

Table 2: Roadmap scenarios 2040

Moving towards 2040, the number of stations increases. The FCET penetration percentage is significantly higher than in 2030, which means that demand for hydrogen is increasing, and the market has reached a phase where scale economies emerge. The results are displayed in table 2. More HRS will be needed in each scenario. By this time, existing refueling station location permits will have expired, and the government should prioritize companies that intend to build new HRS facilities from scratch along the highway in the process of granting concessions. This way, conventional gas stations are gradually ruled out and there is more room and incentives for HRS investors. Also, the costs of building an HRS will have come down, and pipelines are assumed to be in place to start transporting the hydrogen around the Northern Netherlands at a high rate and at relatively low costs.

Figure 4: Locations of HRS facilities 2040 scenario

At this stage, it is also expected that liquid hydrogen distribution by means of trucks will play a role in the supply of hydrogen next to the pipelines. Liquid hydrogen can be transported at a much larger quantity per truck than gaseous hydrogen and at lower costs. In a study from the International Energy Agency, it was confirmed that from a cost perspective, gaseous tube trailer delivery of hydrogen is economically relevant at low levels of demand, liquid hydrogen delivery is preferable for larger capacities, and pipeline distribution is most efficient for very large hydrogen demand. The locations of the HRS that are opened in the realistic scenario of 2040 can be seen in figure 4. Again, three stations around Groningen are opened, however an increasing number of stations emerge around other cities such as Zwolle and Leeuwarden. The dispersion of the stations is increasing, and the average capacity at the stations is 1500 kg of hydrogen because of the increased availability of green hydrogen and the introduction of a suitable pipeline structure.

2050	Fixed Conditions	Pessimistic	Realistic	Optimistic
Type of Hydrogen	Green			
Hydrogen Supply	Pipeline			
FCET penetration		40%	50%	60%
Number of stations		10	17	26
Average capacity (kg H2)		2460	2120	1760

Table 3: Roadmap scenarios 2050

Finally, in 2050 the assumption is made that through technological advancements, economies of scale in green hydrogen production, and large FCET demand growth, the market has reached a mature stage. Liquid hydrogen is assumed not to be necessary anymore and most of the hydrogen will be supplied through the extensive pipeline network at low costs. The results of 2050 can be found in table 3. The average capacity in the realistic scenario is now equal to 2120 kilograms. HRS facilities that have already been built in previous years should be expanded to account for a larger percentage of HDT that flow along the stations demanding hydrogen. The locations of the HRS facilities under the 2050 realistic scenario can be found in figure 5. Another interesting finding through observations and interviews is that fuelling hydrogen at the home location of companies will also start to play an increasingly important role from 2040 to 2050. This is mainly due to the fact that by 2050, the costs of building an HRS will have come down and there are more guidelines and less complex legal formalities, because there is more knowledge and experience with hydrogen.

Figure 5: Locations of HRS facilities 2050 scenario

2.4 Business case

The TCO of a FCET is currently significantly higher than the TCO of a diesel or BET alternative. In appendix 1, an overview can be found of the management summary of a Total Cost of Ownership calculation created by Green Planet and validated by Panteia. This TCO calculation provides transport companies with a fully detailed business case for the deployment of FCETs. The TCO of a FCET is currently more than twice as high when compared to a EUR 6 diesel truck.

A full detailed version of the TCO calculation is as part of this study included in appendix 2.

2.5 Conclusion & Roadmap

All in all, some important practical implications can be extracted from the findings and discussion of this paper. First and foremost, the role of the government in making the FCET market 'take off' is essential. The literature, interviews, and observations made clearly showed that without government support, it will not be possible to create a self-sufficient market in the long term. The role of an accommodating HRS structure where transportation companies can refuel their FCETs with certainty is essential. Through the presented model and its results, it was found that a government investment of 30,000,000 euros could already be enough to build 9 HRS facilities for FCETs by 2030, which could cover approximately 12% of all HDT flow through the NN. In 2040 and 2050 less money would be needed to realise new HRS facilities, however by then, the market should be able to keep building and extending the initial HRS structure without government support. The exact numbers and locations might not be correct, however the uncertainty around hydrogen in transportation makes that no model can accurately predict future requirements. It is more the underlying pattern that indicates that strong action is needed now, to bring the market about in the future.

The second implication is that the capacity of stations in early years should be as large as possible. In the adoption phase of FCETs and HRS facilities, it is a lot cheaper to build a few large stations, than to build numerous small stations because fixed costs are extremely high. HRS investors should transparently communicate announcements to the local transportation sector if they decide to make the investment and start building an HRS facility. This takes the integral uncertainty away and incentivizes companies to invest in FCETs. From now until 2030, collaboration, guidelines, and transparency are key. From 2030 to 2040, the government should keep a mediating role between the FCET market and HRS investors, as technological developments allow for more economies of scale and efficiency improvements. From 2040 onwards, the FCET market should be self-sufficient, and government involvement is not needed anymore. A widespread HRS network along the highway is possible and it can be complemented with smaller stations at the home location of companies. In this way, the FCET market could significantly contribute to decarbonising the transportation sector. In figure 6, a concise roadmap with the main steps needed to achieve this can be found.

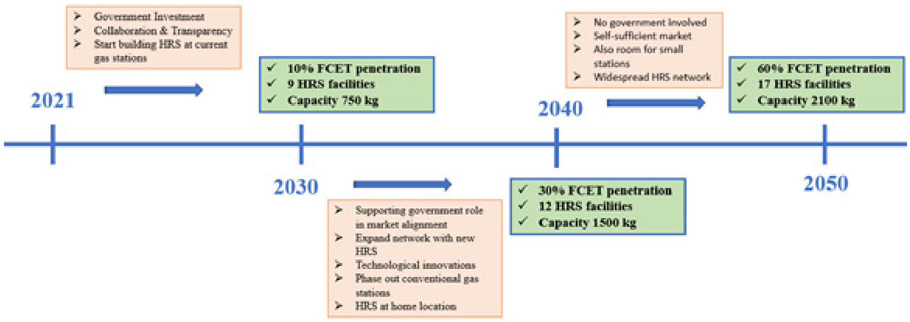

Figure 6: Roadmap to 2050

3. MARITIME TRANSPORTATION

3.1 Introduction Inland Cargo Shipping

The International Maritime Organization set the goal to reduce emissions of maritime transport by 50% by 2050. On top of that, the Dutch government set the goal to have a carbon neutral inland cargo shipping sector in 2050. A transition from a fossilized fueled to a hydrogen-fueled inland shipping sector can potentially contribute to the solution. To make this transition two important steps need to be taken. One step is that an infrastructure capable of refueling hydrogen-fueled ships needs to be built. The second step is to make hydrogen-fueled maritime transport commercially feasible. Technical, economic, and political/legal barriers have been identified that can hinder the transition towards hydrogen-fueled inland cargo vessels. To create a new infrastructure it is important to find optimal locations for refueling stations. This part of the study has been researched by Smid (2021).

3.2 Barriers

In this section barriers in the transition towards a hydrogen-fueled inland cargo shipping sector are identified. The barriers are divided into technical, economical and political/legal barriers.

3.2.1 Technical barriers

Three main technological barriers have been identified. The first identified technological barrier that the maritime sector has to overcome is that the current state of maritime hydrogen technologies is not as advanced as it is for land-based hydrogen technologies. The most important reason for this is that ships are heavy and require a high amount of power. At this moment most hydrogen techniques are developed for light-duty vehicles and cannot efficiently deliver that amount of power yet. The technologies to have inland cargo ships run on hydrogen are available but not refined and at high costs. For cargo ships that are already in use, it is possible to retrofit the ships to work on hydrogen, but this comes with a large overhaul and high costs. Retrofitting cargo ships makes the ships less fuel-efficient than new hydrogen-fueled ships would be. However, retrofitting will be essential to increase the market share of hydrogen-fueled cargo ships. Retrofitting newer ships is more cost-efficient since the expected lifetime of newer ships is higher and the owners are not expected to purchase a new ship again soon.

