

TECHNO-ECONOMIC ASSESSMENT OF A HYDROGEN FUEL-CELL TRACTOR SEMI-TRAILER

EXPLORATORY RESEARCH INTO THE FEASIBILITY

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Techno-economic assessment of hydrogen fuel-cell tractor semi-trailer

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Acknowledgement

On the 11th of February 2019 I started my master thesis at the Sustainable Transport and Logistics department of TNO. This is the last partial fulfilment of the master Complex Systems, Engineering and Management. This thesis identifies the boundary conditions that are required for a hydrogen truck to be feasible for long-haul road freight transport.

I would like to thank everyone at TNO (STL) for their warm welcome and allowing me in the TNO family. This created an inspiring environment for me to develop this thesis. In particular, I would like to thank my company supervisor Stephan van Zyl for this feedback, suggestions and guidance, which has assisted in creating the thesis. Besides that, I would like to thank the experts for their willingness and time for the interviews to verify and validate my results. Moreover, I would like to thank the members of my graduation committee for their feedback and suggestions for methods. Last but not least, I would like to thank my family and friends for their continues support, willingness to provide feedback and positivism throughout the 7 months of this thesis.

Martijn Oostdam

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Glossary

Hydrogen fuel-cell tractor semi-trailer	In this thesis abbreviated as “hydrogen truck”
Fuel-cell electric vehicles	In this thesis abbreviated as “Hydrogen vehicles”
Diesel tractor semi-trailer	In this thesis abbreviated as “diesel truck”
Battery electric tractor semi-trailer	In this thesis abbreviated as “electric truck”
OEM	Original Equipment Manufacturer
Route	Hydrogen supply chain route, a combination of a method/mode for each of the steps of the supply chain. The supply chain is assumed to be production, distribution and refuelling.
GHG	Greenhouse gases
HRS	hydrogen refuelling station
TCO	Total cost of ownership analysis, an evaluation tool that calculates all the costs that are associated with purchasing and using a truck

Summary

Since the last decade, climate change has received increasingly more attention from politicians and scholars. Both are looking for ways to address this issue in different sectors. The transport sector accounts for roughly 20% of the total Greenhouse Gasses (GHG) emissions (European Commission, 2016). Heavy-duty road transport accounts for roughly 25% of all transport emissions, so around 5% of the total GHG emissions originate from heavy-duty road transport (Singh et al., 2015).

There are several options to reduce the emissions, a large reduction potential is given by using different energy carriers and improving vehicle efficiency as currently, conventional diesel is the most used energy carrier in heavy-duty transport (97%) (Singh et al., 2015; Westaway, 2009). Fortunately, innovative energy carriers like electric, bio-diesel and hydrogen are being developed. This thesis focusses on hydrogen.

Current research and policies concerning hydrogen vehicles focus mostly on passenger transport (Hill, Hazeldine, Einem, Pridmore, & Wynn, 2009; Nocera & Cavallaro, 2016). However, passenger transport has different requirements in terms of expected performance and yearly mileage. Furthermore, the hydrogen refuelling stations (HRS) deployment throughout Europe focuses on light duty passenger vehicles and not equipped with high flow refuelling equipment, which is often used by heavy-duty vehicles (Rijkswaterstaat, 2019). There is a similar problem with the production of hydrogen vehicles. There are two vehicle models for passenger transport available in the Netherlands, the Hyundai Nexo and the Toyota Mirai. In contrast, hydrogen trucks currently seem far less developed commercially: there are only pilot programs or future orders for hydrogen trucks (Jin, 2018; Navas, 2017).

Despite this apparent lack of attention in research into the application of hydrogen in heavy duty transport, the potential of GHG emission reduction that lies in the substituting diesel for this more sustainable alternative is evident. Therefore, this thesis aims to give insight into the following question:

Under which techno-economic boundary conditions is a hydrogen fuel-cell tractor semi-trailer a feasible option for long-haul freight road transport in Europe?

For this purpose, this problem is analysed from the perspective of the end-user, the transport companies. In general, innovations are feasible if they are: available, affordable and robust in operation (Logistiek, 2019; TLN, 2017, 2018). This means that ideally, a new truck needs to be available at their favourite dealer or Original equipment manufacturer (OEM) for a comparable price and provide similar characteristics in operation. This all compared to a diesel truck. It becomes clear that the affordability is the most important decision variable while availability and robustness in operation were considered most important boundary conditions, which are preconditional.

This paper uses a Total cost of ownership (TCO) analysis to identify the boundary conditions for feasibility of a hydrogen truck. While looking into the cost components of the TCO and comparing this with a diesel truck, the boundary conditions for feasibility arise. The components of the TCO are filled in using a literature review and 10 expert interviews. In order to accommodate for the uncertainty in the development of these components, a modest and a strong improvement scenario are used.

The TCO consist of the capital expenditure (CAPEX), i.e. the truck cost (depreciation cost), and the operational expenditure (OPEX), which includes fuel costs and other costs. Figure 1 shows the proportion of each of the components for the diesel and hydrogen truck. The uncertainty range (bandwidth) of the diesel truck TCO is approximately €0.10. Three situations are given for the hydrogen truck; the current situation and modest improvement and strong improvement. As can be seen, the

proportion of fuel cost decreases due to the improvements. The improvements are depicted in Figure 2.

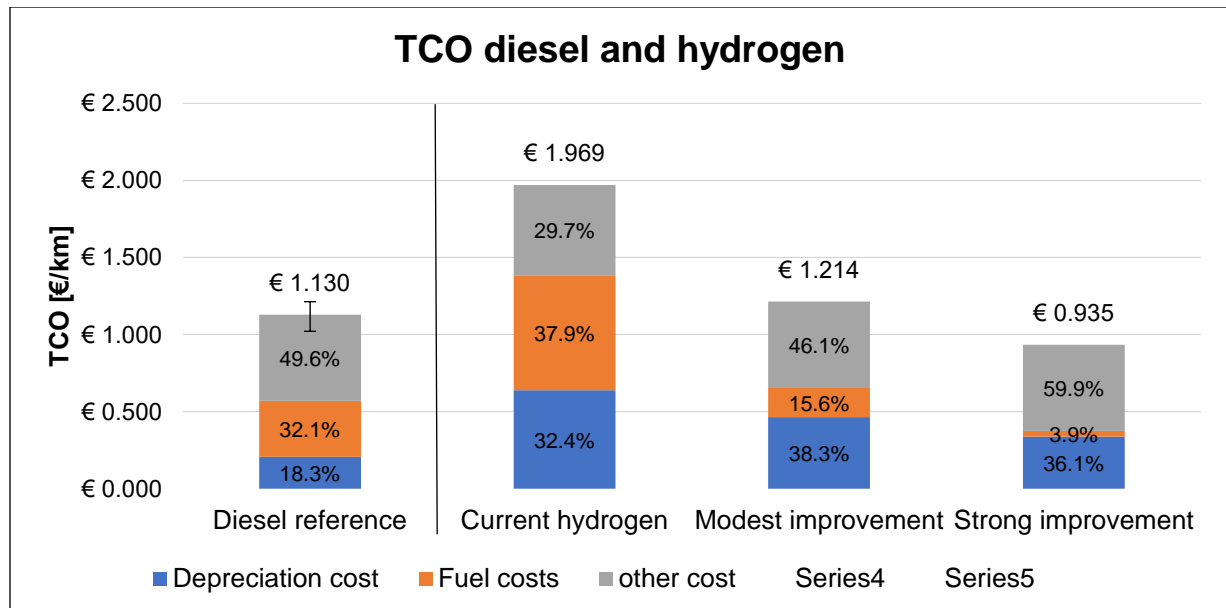


Figure 1 TCO of diesel and hydrogen truck. Diesel truck with uncertainty margin of approximately €0.10. Hydrogen truck with current, modest improvement and strong improvement situation. TCO values for hydrogen truck modest and strong improvement are from route 1.

As can be seen in Figure 2 from the large decrease in TCO, the hydrogen price is an important component within TCO. To get a good understanding of the price development, each of the steps of the hydrogen supply chain is analysed. As there are several alternatives available for each of the steps, the TCO contribution of 7 different hydrogen supply routes (hereafter called: “routes”) is compared. An overview of the routes is seen in Table 1 on the next page.