A second technological barrier is that it is difficult and costly to transfer large amounts of hydrogen into a large tank at once, like a ship requires. To avoid long refueling times and congestion at refueling locations a fast and high capacity refueling machine is necessary, which are expensive to manufacture or purchase.

The refueling infrastructure is a third technological barrier, being a prerequisite for a hydrogen-based transport system. As stated earlier there currently is a 'chicken-and-egg problem'. To solve this problem, a start has to be made in the refueling location infrastructure to make the adoption of hydrogen-fueled maritime transport more attractive. When the infrastructure will start with a single or a few refueling locations, owners of hydrogen-fueled cargo ships may have to deviate from their original routes. Deviating far from original travel routes can be a barrier for potential customers to switch to alternative fuel modalities.

3.2.2 Economical barriers

Besides the issues with funding and the scarcity of green hydrogen that are a barrier for all transport modalities, there is uncertainty on the future of fuel types in the maritime sector. Three main competitors to hydrogen are identified. The first one, conventional fossilized fuels, is currently mainly used in the inland shipping sector. Their costs are low and production and distribution processes are optimized, but they pollute too much to be used endlessly. A second competitor, LNG, is less polluting and an alternative for heavy-duty modalities, is already in use. Using LNG does, however, only cut between 20 and 28% of carbon emissions. Ammonia can be seen as a third competitor. Even though ammonia is a hydrogen carrier, the production process and logistics are completely different. Having a higher energy density, ammonia can be interesting for long-distance shipping.

3.2.3 Political/legal barriers

When looking at hydrogen as a fuel for inland cargo shipping, international regulation needs to be taken into account. The European Union stated regulations and directives affecting the deployment of hydrogen technologies in a publication named HyLAW. When looking at hydrogen refueling locations some regulations have to be obliged on safety requirements and maximum storage size. For hydrogen in maritime transport more specific regulations on safety, bunkering, and refueling are given. Besides the HyLAW there is more regulation for hydrogen storage and transport. HySafe is an international research project where hydrogen technologies were explored and potential hazards were identified. Based on these hazards, safety regulations and measures are stated. The most important hazard identified is the potential of an explosion. For this potential hazard safety barriers and measures for the storage of hydrogen are stated in HySafe.

Hydrogen is considered a dangerous substance by the European Chemicals Agency for two reasons, it is extremely flammable and can be stored as a highly pressurized gas. For the transport of dangerous substances by inland waterways in Europe ADN-regulation is made. In the ADN-regulation requirements for a wide variety of subjects are found. These subjects include requirements on the construction of ships that carry dangerous goods, regulation for the vessel crew, equipment requirements, and loading requirements. While this regulation is aimed at the carriage of the goods and not for the fuel of the vessels, the regulation still needs to be followed until specific regulation for hydrogen is created. Most regulation is aimed at small scale hydrogen usage, while for maritime applications large scale is necessary. At this point the regulatory approval and permit procedure for hydrogen projects is too complex and not fast enough. New systems involving hydrogen technologies need to be implemented or older systems have to be adapted to be more welcoming to new technologies in this area.

3.3 Case study

For the inland cargo shipping sector, a case study was conducted for waterways in the Netherlands and Germany, from Rotterdam to Kiel. A case study for just the Northern Netherlands would yield incomplete results, since most ships travel from and towards other locations. Data has been obtained with origin-destination trips of inland cargo ships and a model is used to determine optimal placement of refueling locations for scenarios in 2030, 2040 and 2050. The scenarios for 2030, 2040 and 2050 are based on various reports. A yearly market growth of 1.57% is taken, based on a report of Panteia[4]. In scenario 2030 1% of inland cargo ships is expected to be fueled with hydrogen, in 2040 10% and in 2050 50%. Four different types of refueling locations are distinguished, being a normal speed refueling location, high speed refueling location, normal speed Truck-To-Ship (TTS) refueling location and a high speed TTS refueling location.

2030

The optimal refueling locations for 2030 are given in figure 7. Only one refueling location is placed in Amsterdam. More locations would not yield any profit.

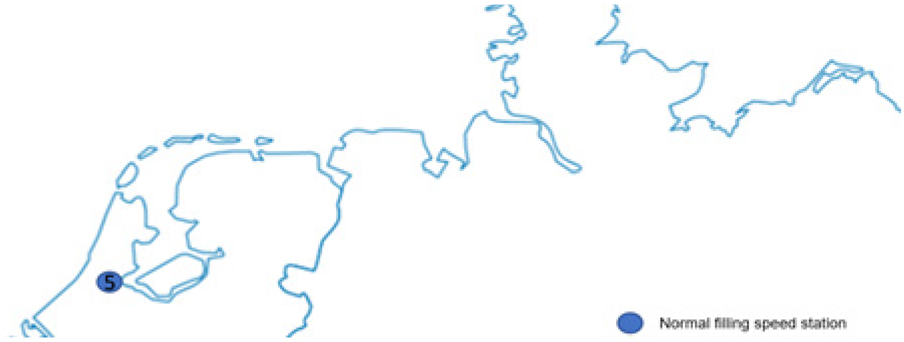

Figure 7: Optimal situation in 2030 without governmental help

Placing only one refueling location by 2030 would be detrimental to the hydrogen network. When no places to refuel exist, less ship owners will switch to hydrogen. For that reason it is advised to place more refueling locations, which requires governmental help. In figure 8 a situation is given where 5 refueling locations are placed, maximizing coverage of the total flow. A total coverage of 92,15% is realized. The maximized total flow captured with a set amount of refueling stations can be seen in figure 9.

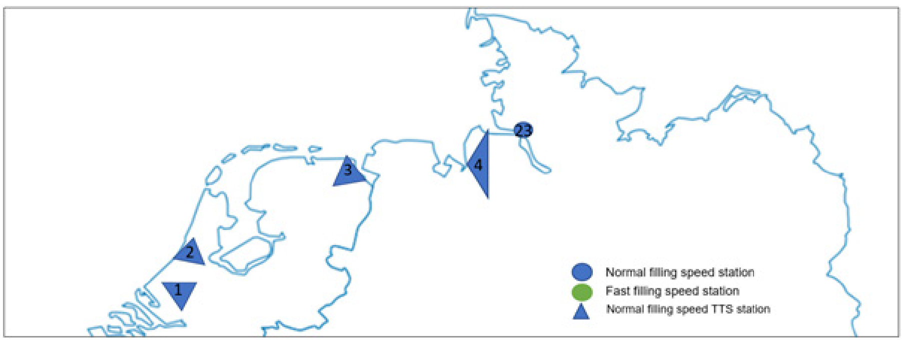

Figure 8: Optimal situation in 2030 with governmental help

[4] *Panteia: Middellange Termijn Prognoses voor de binnenvaart*

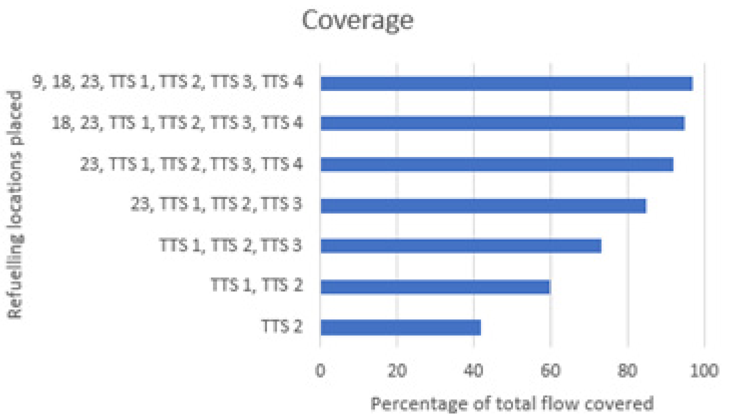

Figure 9: Total flow covered by a set amount of refueling locations in 2030

Important to note is that TTS-locations are very useful to maximize coverage. This is explained by TTS-locations covering multiple ports. To realize this refueling network significant governmental aid is needed in the form of subsidy for both initial siting costs and recurring operational costs.

2040

For the year 2040, the model output can be seen in figure 10. TTS-locations are no longer advised, due to high recurring operational costs when the demand of hydrogen increases over time.

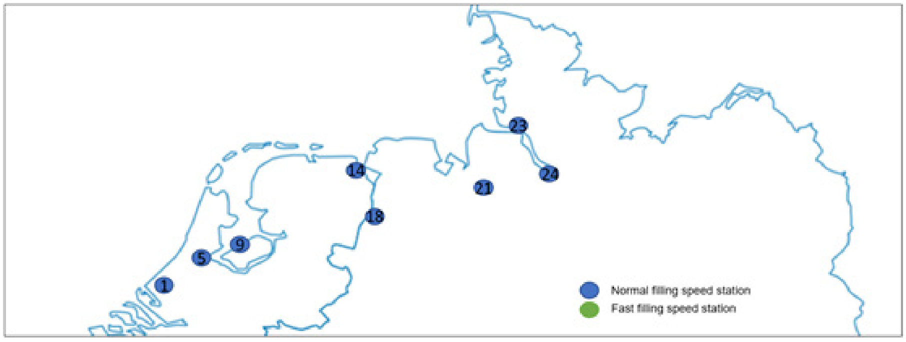

Figure 10: Optimal refueling network inn 2040

2050

In 2050 demand is high enough to justify placing high speed refueling locations. A total of 9 refueling locations are placed, of which 5 are with fast refueling speed and 4 are with normal refueling speed.

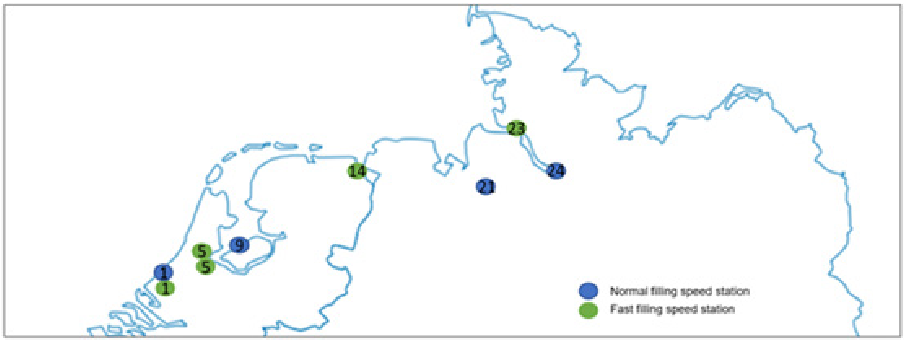

Figure 11: Optimal refueling network in 2050

3.4 Business case

There is not enough data available to convert the TCO calculation – as mentioned in paragraph 2.4 – into a suitable version for maritime transportation. The current state of maritime hydrogen technologies is not as advanced as it is for land-based hydrogen technologies. Because of that, no detailed quotes can be made for hydrogen shipping. The state of development makes it impossible to develop a detailed business case. The pioneers will first have to gain experience with the use of hydrogen ships. With this, knowledge can be gained to eventually arrive at a realistic business case.

3.5 Conclusion

Combining the three scenarios gives the roadmap visualized in figure 12. From the results, practical implications can be derived. Firstly, from a governmental point of view, it is essential to support the transition towards hydrogen-fueled cargo ships with subsidies, international collaboration, and accommodating regulation. Failing to do so will result in a slower transition. Especially, a proactive approach in the first step of creating a refueling network is essential, since the results of this research indicate that it is impossible to start a refueling network in 2030 without governmental aid.

From the owners of refueling locations, flexibility is required. At first, TTS is the most interesting option due to high coverage, which will start to become less attractive as demand and operational costs become higher in 2040. In 2050 some owners will need to make the transition to a fast refueling speed location. Vessel owners have a tough decision to make when it is time to build or retrofit a ship. Switching to hydrogen early might be a good idea for the future, but there are significant barriers to overcome early. Since a ship is built or retrofitted to be used for a period of 15-30 years a decision has heavy consequences. Serious negative downsides to take into account early on in the transition are a lack of refueling locations and legislation.

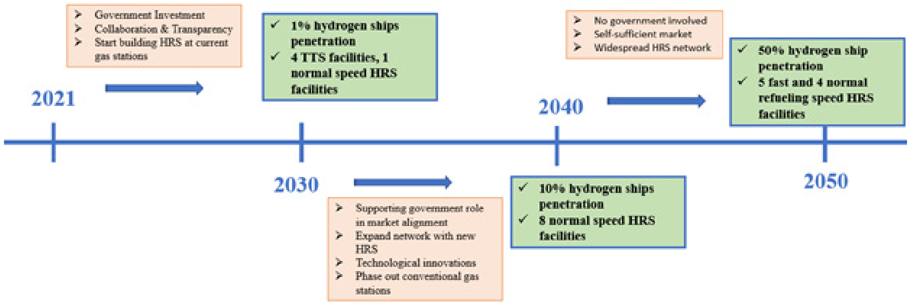

Figure 12: Roadmap to 2050

4. RAILWAY TRANSPORTATION

4.1 Introduction

While the European railway industry has already cut emissions in half since 1990, approximately 75% of trains worldwide are still diesel-fueled. Current improvements were achieved by electrification of railways and increased efficiency in diesel-fueled trains. However, the use of green hydrogen in railways may be a more promising option. Besides emission-free transport, trains running on hydrogen do not need a connection with catenaries and therefore have the benefits of more flexibility and lower infrastructure costs comparable with diesel-fueled trains. However, the high costs and lacking infrastructure hinder broad adoption of hydrogen as of today. These factors prevent companies from opting for hydrogen. As a result, demand is insufficient for the industry to create a complete and cost-efficient infrastructure. To solve this, it is important to determine optimal locations for refueling stations and to make the use of hydrogen as a fuel commercially viable. Technical, economic, and political/legal barriers have been identified that can hinder the transition towards hydrogen-fueled trains. This part of the study has been researched by Hagedoorn (2021).

4.2 Barriers

In this section barriers in the transition towards a hydrogen-fueled railway sector are identified. The barriers are divided into technical, economic and political/legal barriers.

4.2.1 Technical barriers

Hydrogen does not require any adaptations to the infrastructure. If you want to run hydrogen trains tomorrow, all you need is a hydrogen station and the track has to be grounded at the refuel station so that no sparks jump. The earth potential of the hydrogen refueling installation must be the same as that of the hydrogen train.

4.2.2 Economic barriers

As mentioned, the high costs associated with hydrogen are the main barrier to adoption as of today. The levelized cost of hydrogen (LCOH) is mainly dependent on capacity, the costs of electricity, and the costs of electrolysers. A price of less than $2/kg is needed to make hydrogen competitive with diesel. Current methods that can produce hydrogen at $2/kg are gasification techniques and steam reforming. However, these methods produce so-called 'grey hydrogen' as these methods emit CO2 during production. Furthermore, the produced hydrogen is not suited for application in fuel cells, as hydrogen-powered vehicles require a purity level of 99.97% and these methods can only reach purity levels of 97.5%. This means, the hydrogen contains too high values of elements such as CO_2, CO, S, and H_2O. The sum of impurities for application in fuel cells is not allowed to exceed 300 µmol/mol.