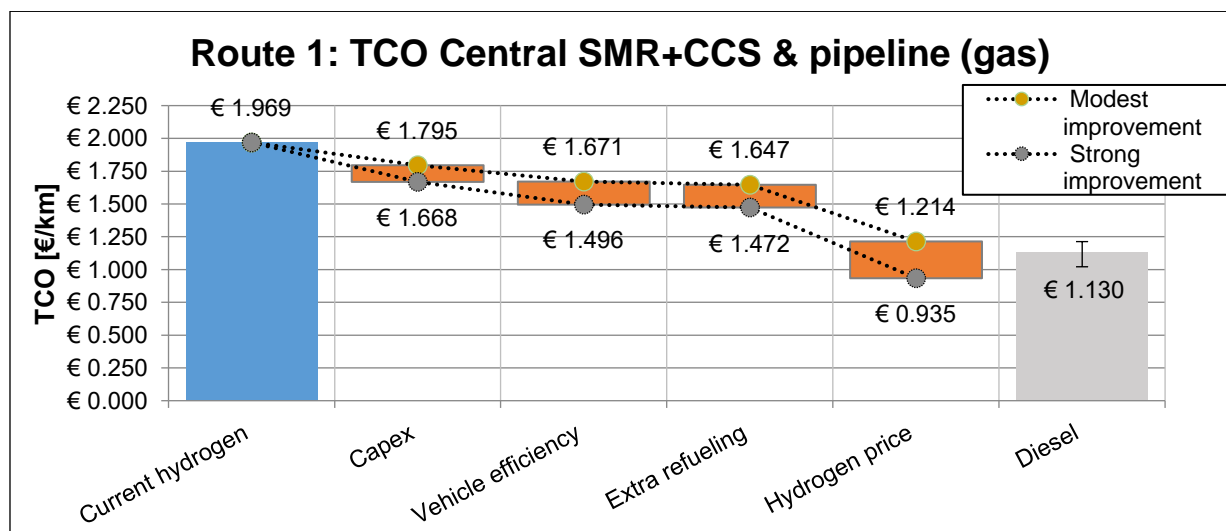


Figure 2 TCO analysis of route 1, with effect of the development of 4 uncertain factors

The analysis of the TCO for the routes concludes that all the routes are within the bandwidth of the diesel reference alternative, see Figure 3. The figure shows that the hydrogen truck TCO is similar in modest improvement scenario and could be cheaper in strong improvement scenario. Furthermore, it becomes clear that all hydrogen supply routes have approximately the same TCO. This means that from a financial point of view, there is no preferred route. However, from an environmental point of view, the biomass and electrolysis routes are preferred over the SMR+CCS routes.

Table 1 Selected routes based on the requirements and expert interview selection.

	Production	Distribution	Refuelling
Route 1	SMR + CCS	Pipeline (gas)	Gas 700 bar
Route 2	SMR + CCS	Truck (liquid)	Gas 700 bar
Route 3	Biomass	Pipeline (gas)	Gas 700 bar
Route 4	Biomass	Truck (liquid)	Gas 700 bar
Route 5	Local electrolysis	-	Gas 700 bar
Route 6	Central electrolysis	Pipeline (gas)	Gas 700 bar
Route 7	Central electrolysis	Truck (liquid)	Gas 700 bar

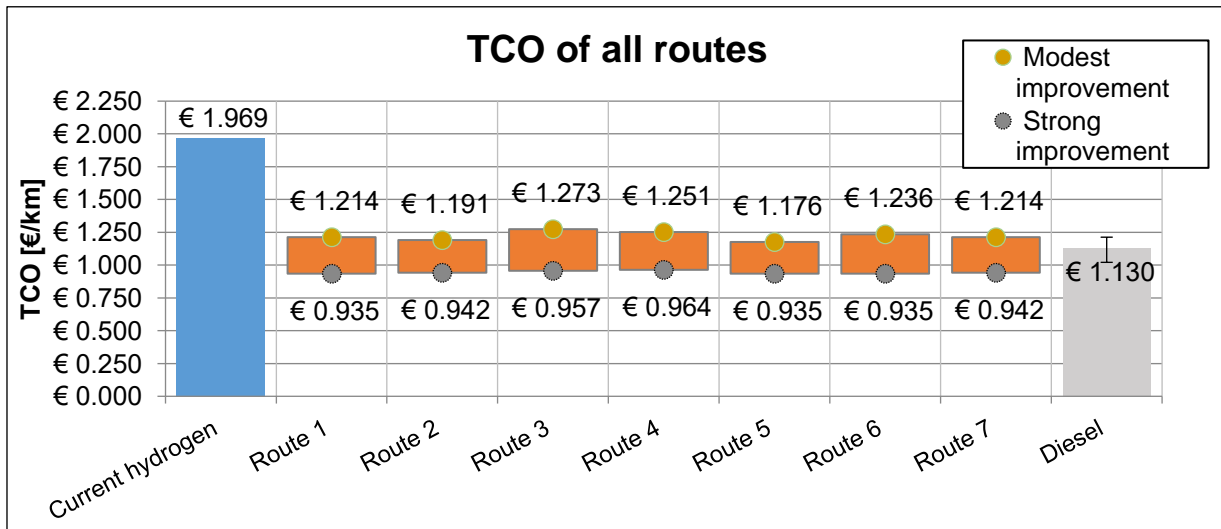


Figure 3 Overview of TCO results of all routes

From this thesis, it becomes clear that a hydrogen fuel-cell tractor semi-trailer can be a feasible option, preconditional certain boundary conditions. This thesis identified three important types of boundary conditions for feasibility that transport companies use in decision making, namely availability, affordability and robustness in operation. For the most important two parts, the hydrogen price and hydrogen truck, these boundary conditions are mentioned.

The most important factors within the hydrogen price are the production and refuelling cost. Currently, the hydrogen price is fixed to €10.00 per kg (incl. value added tax (VAT) and exception from excise duty), this develops towards €5.00 and €3.00 per kg in modest respectively strong improvement scenario. The production cost is the largest factor in the hydrogen price. To reach the above-mentioned price reductions, it is important that sustainable hydrogen becomes available at a large scale. This is only possible if large scale sustainable energy is produced. Concretely, this means that the government needs to stimulate the production capacity of sustainable energy and sustainable hydrogen. For the hydrogen industry, this means that more research and development is needed to expand the sustainable hydrogen production (primarily electrolyzers).

For the refuelling of hydrogen, two factors are important, namely the creation of a high-flow 700 bar refuelling protocol and the availability of hydrogen refuelling stations (HRS). The refuelling protocol makes sure that the fuel tank can be refuelled in less than 10 minutes whereas the availability of the HRS makes sure that there is a network of refuelling stations. The refuelling protocol needs to be established after additional research and development from the hydrogen industry. The deployment of the HRS and the usage of this refuelling protocol should be supported by the government.

The fuel-cell system and the fuel tank are the most important factor within the hydrogen truck. at this moment, a hydrogen truck costs around €440,000. In the future, the truck price could decrease to

about €335,000 or even €260,000 in modest respectively strong improvement scenario. During the analysis, the fuel-cell system and fuel tank are identified as the most important factor which accounts for €284,000 of the current price and for €110,000 in strong improvement scenario. The fuel-cell system consists of the fuel-cell stack and the balance of plant (Inside the fuel cell stack, the electro-chemical process occurs whereas the balance of plant controls the pressure, temperature and intake of hydrogen). It is important that OEMs continue the research and development of the fuel-cell system to get more insight into the configuration of the balance of plant related to the size of other components like fuel-cell stack, electromotor and battery. For the fuel tank it is important that OEMs continue to research and develop hydrogen storage techniques as the fuel tank capacity is around 30 to 40 kg, however, ideally the fuel tank capacity increases towards 80 kg.

This thesis approached the research question from the perspective of transport companies with a strong cost driven focus. However, to determine if an innovation is feasible and will succeed one needs to analyse it from a broader perspective which requires other factors and actors. Besides the economic factors, there are also safety, environmental and societal factors to consider. Moreover, these factors also have a different importance and meaning for different actors. So, something might be a feasible option for transport companies but not for the government or OEMs.

This thesis should be seen as a contribution towards the broader discussion of selecting alternative energy carriers in the transport sector in order to replace conventional energy carriers. This thesis contributes to multiple fields. The scientific contribution consists of the identification of a clear literature gap concerning high flow refuelling with 700 bar for heavy duty vehicles. Literature about this does not exist but is desirable for transport companies. The end-user, transport companies, are helped as this thesis provides insight into the capabilities of a hydrogen truck and in the difference in cost components of a hydrogen truck compared to a diesel truck. Furthermore, this thesis assists policy makers in creating policy for heavy-duty transport as it pinpoints the barriers for implementation of hydrogen trucks. Understanding this helps to create policy to remove these barriers.

Based on this thesis, new inquiries can be started. For instance, this research has an exploratory nature and identified the barriers for feasibility. The next step would be to perform effect research into the implementation of hydrogen trucks. Possible lines of inquiry include, model-based research into lowering the barriers to a certain extent and see the effect and the most suitable alternative to lower a certain barrier. Besides that, performing choice experiments to understand the willingness to pay of transport companies when choosing a different sort of truck. This identifies the additional willingness to pay to purchase a zero-emission truck. Moreover, the balance of plant is identified as important within the hydrogen truck. Understanding more about its configuration related to the size of other systems like the fuel-cell stack and electromotor would be interesting as it assists in developing more standardised fuel-cell systems.