Another method to produce hydrogen is electrolysis. This method produces emission-free hydrogen, or 'green hydrogen', and complies with the required purity level stated in ISO 14687. However, this method has the disadvantage of higher production costs, currently in the region of $4/kg to $6/kg. The cost of green hydrogen can be reduced to $2/kg, but this requires several developments. A decrease of renewable energy costs to $20-$30/MWh, currently in the region of $60/MWh depending on the energy source and location, and a significant reduction in the costs of electrolysers would have the greatest impact on the costs. Other developments that can reduce hydrogen costs are an increase in electrolyser efficiency, extra load hours, increased lifetime of electrolysers, and a lower interest rate.

4.2.3 Political/legal barriers

In addition to the need for developments regarding the price of hydrogen, many legal aspects need to be arranged as well. Regulations regarding the use of hydrogen in new applications, such as trains, are relatively strict or insufficient. This is because hydrogen is legally classified in the same category as natural gas and gasoline. Thereby, hydrogen is subject to health and environmental risks and fire and explosion hazards. For this reason, HRSs must adhere to risk assessments, safety requirements, and safety distances. This includes strict storage regulations that prescribe the allowable amount and pressure level of hydrogen. Subsequent to that, HyLaw states that: "Hydrogen is legally classified as dangerous to transport and is included in the list of dangerous goods in Annex A concerning the International Carriage of Dangerous Goods by Road (ADR)". As a result, hydrogen trailers are not allowed to drive through tunnels, for example.

Furthermore, storage locations have to follow strict rules and regulations regarding the distance between different hydrogen equipment. Fuel stations that want to provide hydrogen have to apply for a permit and comply with PGS 35 that states location-specific rules regarding storage amount and distances. Nonetheless, hydrogen refueling should generally be allowed on land where conventional refueling stations are in use. On-site production of hydrogen is less convenient, as this activity is currently only allowed in industrial zones. Hence, this is important to take into account for potential HRS locations.

Due to the limited experience with hydrogen in new applications, authorities exert a high level of precaution. However, current laws and regulations are considered to be unreasonably high. Research highlighted the risks associated with hydrogen refueling. The overall chance of a fatal accident during refueling is far below the acceptance level of customers. Therefore, indicating that current regulations might indeed be too strict. The three main risks are: leakage from booster compressors with a probability of 69%, followed by leakage from tube storages with 27%, and bore rupture of pipes with a probability of about 4%.

Current regulations allow hydrogen storage for light-duty vehicles (LDVs), such as cars, at 700 bar, while hydrogen for heavy-duty vehicles (HDVs), which includes trains, is stored at 350 bar. Differences in storage pressure affect both safety distances and storage amount allowed. For example, a higher storage pressure means that more hydrogen can be stored in a tank, but also requires more safety distance. As a result, fewer hydrogen modules can be stored at an HRS per km2. On the other hand, more hydrogen can be stored in a tank due to the higher density of hydrogen molecules. So, fewer modules are needed to refuel a certain number of trains. Furthermore, storage pressure influences compression efficiency. Hydrogen compressed at 350 bar results in a compression loss of 10% to 11%, while storage at 700 bar results in a compression loss of 15% to 16%.

Even more, an HRS for trains may only be used for refueling of trains, as there are regulations that cars, trucks, and buses are not allowed to enter a marshalling yard for trains unless a truck specifically brings something for the train operation. This means that an HRS will only be dedicated to trains, resulting in higher TCO and less economies of scale. Even more, little subsidy for hydrogen stations is available at the moment. The government thinks it is a waste of money if an HRS is only used for trains. The moment an HRS can also be used for other modalities, it will become a lot more interesting. Therefore, it is important to adjust current regulations, which are unreasonably high at the moment. To give an example, hydrogen tank installations are being built in a residential area in Bremen, Germany, while in the Netherlands this is only allowed in remote areas. They already have more confidence in the technology and procedures in Germany.

European standardization should be developed for use of hydrogen as a fuel. This could cover standardized procedures, refueling pressure, and pump connections. For example with international transport, a train leaving from Groningen should be able to refuel in Milan as well. Otherwise, a mobile hydrogen refueling installation needs to be brought to the train in Milan, which is not efficient.

The Dutch government states that hydrogen should mainly be used for applications where no alternatives, such as electrification, are present. Thus, current policies prioritize the use of hydrogen for use cases such as steel production, chemical production, and as a fuel for transportation modes that are difficult to electrify. This could mean that the use of hydrogen in trains could be limited for the near future. On the other hand, the government fosters tests and pilots for other applications, such as railways.

The future of hydrogen in trains is heavily dependent on choices made by the ministry. If the government decides to stimulate hydrogen production, for example, to give farmers an alternative way for earning an income, then it could be that provinces choose to opt for hydrogen. Even though it might be technically smarter to drive electrically. Hence, this indicates that it is impossible to predict where hydrogen will be used. Many factors influence these decisions.

4.3 Case study

The Dutch railway network is used to conduct a case study. The Dutch railway network consists of over 3200 km of railway lines, of which more than 75 percent are electrified. The provinces of Groningen, Friesland, Overijssel, and Gelderland are the four provinces having non-electrified railway lines, which make the northern Netherlands an interesting region to implement the use of hydrogen as a fuel. A feasibility study in Groningen showed that hydrogen trains can be a fully-fledged sustainable alternative to the current diesel trains. Therefore, Groningen wants to start using passenger trains powered by hydrogen from 2024 onwards.

HRSs could only be placed at marshalling yards, the potential HRS locations are heavily limited and strictly location-bound. In this study, this resulted in only two possible HRS

locations. HRSs in the network need to cover every origin or destination station (O-D) as trains have predetermined routes and cannot run out of fuel. So, all hydrogen trains need to be captured and all hydrogen trains should be refueled by a potential HRS. A train is refueled during off-peak hours or while taken over by another train. A train running out of fuel would seriously impact the regular timetable. If the captured flow exceeds the capacity of a station, the additional capacity needed is calculated.
In this study, only HyPlanet is used as the provider of hydrogen, resulting in the lowest distribution costs for an HRS in Groningen. However, hydrogen will likely be distributed by multiple different suppliers in the future. The use of pipelines is included for scenarios in the future.

The scenarios contain the non-electrified lines in the northern Netherlands to replace diesel-fueled trains. Groningen has announced the purchase of 4 hydrogen trains from 2024 onwards, while 69 trains are operating in the northern Netherlands in total. Therefore, the first scenario covers 5.80% of the total flow over diesel-fueled lines in the northern Netherlands (4/69). As it is expected that hydrogen use will increase in the future, the second and third scenarios cover all trains driving over the diesel-fueled lines in the northern Netherlands. The current concessions in the northern Netherlands expire by 2035, hence this is a realistic moment to replace diesel trains, with possibly, hydrogen trains. Therefore, a possible scenario is that 100% of the current flow is covered by hydrogen trains from 2040 onwards.

A daily capacity of 8,000 kg is used for a potential HRS in Groningen and a daily capacity of 3,000 kg for a potential HRS in Leeuwarden. A daily capacity of 8,000 kg means that an HRS can refuel 11,680,000 flow km (8,000 kg * 365 days per year * (1 / hydrogen consumption rate)). In this example, the hydrogen consumption rate is set to 0.25 kg/km. The capacities for Groningen and Leeuwarden are in line with the plans stated in the report of Arcadis (2016). The total building costs for an HRS in Groningen with a daily capacity of 8,000 kg are approximately 25 million euros (Arcadis, 2016). The building costs for an HRS with a daily capacity of 3,000 kg for Leeuwarden is around 10 million euros. Therefore, total building costs amount to approximately 35 million euros. The expected costs for the modification of electric trains are used to estimate the costs of a hydrogen train.