All in all, this thesis provides insight into the feasibility of the application of hydrogen trucks. The results show that with some development, it could become a cost competitive alternative compared to conventional diesel trucks. Although further research and effort is required for this to happen, this thesis has identified several topics for this based on the criteria of transport companies.

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1. Introduction

In order to stay well below a 2°C increase in global average temperature compared to pre-industrial levels, a GHG reduction of 80-95% is needed in 2050 compared to 1990 (UNFCCC, 2018). The transport sector accounts for approximately 25% of all GHG emissions in Europe. With road transport being the largest emitter: approximately 70% of all GHG emissions from transport in 2014 (European Commission, 2016). 97% of road transport is powered by fossil fuels (primarily diesel and petrol) (Singh et al., 2015; Westaway, 2009)

Heavy-duty road transport accounts for roughly 25% of all transport emissions. This means that heavy-duty road transport creates around 5% of the total GHG emissions. Since economic growth and transport demand is strongly coupled, it becomes difficult to reduce the emissions of freight transport without harming the economy (Meersman & Van de Voorde, 2016).

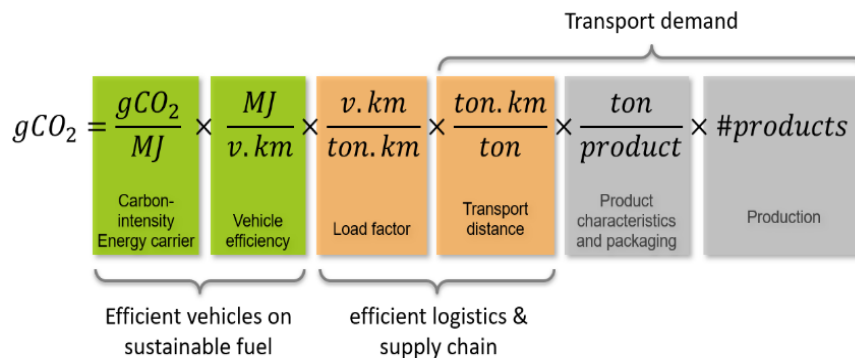


Figure 4 Relation between CO₂ emissions and transport demand (Richard Smokers personal communication, 2018)

However, there are several options to reduce emissions, see figure 4. Three types of options can be identified. First of all, the transport demand, consisting of the demand for products and the product characteristics. Given the economic growth scenarios for global trade, production is increasing. Accompanying this, freight transport is expected to grow with at least a factor 2 in the next 30 years (Lande, 2019). The product characteristics and packaging can be more efficient. However, so far, the packaging is mainly driven by marketing factors.

Secondly, the logistics efficiency can be increased by increasing the load factor of vehicles and optimising transport distance. With developments of hub location near major highways and last-mile distribution, this load factor can be improved. With city logistics packages for a group are collected and delivered with full truckload vehicles instead of ten different vehicles delivering one package each.

A large reduction potential is given by using different energy carriers and improving vehicle efficiency. As mentioned, conventional diesel is the most used energy carrier in heavy-duty transport. However, innovative energy carriers are being developed. Out of these innovative energy carriers, bio-diesel can be zero-emission Well-to-Wheel (WTW). However, this depends on the feedstock and the blend that is used. Bio-diesel is often created from corn, palm oil and residual products. Some feedstocks contain more CO₂. Currently, bio-diesel is blended in small percentages with regular diesel. This could be blended to up to 100% bio-diesel. Although biodiesel is WTW zero-emission, it is not zero-emission in its components. During the creation of the feedstock (Well-to-Tank, WTT), CO₂ is captured as organic products use photosynthesis to create glucose out of CO₂ and O₂. The CO₂ is emitted again upon combustion (Tank-to-Wheel, TTW).

Another option is to use electric vehicles. They are also TTW zero-emission vehicles, though, the WTT emission is dependent on the method of electricity production. If renewable energy sources are used, there is WTW zero-emission. When electric vehicles are used in long-distance transport, they face a problem with maximum driving range. In order to increase the range, the batteries need to be larger and heavier. This reduces the freight capacity of the truck.

Hydrogen is a promising alternative to overcome range issues. Hydrogen has a large energy density (120 MJ/kg), but a small volume mass density (0.09 kg/m³). However, hydrogen trucks are still being tested in prototype phase. Hydrogen is technically feasible, though it has many challenges to overcome before it can reach a large scale.

Literature gap

Current research and policies concerning hydrogen vehicles focus mostly on passenger transport (Hill et al., 2009; Nocera & Cavallaro, 2016; Singh et al., 2015). Passenger transport has different requirements in terms of expected performance and yearly mileage. For instance, the HRS development throughout Europe focuses on light duty passenger vehicles and to a lesser extent on heavy-duty freight vehicles (European Parliament & European Council, 2014). There are 4 refuelling stations in the Netherlands. However, these are designed for passenger vehicles. They are not equipped with high flow refuelling equipment, which is often used by heavy-duty vehicles (Rijkswaterstaat, 2019). There is a similar problem with the production of hydrogen vehicles. There are two vehicle models for passenger transport available in the Netherlands, the Hyundai Nexo and the Toyota Mirai, whereas there are only pilot programs or future orders for hydrogen trucks (Jin, 2018; Navas, 2017).

1.1. Research question

Despite this apparent lack of attention in research into the application of hydrogen in heavy duty transport, the potential of GHG emission reduction that lies in the substituting diesel for this more sustainable alternative is evident. Therefore, this exploratory thesis aims to give insight into the boundary conditions that are needed to determine the feasibility of a hydrogen truck in long-haul freight road transport. The aim of this study can be translated into the following core research question:

Under which techno-economic boundary conditions is a hydrogen fuel-cell tractor semi-trailer a feasible option for long-haul freight road transport in Europe?

The bullets below further elaborate on the definitions of specific words of the research question.

- **Boundary conditions** refer to technical and economic key parameters that need to be in place to assure the feasibility of a hydrogen fuel-cell truck.
- **Feasibility**, Transport companies consider the following criteria: availability, affordability and robustness in operation. A more elaborate explanation can be found in section 2.1.
- **Hydrogen fuel-cell tractor semi-trailer** refers to a primarily hydrogen-powered drivetrain. Hydrogen combustion engines are beyond the scope of this thesis.
- **Long-haul freight road transport** refers to the movement of goods using the road, most of the time with (heavy) trucks. Long-haul refers to the mission profile which entails among others daily mileage and the number of stops. This is further discussed in section 3.3
- **Europe** refers to the European design standards which apply for the hydrogen truck.

Based on this, several sub-questions are formulated that together help answer the main research question. Elaboration on the methods that are used can be found in chapter 2.

SQ1) What is the current cost of hydrogen, and how will the price develop in the future?

This sub-question will discuss the cost of hydrogen. To analyse this cost the hydrogen supply chain is analysed. This can be divided into production, distribution and refuelling. Each of these processes can be executed using several methods, each with different costs. These methods are developing, which

influences the cost. This chapter ends by creating possible hydrogen supply chain routes to estimate the hydrogen price in modest and strong improvement scenarios.

SQ2) What is the current cost of a hydrogen truck and how will this develop in the future?

This sub-question discusses the cost of a hydrogen truck. As there are no commercially available hydrogen trucks, this question is approached by looking into the components of the hydrogen truck. Each of these components develops, influencing the price.

In the end, the components are combined into an integral analysis of the cost of a hydrogen truck. The hydrogen truck price is presented for the current situation, together with a modest and strong improvement scenarios.

SQ3) What Is the most cost-effective route compared to reference diesel?

This sub-question compares the routes using a TCO analysis and selects the most cost-effective route. The TCO combines the routes, as defined in SQ1, with the cost of the truck, derived from SQ3.

1.2. Thesis overview

This thesis is structured as follows:

- Chapter 1, this chapter, describes the importance of this research and the research question.
- Chapter 2 describes the theory and methods used to analyse the feasibility of the hydrogen truck.
- Chapter 3 describes the evaluation framework.
- Chapter 4 examines the hydrogen price.
- Chapter 5 discusses the hydrogen truck.
- Chapter 6 calculates The TCO for different routes that are identified for hydrogen cost.
- Chapter 7 contains the conclusion.
- Chapter 8 provides the reflection, contribution and future research.

In Figure 5, the thesis overview is given, together with the methods used for each sub-question and the sequence of steps in the research. More about the method is described in chapter 2.