4.4 Roadmap

The results indicated that the most cost-efficient investment decision would be to build one HRS in Groningen with a daily capacity of 500 kg per day for 2030. By 2040, the capacity of the HRS in Groningen should be upgraded to 4,500 kg per day (9 modules), and a new HRS should be built in Leeuwarden with a daily capacity of 1,000 kg, or 2 modules. By 2050, the capacity of the HRS at Groningen could be decreased to 4,000 kg per day as developments in fuel cell efficiency imply less hydrogen for refueling. The capacity of an HRS at Leeuwarden should not be changed (see figure 13). However, multiple developments are needed to reach these levels of hydrogen demand for railways in the future.

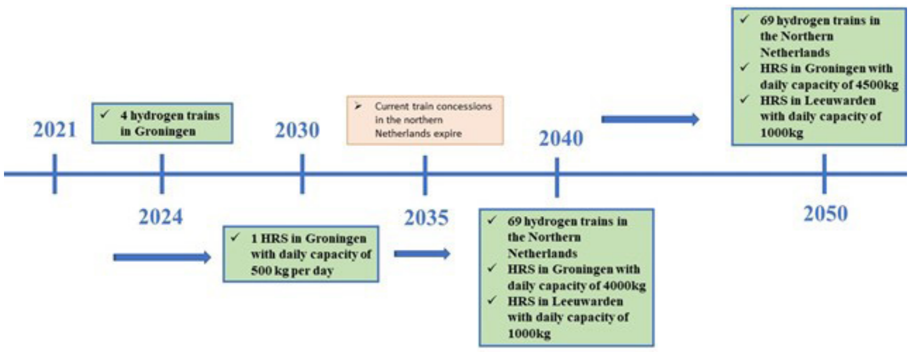

Figure 13: Roadmap to 2050

It is unlikely that the actual capacity of an HRS will be downscaled in the future. Regulations should allow refueling of other modalities at HRSs for trains to accelerate economies of scale. This makes it more attractive for the government to make additional subsidies available as well. Besides, hydrogen should be distinguished from natural gas and fossil fuels. Current regulations are unreasonably high, which hinder adoption of hydrogen. Examples of barriers entail safety distances, storage amount, storage pressure, and transport guidelines as stated in PGS 35 and ADR. Less strict legislations stimulate developments and help to bring down the costs of a hydrogen infrastructure as well as the price per kg.

The investment costs are approximately 19 million euros for both HRSs, using capacities of 4,500 and 1,000 kg per day. In addition, the purchase of 69 hydrogen trains will cost about 89.7 million euros. The total investment costs amounted to 108.7 million euros, which is way below the investment budget needed for full electrification of all unelectrified lines in the northern Netherlands, which was calculated to be 593 million euros. The difference of 484.3 million euros is significant and can be used to offset the higher costs of hydrogen as a fuel. Using total hydrogen- and distribution costs of 6 million euros per year, which is in line with the scenario for 2040, the estimated savings can be used to finance 80 years of hydrogen use (484.3 / 6). The electricity costs for catenary electric trains are not included in this calculation, which would only make the difference greater.

The distribution costs could be reduced by building additional electrolysers close to HRSs and connecting electrolysers with an HRS through pipelines. This would ensure a reliable supply of hydrogen without strict capacity restrictions. While this is unlikely for 2030 due to low demand, regulations that allow hydrogen pressure of 700 bar for HDVs might be available by 2030. This could decrease distribution costs for transport by truck, as more hydrogen can be stored in the trailer. For 2040 and 2050, the connection of an HRS with the pipeline network would be beneficial due to the higher and dense demand of hydrogen at specific HRSs.

4.5 Conclusion

This study investigated potential hydrogen refueling station locations for railway transport, as diesel-fueled trains will be replaced to reduce CO2 emissions. No research has yet been done on the development of a hydrogen infrastructure for railways, therefore optimal HRS locations for this application in the northern Netherlands are determined. The application of green hydrogen in railway transport is a promising alternative for expensive electrification, but the future is unclear. The technology is feasible, but the high costs and lacking infrastructure hinder adoption as of today. Prices are expected to drop in the future, but it is difficult to predict future hydrogen demand in railways as many aspects for the application of hydrogen need to be developed further. Factors influencing future hydrogen demand in railways concern the availability of subsidies, government policies, regulations, and technological developments. Little subsidies are available for HRSs for railways as these can only be used by trains, which hinders adoption. Government policies concern, among other things, which applications hydrogen should be used for and where it should be produced. Current policy states that hydrogen should mainly be used for applications where no alternatives, such as electrification, are present. Thus, prioritizing the use of hydrogen for use cases such as steel production, chemical production, and as a fuel for transportation modes that are difficult to electrify. This could mean that the use of hydrogen in trains could be limited for the near future. Regulations concern the unreasonably high legislations that apply to hydrogen, as it is classified in the same group as natural gas and fossil fuels. As a result, entities involved with hydrogen need a permit and comply with PGS 35 that states location-specific rules regarding storage amount and distances. Also, hydrogen is included in Annex A of ADR, which states strict transport guidelines. Lastly, technological developments relate to fuel cell efficiency, achievable range, distribution methods, and hydrogen price. Developments in these areas help to reduce the total cost of ownership of hydrogen trains and the infrastructure. The scenarios showed that developments in fuel cell efficiency have a greater effect on the amount of hydrogen needed compared to developments in achievable range.

The results of this study showed that current calculations for HRSs in Groningen and Leeuwarden have overcapacity. This study showed that an HRS in Groningen with a daily capacity of 500 kg is sufficient to serve demand in 2030. By 2040, an HRS with a daily capacity of 4,500 kg in Groningen and 1,000 kg in Leeuwarden are needed. By 2050, the HRS at Groningen needs a daily capacity of 4,000 kg and Leeuwarden 1,000 kg. An HRS for trains is not allowed to be used by other modalities as of today. The connection of HRSs with the pipeline network could bring distribution costs down and assure permanent supply of hydrogen in the future.

Developments in the future will decide whether the railway sector will opt for hydrogen or another alternative. Competitive alternatives are full electrification and the battery train. Therefore, it is recommended to be reluctant with high investments as of today. An increasing carbon price could accelerate the replacement of diesel-fueled trains. Besides, more stimulating policies and European standardization are needed for broad adoption of hydrogen in railways. The developed model can be used to locate hydrogen refueling stations when hydrogen trains will be adopted in the future.

5. GENERAL CONCLUSION

In this study, the potentials of hydrogen in heavy duty transportation have been investigated. More specifically, hydrogen refueling station (HRS) networks for trucks, ships and trains were looked into. In each case, some important barriers were identified. At the moment, hydrogen is a very promising option for the decarbonisation of the transportation sector, however enormous efforts are yet to be made to realise this. The role of the government is extremely important in making the market take off. This can be done by subsidizing firms that want to make the switch to hydrogen or by penalizing the use of fossil fuel. Additionally, collaboration and transparency between different parties in the hydrogen chain is important to remove economic barriers and reduce hostile competition that hinders the growth and innovation of hydrogen. If these important barriers are removed, the concrete goals displayed in the roadmaps for each mode of transportation can be achieved. Future research needs to be done on the possibility to combine different transport modality refueling networks. This way demand could be increased and the hydrogen network could take steps earlier.

6. APPENDIX

Appendix 1: Total Cost of Ownership overview H2-truck vs. dieseltruck

Managementsummary

TCO comparison H_2-Truck versus Dieseltruck

Managementsummary €000"	Year 1 Progn	Year 2 Progn	Year 3 Progn	Year 4 Progn	Year 5 Progn	Year 6 Progn	Year 7 Progn	Year 8 Progn	Year 9 Progn	Year 10 Progn	Total Progn
Exploitation diesel											
Total exploitationcosts (excl. CO2-tax & toll collection)	96	92	91	89	88	88	87	87	86	86	890
Total toll collection	-	23	23	23	23	23	23	23	23	23	207
Costs CO2 taks	-	-	-	-	-	-	-	-	-	-	-
Total exploitationcosts	96	115	114	112	111	111	110	110	109	109	1.097
Cumulatively exploitationcosts	96	211	325	437	548	659	769	879	988	1.097	
Kilometre cost price	0,53	0,64	0,63	0,62	0,62	0,62	0,61	0,61	0,61	0,61	
Average km/cost price	**0,61**										
Amount of ton CO2 emission per year WTW	146	146	146	146	146	146	146	146	146	146	1.458
Exploitation H_2-Truck											
Total exploitationcosts (excl. CO2-tax & toll collection)	260	242	227	213	203	194	185	180	174	169	2.047
Total toll collection	-	23	23	23	23	23	23	23	23	23	207
Costs CO2 taks	-	-	-	-	-	-	-	-	-	-	-
Total exploitationcosts	260	265	250	236	226	217	208	203	197	192	2.254
Cumulatively exploitationcosts	260	525	775	1.011	1.237	1.454	1.662	1.865	2.062	2.254	
Kilometre cost price	1,44	1,47	1,39	1,31	1,26	1,21	1,16	1,13	1,09	1,07	
Average km/cost price	**1,25**										
Amount of ton CO2 emission per year WTW	-	-	-	-	-	-	-	-	-	-	-

Total Cost of Ownership rapport H_2-Truck

today for tomorrow

Voorwoord

Over Green Planet

Green Planet staat voor 'today for tomorrow'. Dit houdt in dat wat zij vandaag de dag doen, betekenis heeft voor de dag van morgen. De klant kan hierbij zelf de keuze maken tussen fossiele of duurzame brandstoffen. Dit noemen wij "the best of both worlds". Schoner en bewuster rijden is de basis bij Green Planet.

Green Planet zal gaan fungeren als proeftuin voor meerdere innovatieve projecten. Zoals High Power Charging voor vrachtwagens en auto's en waterstof tanken voor vrachtwagens. Op den duur zal verdere uitbreiding op locatie plaatsvinden, er zullen onder andere overnachtingsmogelijkheden voor chauffeurs worden gerealiseerd.

Waarom deze TCO?

De hoeveelheid gegeven financiële informatie kan van grote invloed zijn op besluitvorming. Een manier om de totale kosten van het rijden op een bepaald type brandstof te berekenen, is de Total Cost of Ownership (TCO).

Deze tool is opgesteld om de kosten van het rijden op alternatieve brandstoffen te kunnen vergelijken met het rijden op diesel. De kosten in de TCO-tool bestaan uit de indirecte en directe uitgaven die zich voordoen bij de aanschaf en het gebruik van de trucks, natuurlijk over de gehele economische levensduur. Bij de kostenberekening worden ook de aanschafkosten (CAPEX) en de operationele kosten (OPEX) meegenomen.

Gevalideerd door Panteia

Betrouwbaarheid en nauwkeurigheid is belangrijk als het gaat om financiële doorrekeningen. In samenwerking met Panteia is deze TCO gevalideerd en heeft daarmee de Panteia stempel behaald.

Panteia
Research to Progress

Inhoudsopgave

Invoerblad vervoerder

TCO vergelijking H_2-Truck versus Dieseltruck

Heeft u een vraag? Neem dan contact op via: adviseur@greenplanet.nl

Blauw: kan worden aangepast
Paars: kan worden aangepast maar heeft ook standaardwaarden
Zwart: niet aanpassen

Jaar van start exploitatie	2023	
Voertuig type	Trekker	
Actieradius	440	km
Investeringen		
Chasis	€ 80.000	
Basis voertuig	€ 80.000	
Ombouw naar elektrisch	€ 90.000	
Batterijpakket 140kWh	€ 140.000	
H2 tanks 40 kilo	€ 76.000	
Brandstofcel + registratie	€ 80.000	
Elektrificatie	€ 386.000	
Totaal investeringen	€ 466.000	
Vrachtwagenheffing Nederland?	Ja	Alleen diesel
Tolheffing Duitsland	Nee	Alleen diesel
CO2 Belasting Nederland	Nee	
Type bedrijf t.b.v. DKTI (Learning by Using)	Geen subsidie	
Aantal rijdagen	300	dagen
Gemiddeld aantal km per rijdag	600	km
Waarvan kilometers in Duitsland	0	km
Aantal kilometers in Nederland	180.000	km
Totaal aantal kilometers per jaar	180.000	km
Inhoud batterijpakket	140	kWh
Actieradius in km alléén op batterijpakket	100	km
Grijze of groene stroom	Groen	
Prijs per kWh	€ 0,03	
Waterstof tanken bij Green Planet?	Ja	
Waterstof (Groen, Blauw of Grijs)	Groene waterstof	
Prijs per kg H_2	€ 9,00	
Brandstofverbruikscijfer waterstof	10	km/kg H2
Shell adviesprijs per liter **	€ 1,36	24-3-2021
Prijs per 1 liter diesel	€ 0,99	Dit is de Shell adviesprijs minus €0,13 per liter exclusief BTW
Brandstofverbruikscijfer	4,00	km/liter diesel
Onderhoud diesel per kilometer	€ 0,10	
Verzekering		
Verzekering diesel per jaar	€ 3.000,00	
Verzekering H_2 per jaar***	€ 3.728,00	
Houderschapsbelasting		
Houderschapsbelasting diesel per jaar	€ 900,00	
Eurovignet		
Diesel per jaar	€ 1.250,00	
Pompsnelheid waterstof	7,2	Kg/minuut
Pompsnelheid diesel	130	Liter/minuut
Wachttijd chauffeur tijdens laden meenemen als kosten in de berekening?	Nee	
Uurloon	€ 40,00	

4

Managementsummary

TCO comparison H_2-Truck versus Dieseltruck

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Amount of ton CO2 emission per year WTW	-	-	-	-	-	-	-	-	-	-	-