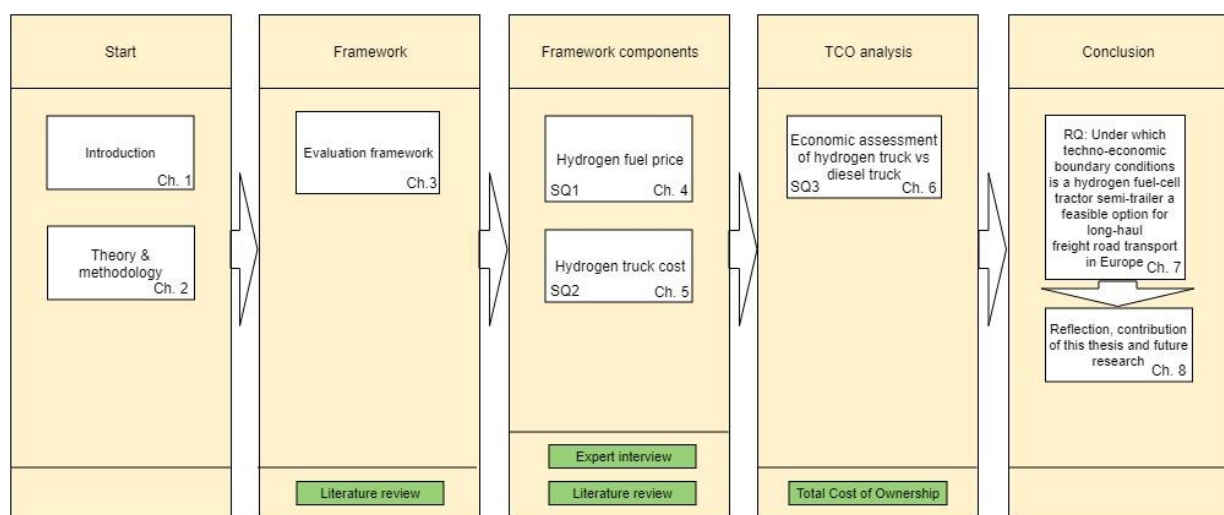


Figure 5 Research flow diagram with chapter, method and sub-question

2. Theory & methodology

This thesis discusses under which boundary conditions a hydrogen truck in long-haul freight transport is feasible. This thesis uses an exploratory research approach as limited information is available on the application of hydrogen in heavy-duty transport as seen from the literature gap. This chapter defines what is meant with feasibility and how feasibility can be analysed. Section 2.1 describes the theory that is used to assess the feasibility and concludes with the creation of the theoretical framework of this thesis. Section 2.2 discusses methods that are used to assist filling in the parts of the framework.

2.1. Theory

It is important to understand more about the drivers and barriers of a successful innovation as this determines if an innovation is adopted or not. So, Section 2.1.1 gives an overview of the concept of innovation theory. Section 2.1.2 applies innovation theory for the case of a hydrogen truck in long-haul freight transport sector. Section 2.1.3 continues by positioning this thesis within the long-haul freight transport sector as the hydrogen truck assessment is performed from the perspective of transport companies.

2.1.1. Innovation theory

Multiple scholars have tried to answer the following question: *“Why have certain innovations been adopted while others have not?”* (Feitelson & Salomon, 2004). Innovation theory is the scientific discipline that studies this question. They try to identify critical factors that need to be in place for successful implementation and adoption of an innovation.

Geels (2002) looked into technical transitions and how they come about. He identifies three layers: landscape, patchwork of regimes and innovations or niches, see the left side of Figure 6. The landscape is a robust representation of the current state of high-level affairs and deep structured trends. Examples of this are climate change, world peace, the global financial situation. Underneath this landscape are all sorts of socio-technical regimes. These regimes contain a complex multi-actor situation with producers, consumers, interest groups, financial institutes, research institutes and government.

Each of these regimes has a set of important variables. Geels (2002) identifies six variables: Technology, user practices, regulation, industrial networks, infrastructure, symbolic meaning of culture. Van den Bergh et al., (2007) identified the following factors: technical, administrative, legal and economic. Some frameworks have a different focus; for instance, Feitelson & Salomon (2004) created a more political-economic model stressing the need for technical, social and political feasibility of an innovation.

A network of nested hierarchy connects these layers. This entails that there are complex connections between the layers. This interaction can be described either bottom-up or top-down (Geels, 2002).

- Bottom-up: innovations are discovered and developed and try to give an alternative to current standards and procedures. The regimes might adopt the innovation and the system changes. This, in turn, could lead to (minor) adjustments of the landscape.
- Top-down: a disturbance of the landscape due to a crisis or increased attention for a topic influences the underlining system. The disturbance changes the behaviour or current standards within regimes. This could open a so-called policy window (Feitelson & Salomon, 2004; Geels, 2002). This is a moment in which the regime could be more perceptive to an innovation. During such a window, multiple innovations compete for attention. The innovations are evaluated based on the set of important factors of that regime.

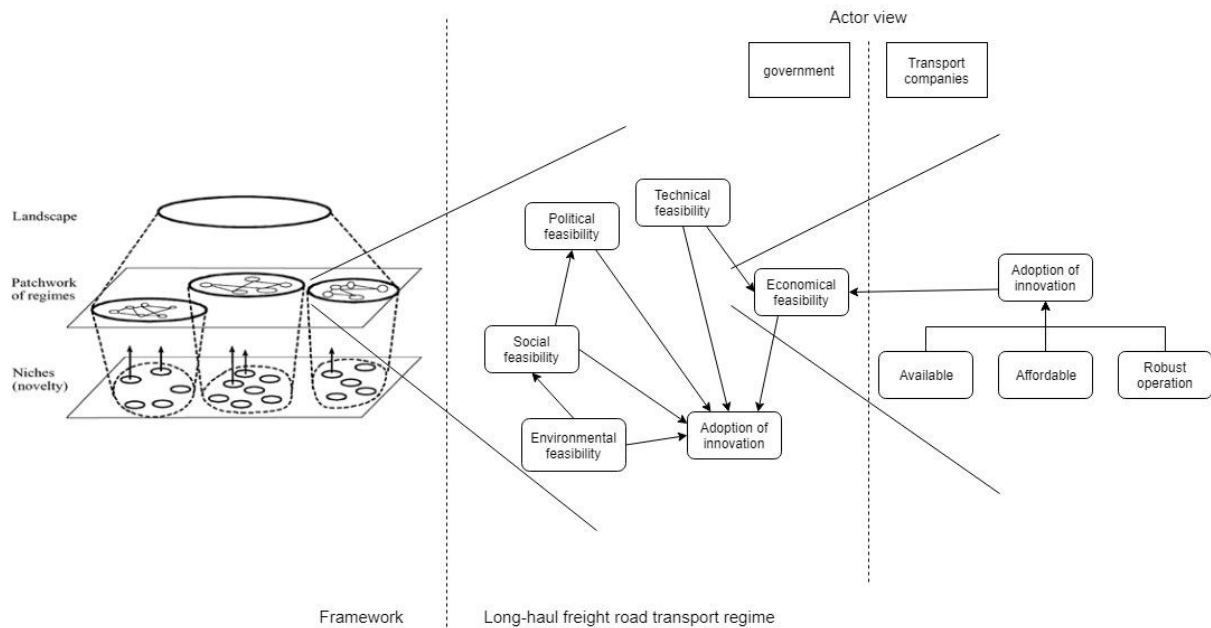


Figure 6 Schematic overview of long-haul freight transport regime with 2 actor views. On the left, the three-layer model from Geels, (2002). In the middle, a schematic overview of long-haul freight transport regime which can be seen as the governmental actor view. On the right, the business actor view with important factors.

2.1.2. Long-haul freight transport regime

The described innovation theory can be applied for the case of a hydrogen truck. In the global landscape, there is increased attention for climate change. This has its effects on the lower level regimes, including the long-haul freight road transport.

In this system, some of the important factors of influence are technical, user practices, economic, infrastructure, regulation and environmental. Due to the increased attention of climate change, there is a need for reduction options like zero-emission trucks. However, alternatives need to compete on the factors mentioned above against the best practice of the moment: a diesel truck.

Some of the important actors in this system are transport companies, vehicle manufacturers (OEM), government and environmental interest groups. The Dutch government signed the Paris climate agreement in which it binds itself and the 'systems' it contains to the reduction of CO₂ emissions (Straver & Zuidervaart, 2017). The government tries to stimulate this with all sorts of instruments and regulation, e.g. OEMs are stimulated to innovate by the government (Rijksoverheid, 2019).

The transport companies are the end-users in this system, the actor that emits the CO₂. This means that it is essential to understand the decision variables of transport companies. In general, transport companies require innovations that are: available, affordable and robust in operation (Logistiek, 2019; TLN, 2017, 2018). This means that ideally a new truck is available at their favourite dealer or OEM for a comparable price and provide similar characteristics in operation, compared to a diesel truck.

As can be seen in Figure 6, there is a clear difference in perception and criteria between the government on the left side and the transport companies on the right side. The government governs the complete system consisting of all factors and actors. The government looks after all the factors; nonetheless, it needs to balance this as the factors are conflicting in some cases. For instance, diesel is economically the best option. Whereas, if the environmental factor is considered, this is not the case. This results in factors like social benefit and overall acceptance. In contrary to transport companies, which approach it from a business perspective and consider their own criteria. These criteria involve more private values like affordability and robustness in operation.

2.1.3. Position of this thesis

This thesis evaluates the techno-economic feasibility of a hydrogen truck from the perspective of the end-user.

This approach is chosen because the end-user is the key stakeholder in the deployment of the truck: it needs to purchase the truck. So, understanding more about this decision-making process is interesting. This means that the right side of the framework is examined. Although the other factors on the left side are essential to consider when looking at the broader innovation adoption, this thesis focuses only on the end-user and its evaluation of the innovation.

From a technical point of view, the hydrogen truck and refuelling infrastructure are still in the testing phase. The performance of the truck and refuelling infrastructure needs to improve to provide a robust operation (Bouwman, 2019). From an economic point of view, hydrogen trucks are still very costly. The literature indicates that currently, the price of a hydrogen truck is roughly 3 to 4 times higher than a diesel truck (Fulton & Miller, 2015; Hunter & Penev, 2019; Kleiner & Friedrich, 2017; Moultaq, Lutsey, & Hall, 2017). This is understandable as it is a new application that is not produced at a large scale. Looking at these points, it is clear that on both technical and economic point hydrogen truck, as well as hydrogen as an energy carrier, need to develop to be able to compete with a diesel truck.

The techno-economic feasibility is evaluated using the following criteria: availability, affordability and robustness in operation. These criteria are operationalised using measurable variables. When operationalising these three criteria, a distinction can be made. Affordability can be measured using, a Total Cost of Ownership (TCO) analysis. Availability and robustness in operation are difficult to operationalise. For instance, defining to what extent something is available is complex. In order to understand what these criteria represent, a list of requirements is formulated, see Table 2. The list of requirements is established based on own insight after having performed the literature reviews.

For this reason, it was chosen to focus on the affordability of a hydrogen truck. Availability and robustness in operation were considered important boundary conditions which are preconditional. The key criteria for purchase and use are however the cost-effectiveness.

Chapter 3 discusses the TCO framework that is used in this thesis.

Table 2 Overview of boundary requirements split into two categories, availability and robustness in operation

Requirement	Definition
Availability	
There should be abundant hydrogen available.	There should be enough hydrogen to fulfil the demand for hydrogen of all sectors. Moreover, the production of hydrogen should be large enough, so economy of scale effects can occur.
Renewable energy should be used to produce hydrogen	During the production of hydrogen, there should not be any CO ₂ emitted (netto).
There should be a network of hydrogen distribution	There should be a network in place that could fulfil the demand of the HRS.
There should be enough throughput of hydrogen to facilitate the demand for hydrogen by the transport sector	There should be an efficient method to distribute hydrogen.
There should be an HRS network	Along the major highways (Trans-European Transport Network (Ten-T) freight road network) there should be sufficient HRS that could refuel trucks with high speed.
The HRS should refuel trucks in a comparable time as diesel fast fuelling stations.	Diesel refuelling time between 5-10 minutes. Similar refuelling times.
There should be a hydrogen truck available at truck OEMs.	Hydrogen trucks are produced at such a scale that economies of scale occur.
Robustness in operation	
The hydrogen tank should be large enough to contain enough hydrogen to drive from one break to the next.	Truck drivers must take a break after 3 hours of driving. The fuel tank should be large enough to be able to drive until the next mandatory break.
There should be a sufficient covering network of HRS	This entails that trucks should not have to make a detour to reach a hydrogen fuelling station.

2.2. Methodology

This section discusses the methodology used to fill in the unknown factors of the TCO analysis. The literature review is used to gather the information that is available in the literature (2.2.1). However, literature could be out-dated. To verify, validate and update this information, semi-structured interviews are performed. This method is described in Section 2.2.2. Section 2.2.3 describes the TCO method. Table 3 describes which method is used to answer the sub-questions.

Table 3: Research question and sub-questions and methods used to answer

	Question	Methods
SQ1:	What is the current cost of hydrogen and how will this develop in the future?	Literature review, expert interview
SQ2:	What is the current cost of a hydrogen truck and how will this develop in the future?	Literature review, expert interview
SQ3:	What is the most cost-effective route compared to reference diesel?	TCO analysis, expert interview and SQ2 and SQ3

2.2.1. Literature review

A literature review is a useful method to get a good understanding of the current literature. Sekaran & Bougie (2010) describe that a literature review is a beneficial method as it ensures you to find all relevant factors. This is useful as it helps to identify and explore the methods, techniques and developments of the supply chain of hydrogen and the components of the truck.

However, a drawback of this method is that one can only find information about topics that have been researched before. As the application of hydrogen in freight road transport has not been researched that much, it is difficult to gather information. To overcome this limitation, the literature review is supported by empirical data from semi-structured interviews. This is described in the next section.

The literature review method is used in answering 2 sub-questions. For each of the sub-questions, a different search plan is used, see Table 4. The search words, leading parties and journals on a topic are identified based on an initial literature study, see appendix A.

The literature study is conducted according to the following process. One starts with an initial search with the keywords on Google scholar. After an initial search, more advanced queries are created, and other databases like Scopus and IEEE are used. By snowballing, both forwards and backwards, the literature is gathered.

Table 4: Search plan for literature review

Question	Partial elements of the question	Leading journals/ parties	Search words
SQ1: What is the current cost of hydrogen and how will this develop in the future?	production	FCH JU, International Journal of Hydrogen Energy	Hydrogen production, methods to produce hydrogen, sustainable energy production, electrolysis
	Distribution	FCH JU, Transportation Research Part D: Transport and Environment	transportation of hydrogen, hydrogen supply chain, hydrogen distribution, gaseous vs liquid hydrogen
	Refuelling	SAE	Alternative fuel infrastructure Directive (AFID), TEN-T, European infrastructure coverage, Transport of hydrogen, refuelling infrastructure, hydrogen refuelling speed,
SQ2: What is the current cost of a hydrogen truck and how will this develop in the future?		FCH JU, Journal of Power Sources, Nikola, Toyota	FCEV development, hydrogen combustion, hydrogen fuel tank capacity, Range extension vs full FCEV, TCO hydrogen truck, maintenance cost, economic lifetime, technological lifetime,

2.2.2. Semi-structured interview

Semi-structured interviews are used to verify and validate the literature review results used to answer SQ1 and SQ2. With the help of expert interviews, the literature review results are discussed and evaluated more in-depth. This method is suitable as new technology is uncertain and expert in the field can give their opinion and vision about how this might develop in the future (Goluchowicz & Blind, 2011).

The interviews are semi-structured based on the questions formulated from the literature review results. The semi-structured interview guides the conversation, this is done to focus the interview on the important topics. Although, general comments were also encouraged.

The literature review results and questions are presented in an information package, see appendix D. The information package consists of five themes with results, interpretation of the literature results, identification of possible trends and questions. The questions are created based on the first three points. As mentioned before, the purpose of the interviews is to verify and validate the literature results; that is why the line of questioning focused on that — for instance, the questions aimed to verify the extent of a development and the expected future value. Appendix D gives the full information package.

The interview process consists of the following steps

- Experts are approached via e-mail for the interview. A general description of the thesis is given, and the specific area of their expertise is highlighted.
- In preparation of the interviews, the information package is sent that allows them to prepare and see the literature results.
- Most of the interviews are performed face-to-face, 8 out of 11. The other three interviews are performed over the phone. On average, the interviews took approximately 1 hour.
- After the interviews, an interview report is created and sent for verification to the interviewees before the information is used. Interview reports can be seen in appendix E.

Given that the interviews are already structured, it is not needed to code or label the information before using it. The interview package consists of 6 categories which clearly align with topics in chapter 4 and 5. Besides that, the questions are created to verify and validate the information of the literature reviews. This provides sufficient assistance to implement the comments without the need for labelling.

The selected experts cover all components or topics of the TCO framework (see Figure 9) and represent different actor views on the topic, this creates a clear and balanced view of a topic. Table 5 shows that each of the topics is covered by at least four experts. To prevent getting a biased and/or one-sided opinion, a two-step verification is used for projections of price developments. This entails that a price needs to be mentioned by at least two independent sources/experts before this is included or deemed valid. Hence, the results of experts on the same topic are compared and referred to separately. As explained in the theory, there are several actors that influence the freight road transport segment. To get insight into the importance of factors and knowledge of different actors, the interviewed experts consist of researchers, civil servants, truck manufacturers and internal employees of TNO, see Table 6. In conclusion, the 10 interviews cover all the topics with a minimum of 4 experts per topic, moreover, the experts represent different actor groups within the freight road transport regime. The next paragraph further explains the role of the experts and their expertise on hydrogen.

Table 5 Experts and topics

	Production	Distribution	Refuelling	Fuel-cell system	Hydrogen tank	Routes
Bilim Atli-Veltin		x	x		x	
Cemil Bekdemir				x	x	
Ruud Bouwman			x	x	x	
Robert van den Hoed	x	x	x			x
Karin van Kranenburg	x	x	x			
Dirk Schaap	x	x				x
Ruud Verbeek	x	x				x
Marcel Weeda	x	x	x			x
Ad van Wijk	x	x	x	x	x	x
Steven Wilkins				x	x	

Robert van den Hoed and Ad van Wijk are both professors on the topic of hydrogen at Hogeschool van Amsterdam (HvA) and Delft University of technology respectively. Dirk Schaap is a policy advisor of the Ministry of Infrastructure and Water management and responsible for the topic of hydrogen in transport. Ruud Bouwman is part of the strategy unit of VDL Enabling Transport Solutions (ETS). He is responsible for assessing innovative transport solutions at VDL.