5

Bijlage

1 Uitgangspunten

2 Gedetaileerde TCO

3 Grafisch cumulatief

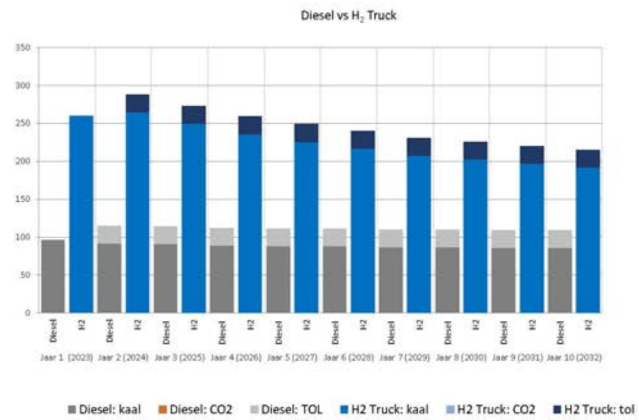
4 Grafisch gecombineerd

6

Grafische exploitatie

TCO vergelijking H2-Truck versus Dieseltruck

Heeft u een vraag? Neem dan contact op via: adviseur@greenplanet.nl



7

Gedetailleerde TCO

TCO vergelijking H2-Truck versus Dieseltruck

EXPLOITATIE

Eerst wordt de dieseltruck berekend, daaronder de H_2-truck

bedragen in €	Jaar 2023	Jaar 2024	Jaar 2025	Jaar 2026	Jaar 2027	Jaar 2028	Jaar 2029	Jaar 2030	Jaar 2031	Jaar 2032
Exploitatie diesel										
Brandstofkosten diesel	44.550	45.000	45.450	45.900	46.350	46.800	47.250	47.700	48.150	48.600
Loonkosten laad-/tanktijd per jaar	-	-	-	-	-	-	-	-	-	-
Kosten AdBlue toevoeging	3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150
Jaarkosten onderhoud	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000
Verzekering	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Houderschapsbelasting	900	900	900	900	900	900	900	900	900	900
Eurovignet	1.250	-	-	-	-	-	-	-	-	-
Afschrijving dieseltruck	24.972	22.412	20.200	18.338	16.863	15.691	14.621	13.961	13.247	12.673
Totale exploitatiekosten (excl. tolheffing & CO2-belasting)	95.822	92.462	90.700	89.288	88.263	87.541	86.921	86.711	86.447	86.323
Tolheffing Nederland****	-	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Tolheffing Duitsland****	-	-	-	-	-	-	-	-	-	-
Totale tolheffing	-	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Kosten CO2-belasting Nederland	-	-	-	-	-	-	-	-	-	-
Totale exploitatiekosten	95.822	115.862	114.100	112.688	111.663	110.941	110.321	110.111	109.847	109.723
Cumulatieve exploitatiekosten	95.822	211.684	325.784	438.472	550.135	661.076	771.397	881.508	991.355	1.101.078
Aantal ton CO2 uitstoot per jaar WTW	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76
Exploitatie H_2-Truck										
Brandstofkosten E+H_2	136.260	134.760	133.260	131.760	130.260	128.760	127.260	125.760	124.260	122.760
Loonkosten laad-/tanktijd per jaar	-	-	-	-	-	-	-	-	-	-
Jaarkosten onderhoud	16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650
Verzekering	3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728
Houderschapsbelasting	-	-	-	-	-	-	-	-	-	-
Eurovignet	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250
Afschrijving H_2 truck	101.942	85.762	71.789	60.021	50.705	43.302	36.535	32.368	27.857	24.229
Totale exploitatiekosten (excl. tolheffing & CO2-belasting)	259.830	242.150	226.677	213.409	202.593	193.690	185.423	179.756	173.745	168.617
Tolheffing Nederland****	-	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Tolheffing Duitsland****	-	-	-	-	-	-	-	-	-	-
Totale tolheffing	-	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Kosten CO2-belasting Nederland	-	-	-	-	-	-	-	-	-	-
Totale exploitatiekosten	259.830	265.550	250.077	236.809	225.993	217.090	208.823	203.156	197.145	192.017
Cumulatieve exploitatiekosten	259.830	525.381	775.457	1.012.266	1.238.260	1.455.349	1.664.173	1.867.328	2.064.473	2.256.490
Aantal ton CO2 uitstoot per jaar WTW	-	-	-	-	-	-	-	-	-	-
Aantal ton CO2 minder uitstoot WTW E+H_2-truck t.o.v. Dieseltruck	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76	145,76

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Green Planet

Uitgangspunten

TCO vergelijking H2-Truck versus Dieseltruck

Invoerdocument van TCO H_2-truck. De blauwe getallen kunt u desgewenst overschrijven.
Deze werken automatisch door in de prognose Exploitatie.
Eerst wordt de dieseltruck weergegeven, daaronder de H_2-truck

bedragen in €			Jaar	Jaar	Jaar	Jaar	Jaar	Jaar	Jaar	Jaar	Jaar	Jaar
Exploitatie			1	2	3	4	5	6	7	8	9	10
			2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Aantal rijdagen			300	300	300	300	300	300	300	300	300	300
gemiddeld aantal km per rijdag			600	600	600	600	600	600	600	600	600	600
Totaal aantal kilometers per jaar			180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000
Waarvan kilometers in Duitsland			-	-	-	-	-	-	-	-	-	-
Kilometers in Nederland			180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000
Meerkilometers t.o.v. 75000/jaar			105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000	105.000
Exploitatie diesel												
Brandstofkosten diesel												
Prijs per 1 liter diesel			0,99	1,00	1,01	1,02	1,03	1,04	1,05	1,06	1,07	1,08
Verbruik aantal km/liter diesel			4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00
Kosten diesel per dieselkilometer			0,25	0,25	0,25	0,26	0,26	0,26	0,26	0,27	0,27	0,27
Totale brandstofkosten per rijdag diesel			148,50	150,00	151,50	153,00	154,50	156,00	157,50	159,00	160,50	162,00
Ter info: jaarverbruik aantal liters diesel			45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000
Totale brandstofkosten per jaar diesel			44.550	45.000	45.450	45.900	46.350	46.800	47.250	47.700	48.150	48.600
Kosten AdBlue toevoeging												
Prijs per 1 liter AdBlue			0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35
Verbruik aantal km/liter AdBlue			20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00
Kosten AdBlue per AdBluekilometer			0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Totale brandstofkosten per rijdag AdBlue			10,50	10,50	10,50	10,50	10,50	10,50	10,50	10,50	10,50	10,50
Ter info: jaarverbruik aantal liters AdBlue			9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000
Totale brandstofkosten per jaar AdBlue			3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150	3.150
Kosten laad/tanktijd												
Loonkosten laad-/tanktijd per jaar			-	-	-	-	-	-	-	-	-	-
Onderhoud												
Diesel per kilometer			0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100
Jaarkosten onderhoud			18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000
Verzekering												
Diesel per jaar			3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Houderschapsbelasting												
Diesel per jaar			900	900	900	900	900	900	900	900	900	900
Eurovignet												
Diesel per jaar			1.250	-	-	-	-	-	-	-	-	-
Tolheffingen Diesel ($E+H_2$ vrijgesteld)		per km										
Tolheffing Nederland****	Ja	0,130	0	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Tolheffing Duitsland****	Nee	0,107	0	0	0	0	0	0	0	0	0	0
Tolheffingen			0	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Investeringen en BIK subsidie (3%)												
Chassis		80.000										
Bak		0										
Basis voertuig		80.000										
BIK subsidie		2.400										
Totaal investeringen incl. subsidies		77.600										
Afschrijving												
Afschrijving %*			18,66%	17,02%	15,51%	14,16%	12,97%	11,92%	10,98%	10,16%	9,42%	8,77%
Waardeverlies % (cumulatief)			18,65%	34,00%	46,50%	56,60%	64,80%	71,49%	76,80%	81,26%	84,80%	87,60%
Waardeverlies € (cumulatief)			14.472	26.384	36.084	43.922	50.285	55.476	59.597	63.058	65.805	67.978
Restwaarde truck in %			81,35%	66,00%	53,50%	43,40%	35,20%	28,51%	23,20%	18,74%	15,20%	12,40%
Restwaarde truck in €			63.128	51.216	41.516	33.678	27.315	22.124	18.003	14.542	11.795	9.622
Meerafschrijving kilometers boven 75.000 per jaar	0,10	per km	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500
Afschrijving dieseltruck			24.972	22.412	20.200	18.338	16.863	15.691	14.621	13.961	13.247	12.673
Boekwaarde dieseltruck**			52.628	30.216	10.016	-	-	-	-	-	-	-
CO2 huishouding diesel												
Kg CO2 uitstoot per liter diesel WTW *			3,24	3,24	3,24	3,24	3,24	3,24	3,24	3,24	3,24	3,24
Ter info: jaarverbruik aantal liters diesel			45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000	45.000
Totale kg CO2 uitstoot per jaar WTW			145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762
CO2 belasting Nederland?	Nee											
Totale kg CO2 uitstoot per jaar WTW Nederland			145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762	145.762
Milieubelasting per ton CO2 Nederland - 2021: €50 2030: €100 2050: €200			50	50	50	50	50	50	50	100	100	100
Kosten CO2-belasting Nederland			-	-	-	-	-	-	-	-	-	-
Exploitatie H_2-Truck												
Brandstofkosten $E+H_2$												
Inhoud batterijpakket in kWh			140	140	140	140	140	140	140	140	140	140
Actieradius in km op alléén batterijpakket			100	100	100	100	100	100	100	100	100	100