Within TNO, there is a lot of knowledge available. Marcel Weeda works at ECN part of TNO in the department of Energy transition studies. He has extensive knowledge of the hydrogen supply chain. Steven Wilkins and Cemil Bekdemir work at TNO Powertrain. This department looks into vehicle and powertrain technology. Bilim Atli-Veltin works at TNO structure dynamics. This department looks into material dynamics and safety of storage techniques. Karin van Kranenburg works at the Strategy Business Analysis (SBA) department of TNO. This department looks at the business case of innovations like hydrogen. Ruud Verbeek of TNO Sustainable Transport & Logistics works among others on research about alternative energy carriers.

Table 6 List of interviewed experts, affiliation and knowledge domain

	Affiliation	Knowledge domain
Bilim Atli-Veltin	TNO structure dynamics	Storage techniques for hydrogen.
Cemil Bekdemir	TNO Powertrains	Development of fuel-cell technology and VDL truck
Ruud Bouwman	VDL	Production of hydrogen truck 27 ton and 40 ton
Robert van den Hoed	HvA	Professor Energy in transition. Production, distribution and refuelling of hydrogen
Karin van Kranenburg	TNO SBA	Business case of hydrogen production methods and distribution
Dirk Schaap	Ministry I&M	Policy instruments to stimulate hydrogen and zero-emission policy
Ruud Verbeek	TNO STL	Production, distribution, refuelling of hydrogen and vehicle technology.
Marcel Weeda	ECN part of TNO	Knowledge of production, distribution and refuelling of hydrogen.
Ad van wijk	TU Delft	Professor future energy systems. Production, distribution and refuelling of hydrogen
Steven Wilkins	TNO Powertrains	Expert on fuel-cell technology and vehicle technology

2.2.3. Total cost of ownership (TCO)

This thesis performs a techno-economic assessment of the hydrogen truck. The TCO analysis is chosen to structure this analysis. This section describes what a TCO analysis entails and why this method is chosen.

The TCO analysis incorporates all the costs that are needed for operation. According to Wadud, (2017): *“TCO analysis is the vehicular counterpart of life cycle cost analysis, which is well known in business procurement and project appraisal. The technique is primarily used to compare the relative economic advantages of different competing vehicle technologies.”*. Ellram, (1995) describes the TCO analysis as a dollar-based analysis that analysis the cost associated with a decision and all the cost it brings along. This makes it a typical instrument for the transport sector as it is a highly competitive sector, according to Rico Luman sector specialist transport and logistics at ING (Weerd, 2017).

However, one could argue that another evaluation method should be used. Roosen, Marneffe, & Vereeck, (2015), performed a literature review on evaluation methods based on vehicles cost. This resulted in four categories of evaluation methods: The life cycle analysis (LCA), Well-to-Wheel (WTW), Total cost of ownership (TCO), Cost-benefit analysis (CBA). In short, the LCA considers private and external costs, whereas the WTW analysis is limited to external costs. The TCO analysis focuses on private costs, and the CBA calculates the public cost. However, the difference between the methods is not clear as the methods are often substituted in the literature (Roosen et al., 2015). As described in section 2.1.3, this thesis approaches this problem from the perspective of transport companies. This means that the TCO method is suitable as it focuses on the private cost. Within a TCO analysis, one could define the following cost categories. The capital expenditure (CAPEX), i.e. the investment cost and the operational expenditure (OPEX), which includes both fixed cost like maintenance cost and variable cost like fuel cost, see Figure 7 (Bubeck, Tomaschek, & Fahl, 2016). Chapter 3 discusses the TCO framework in detail for among others the hydrogen truck.

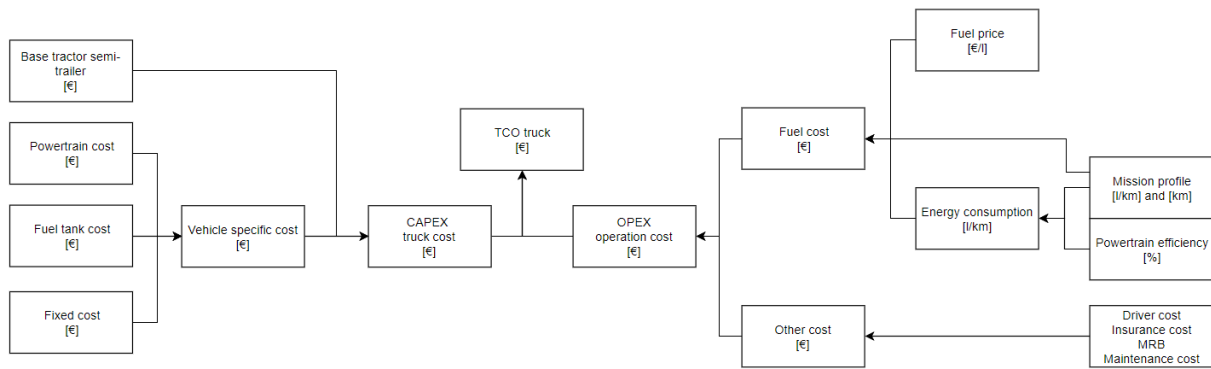


Figure 7 Generic TCO framework

3. Evaluation framework

Chapter 2 discussed that in this thesis, a techno-economic assessment is performed using the TCO method. A generic TCO framework was presented. This chapter discusses the evaluation framework that is used to compare a hydrogen truck with a diesel truck.

Section 3.1 starts with the TCO framework for the diesel reference truck. Section 3.2 discusses the TCO framework for the hydrogen truck. In this thesis, the trucks are compared based on the cost of operating a Long-haul mission profile, this describes, among others, the daily mileage and the number of stops (3.3). Based on the TCO framework and the mission profile, the model setup is given in section 3.4. This provides the generic components that are similar in both TCO frameworks. As a lot is known already about the components of the diesel truck TCO, section 3.5 calculates the TCO of the diesel reference truck. In contrary to the components of the hydrogen truck, which are less known. These are discussed in chapter 4 and 5 after which chapter 6 calculates the TCO of the hydrogen truck.

3.1. TCO framework diesel truck

The TCO framework consists of CAPEX and OPEX. The framework for the diesel truck (Figure 8) is straightforward. Diesel trucks have been developed and sold for years already, so all the information is available, therefore, the diesel truck is only divided into three components besides the tractor: combustion engine, fuel tank and diesel fixed cost. On the right side, the fuel cost is composed of the diesel price and diesel energy consumption. This framework is filled in in section 3.5.

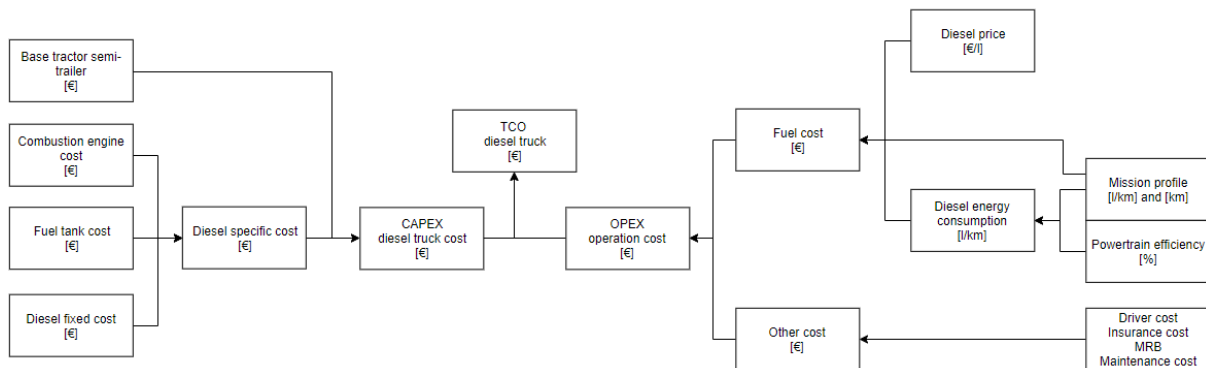


Figure 8 TCO framework of diesel truck

3.2. TCO framework hydrogen truck

Several factors influence the TCO of a hydrogen truck. This section discusses the components of this model. Firstly, the left side of the framework is discussed, the CAPEX cost. After that, the OPEX on the right side is discussed. Figure 9 displays the TCO framework for the hydrogen truck.

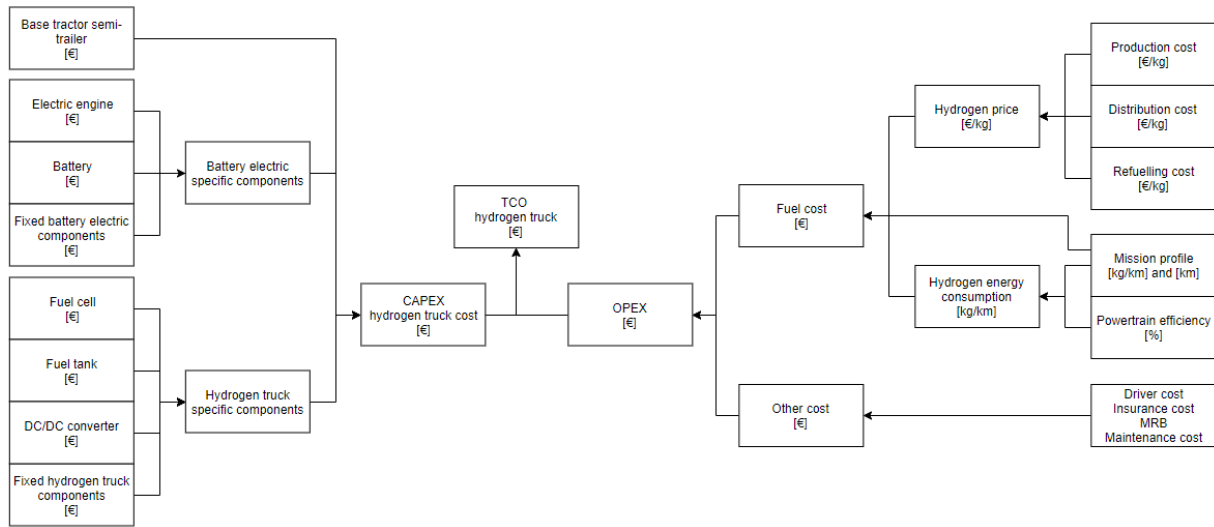


Figure 9 TCO framework hydrogen truck

The CAPEX model consists of the truck cost. As mentioned before, currently there are no hydrogen trucks commercially available, this makes it difficult to estimate the price for such a truck. To estimate the price and the development, a modular build-up is used. Figure 10 shows the most important components of a hydrogen truck. Three categories of components can be identified. Firstly, the stripped tractor is taken; this is a tractor without any powertrain system, which is used to assemble the hydrogen truck. The second category consists of hydrogen truck components, this consists of the fuel-cell system, the fuel tank and the DC/DC converter. The third category consists of electric vehicle components; this consists of the battery, the inverter and electromotor (EM). The explanation of each of the components and the cost development can be found in Chapter 5.

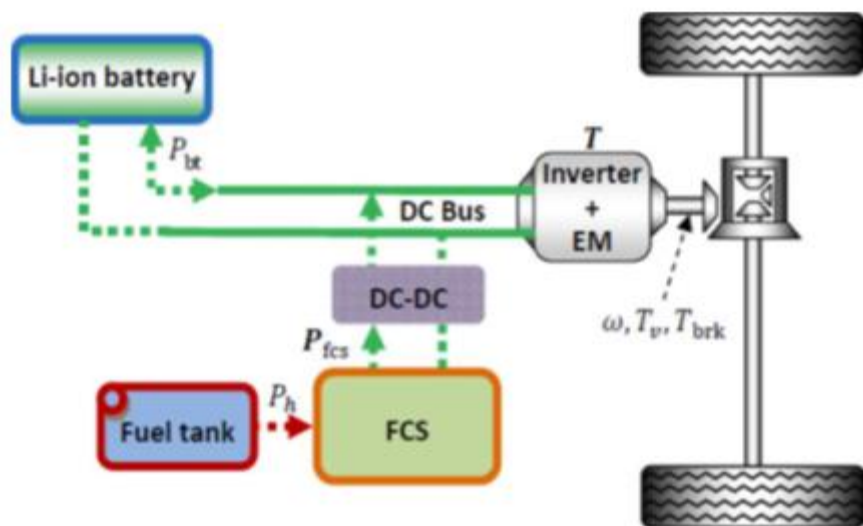


Figure 10 Hydrogen fuel-cell truck propulsion system (Koffrie & Hommen, 2017)

The OPEX model consists of fuel cost and other costs. The fuel cost is built-up of the hydrogen price, the hydrogen energy consumption and the mileage. Figure 9 shows that the hydrogen price is built-up of the production cost, distribution cost and the refuelling cost. However, as can be seen in Figure 11, the hydrogen supply chain contains more elements than those mentioned above. For instance, the

storage of hydrogen in between the steps of the supply chain. This thesis does not consider these factors, so it is assumed that the hydrogen is immediately distributed upon production. The Hydrogen fuel cost is discussed in chapter 4.

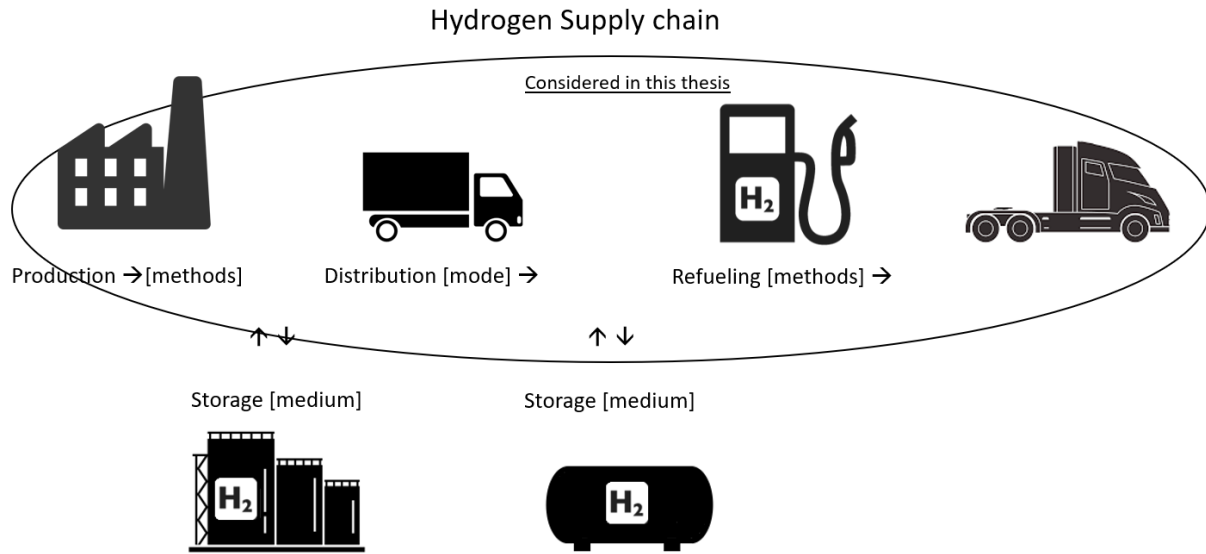


Figure 11 Hydrogen supply chain

The hydrogen energy consumption is based on the energy consumption at the wheels and the powertrain efficiency of the hydrogen truck. The energy consumption is calculated using the dynamic vehicle model. This is a model that has been created by TNO (Van Zyl, Heijne, & Ligterink, 2017) that calculates the energy consumption of a vehicle driving a particular mission profile. Section 3.3 discusses the mission profile. The powertrain efficiency is discussed in 5.2.1.1.

The other costs consist of the driver cost, maintenance cost and additional time at the refuelling station. The additional time at the refuelling station influences the driver cost. This variable is defined as a multiplier of the total daily operation time. The multiplier indicates the per cent of the time that is additionally needed compared to the daily operation time of diesel. Currently, the refuelling speed of hydrogen is relatively low as there is no high-speed refuelling station in the Netherlands. This means that the refuelling time takes considerably longer than diesel.

From this section, it has become clear that this research requires a lot of information about the components of the TCO framework. Information about the cost of the components and how this develops in the future. This is discussed in the next chapters. To accommodate the uncertainty of the cost in the future, this thesis considers both a modest improvement and a strong improvement scenario each of the components of the hydrogen truck.

3.3. Mission profile

A mission profile consists of one or more routes, which can consist of multiple stops, on which a truck operates. Each route has some characteristics in terms of velocity, tonnage and slope (Huisman, 2018). To compare the cost of two different trucks, it is essential to look at the required performance. There is a clear difference between a regional distribution and a long-distance distribution route. This is defined by the mission profile.

This thesis uses the mission profile as represented in Figure 12. This profile consists of only one route with one stop at the end of the day. The daily mileage is 500 kilometres, divided into 2 parts of 250 km. Due to labour laws that require mandatory resting time every 4.5 hours, there is a 45 minutes break (TLN, 2014). Given the different road types and associated speed limits, the average speed is approximately 70 km/h. The mission profile is created for a tractor semi-trailer combination that carries 25 ton of freight. If the slope of the road increases, more energy it requires to move the truck.