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kosten per kWh			0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
Kosten per volledige lading			4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20
Kosten E per E kilometer			0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Ter info: jaarverbruik aantal kWh			42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000
Loonkosten laad-/tanktijd per jaar			-	-	-	-	-	-	-	-	-	-
Prijs per kg H_2			9,00	8,90	8,80	8,70	8,60	8,50	8,40	8,30	8,20	8,10
Verbruik aantal km/kg H_2			10	10	10	10	10	10	10	10	10	10
Kosten H_2 per H_2 kilometer			0,90	0,89	0,88	0,87	0,86	0,85	0,84	0,83	0,82	0,81
Ter info: jaarverbruik aantal kg H_2			15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000
Aantal km op E per rijdag			100	100	100	100	100	100	100	100	100	100
Aantal km op H_2 per rijdag			500	500	500	500	500	500	500	500	500	500
Kosten per rijdag E kilometers			4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20	4,20
Kosten per rijdag H_2 kilometers			450,00	445,00	440,00	435,00	430,00	425,00	420,00	415,00	410,00	405,00
Totale brandstofkosten per rijdag E+H_2			454,20	449,20	444,20	439,20	434,20	429,20	424,20	419,20	414,20	409,20
Totale brandstofkosten per jaar E+H_2			136.260	134.760	133.260	131.760	130.260	128.760	127.260	125.760	124.260	122.760
Onderhoud												
H_2-truck per kilometer			0,0925	0,0925	0,0925	0,0925	0,0925	0,0925	0,0925	0,0925	0,0925	0,0925
Jaarkosten onderhoud			16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650	16.650
Verzekering												
H_2-truck per jaar			3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728	3.728
Houderschapsbelasting												
H_2-truck per jaar			0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Eurovignet												
H_2-truck per jaar			1.250	0	0	0	0	0	0	0	0	0
Tolheffingen H_2-truck		per km										
Tolheffing Nederland****	Ja	0,130	0,00	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400
Tolheffing Duitsland****	Nee	0,000	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Tolheffingen			0,00	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400	23.400

Investeringen en subsidies	
Uitgangspunten bij berekeningen:	
BIK	3%
MIA percentage, is aftrek van de grondslag VPB	36%
- grondslag is chassis + bak + electrificatie	
VPB percentage waar we mee rekenen	20%
Type bedrijf***	Geen subsidie
DKTI percentage	0%
- grondslag is electrificatie	
Uurtarief testuren chauffeur	40,00
Aantal testuren voor inbedrijfname	300
Investeringen	
Chassis	80.000
Bak	-
Basis voertuig	80.000
Ombouw naar elektrisch	90.000
Batterij pakket	140.000
15kg H_2 tanks	76.000
Fuel Cell + registratie	80.000
Electrificatie	466.000
Totaal investeringen	546.000
Subsidies	
BIK	16.380
MIA Subsidie	39.312
DKTI subsidie	-
Declarabele testuren o.b.v. DKTI percentage	-
Totaal subsidies	55.692
Totaal investeringen in electrificatie	466.000
AF: Initiële subsidie	-55692
Netto investering electrificatie H_2 truck	410.308

Afschrijving											
Afschrijving %*		18,66%	17,02%	15,51%	14,16%	12,97%	11,92%	10,98%	10,16%	9,42%	8,77%
Waardeverlies % (cumulatief)		18,65%	34,00%	46,50%	56,60%	64,80%	71,49%	76,80%	81,26%	84,80%	87,60%
Waardeverlies € (cumulatief)		91.442	166.705	227.993	277.514	317.720	350.521	376.557	398.424	415.781	429.510
Waarde truck in %		81,35%	66,00%	53,50%	43,40%	35,20%	28,51%	23,20%	18,74%	15,20%	12,40%
Restwaarde H_2 truck per jaar		398.866	323.603	262.315	212.794	172.588	139.787	113.751	91.884	74.527	60.798
Meerafschrijving kilometers boven 75.000 per jaar	0,10 per km	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500	10.500
Afschrijving H_2 truck		101.942	85.762	71.789	60.021	50.705	43.302	36.535	32.368	27.857	24.229
Boekwaarde H_2 truck**		388.366	302.603	230.815	170.794	120.088	76.787	40.251	7.884	-	-
CO2 huishouding E+H_2											
Electrisch											
Jaarverbruik aantal kWh		42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000	42.000
Kg CO2 uitstoot per kWh WTW		0	0	0	0	0	0	0	0	0	0
CO2 huishouding H_2											
Kg CO2 uitstoot per kg H_2 WTW*		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Jaarverbruik aantal kg H_2		15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000
Totale kg CO2 uitstoot per jaar WTW		-	-	-	-	-	-	-	-	-	-
CO2 belasting Nederland?	Nee										
Totale kg CO2 uitstoot per jaar WTW Nederland		-	-	-	-	-	-	-	-	-	-
Milieubelasting per ton CO2 Nederland - 2021: €50 2030: €100 2050: €200		50	50	50	50	50	50	50	100	100	100
Kosten CO2-belasting Nederland		-	-	-	-	-	-	-	-	-	-

*Afschrijving is gebaseerd op percentages afkomstig van TNO

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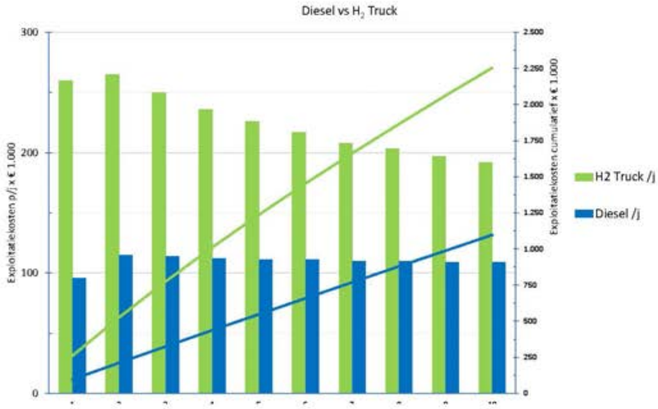
Grafisch gecombineerd

TCO vergelijking H2-Truck versus Dieseltruck

Heeft u een vraag? Neem dan contact op via: adviseur@greenplanet.nl



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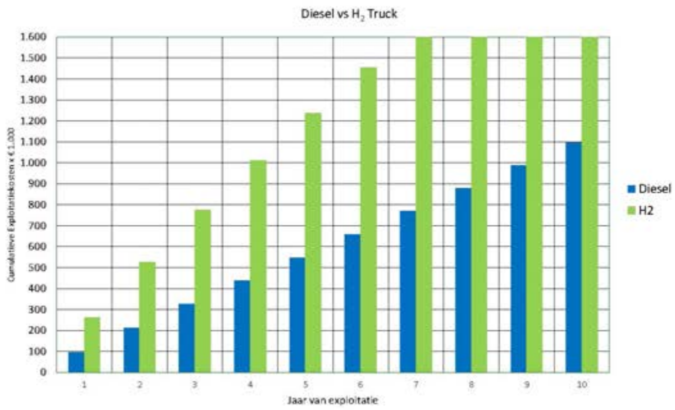
Grafisch cumulatief

TCO vergelijking H2-Truck versus Dieseltruck

Heeft u een vraag? Neem dan contact op via: adviseur@greenplanet.nl



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