This thesis assumes that there is no slope in the road. The green bar on the right side of the graph indicates that the truck refuels entirely at the end of each shift. This mission profile is repeated every day for 250 days a year.

The mission profile is used to calculate the average energy consumption per kilometre given the route, tonnage, road type and type of vehicle. The energy consumption is one of the components to determine the diesel or hydrogen fuel cost.

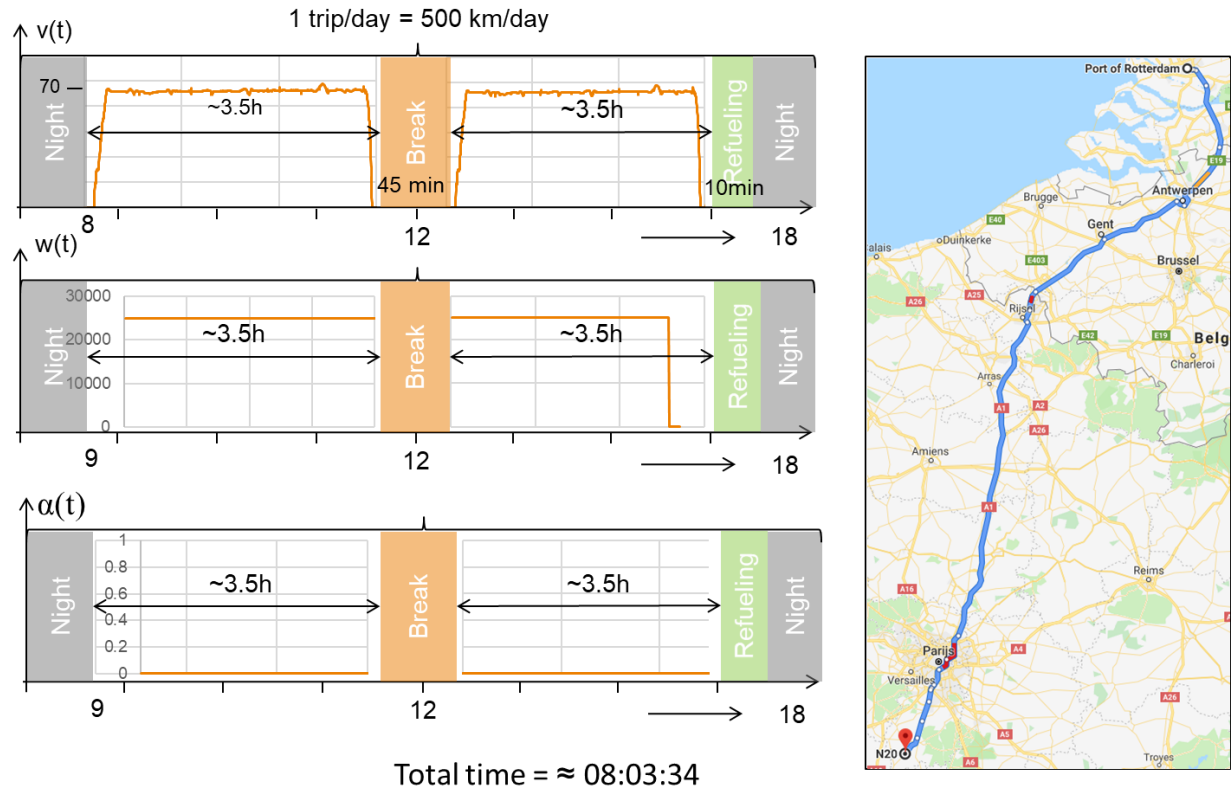


Figure 12 Mission profile Diesel truck, speed profile, tonnage profile and slope profile. 1 trip of 500 kilometres driven in two periods of 3.5 hours

3.4. Model setup

This section discusses the general assumptions that are used to calculate the TCO (see Table 7). The period of operation is set on 6 years, with a yearly mileage of 125,000 km (500 km/day multiplied by 250 days/year). This would mean that the truck drives around 750,000 km in 6 years. This influences the residual value of the truck, this is the resale value of the truck after usage of 6 years. Considering that the lifetime of a truck which is approximately 1 to 1.5 million kilometres (Bouwman, 2019; Wilkins, 2019).

The TCO is measured in €/km, which means that all the cost components are divided by the mileage per year. The CAPEX cost consists of a one-time investment. This is considered by depreciating the truck cost. Given a lifetime of 6 years, a purchase price, a residual value and an interest rate of 6% (TNO, 2019), the depreciation cost per year can be calculated. The total investment cost is calculated by subtracting the residual value from the purchase value. By using the 'PMT'-formula in excel, the constant periodic cost can be calculated to pay-off an investment, given an interest rate and period ("The Excel PMT Function," 2019).

The maintenance cost for both the hydrogen and the diesel truck is assumed to be €10,000 per year. This is assumed to be fixed and independent from the mileage. Although the hydrogen truck has less "moving parts", which require more maintenance, the price of the hydrogen components is higher. Moreover, other issues like poisoning of the fuel cell arise with a hydrogen truck. So, that is why the

same value for maintenance cost is selected (Bekdemir, 2019). The driver's salary is assumed to be €60,000 per year.

Table 7 Overview of fixed variables

	Unit	Value
Years of operation	years	6
Interest rate	%	6
Maintenance cost	€	10,000
Driver salary	€/year	60,000
Initial refuelling time	Minutes	5

3.5. TCO Diesel reference

Until now, this chapter discussed the TCO framework, the mission profile and the general assumptions. This section calculates the TCO of the reference diesel truck. First, the CAPEX is discussed, after that the OPEX. This section finishes with the calculation of the TCO and possible developments.

Table 8 Specifications of diesel truck

	Unit	Current	Future	
			Modest	Strong
Size of internal combust engine (ICE)	KW	310	310	310
Size of fuel tank	L	1,000	1,000	1,000

The CAPEX cost is calculated using the modular build-up, as described in section 3.1. The diesel trucks are also fully developed and limited improvement is expected here (TNO, 2019). The reference alternative is a new euro 6 diesel truck. Table 8 shows the technical characteristics of the diesel truck. Together with the cost of the components in Table 9, the CAPEX is calculated in Table 10. The cost of the components is derived from the literature (Fulton & Miller, 2015; Kleiner & Friedrich, 2017; Moultaq et al., 2017). The residual value of the diesel truck is approximately €30,000. The cost of the diesel truck is expected to remain the same since it is already fully developed.

Table 9 Cost of the components

	Unit	Current	Future	
			Modest	Strong
Tractor	€	135,000	135,000	135,000
ICE engine	€/kW	65	65	65
Fuel tank	€/L	2	2	2

Table 10 CAPEX cost diesel truck

	Unit	Current	Future	
			Modest	Strong
Tractor	€	135,000	135,000	135,000
ICE engine	€	20,150	20,150	20,150
Fuel tank	€	2,000	2,000	2,000
Fixed ICE vehicle cost	€	50	50	50
Total cost diesel truck	€	157,200	157,200	157,200

The OPEX cost consists of fuel cost and other costs. As described in the TCO framework, the fuel cost is calculated by multiplying the diesel price, the diesel energy consumption and the yearly mileage. The diesel powertrain efficiency consists of two components: the brake thermal efficiency and auxiliary systems. The brake thermal efficiency is approximately 43%, due to the auxiliary system efficiency, the powertrain efficiency is approximately 31%. The diesel price is set to be approximately 1 euro per litre (CBS, 2019b). The diesel energy consumption is calculated using the dynamic vehicle model; Table 11 shows the results. The other cost is all described in section 3.4 model setup.

Table 11 Output of dynamic vehicle model based on the selected mission profile

	Unit	/km	/total	Comment
Kilometres	km	1	500	Mission profile
Wheel power demand	kWh	1.12	560	Dynamic vehicle model output
Diesel Fuel	kWh	3.63	1.815	Diesel powertrain efficiency of 30.8% (TNO)
Diesel fuel	L	0.363	181.50	Energy density diesel: 10 kWh/L

All components are defined, so the TCO can be calculated. The first bar off Figure 13 shows the TCO of the diesel truck is €1.130 per km. The TCO consists of approximately 50% other costs, of which the driver salary is the most significant component.

In the future, the TCO might change. Uncertain factors are the diesel powertrain efficiency and the diesel price. The diesel powertrain efficiency increases to 40% due to the brake thermal efficiency increase from 43% to 50% (Delgado & Lutsey, 2014). Due to CO₂ emission regulation, the diesel price could increase towards €1.30 per L. Table 12 shows two scenarios in and the effect of it on the TCO price of diesel. These scenarios can also be seen in Figure 13 (next page), the second and third bar. While discussing the development of the TCO of the hydrogen truck, the scenarios mentioned in Table 12 act as possible bandwidth for the diesel reference truck.

Table 12 Scenarios diesel reference

	Current	Future	Effect on TCO diesel
Diesel powertrain efficiency	31%	40%	- €0.083
Diesel price	€1.00	€1.30	+€0.109

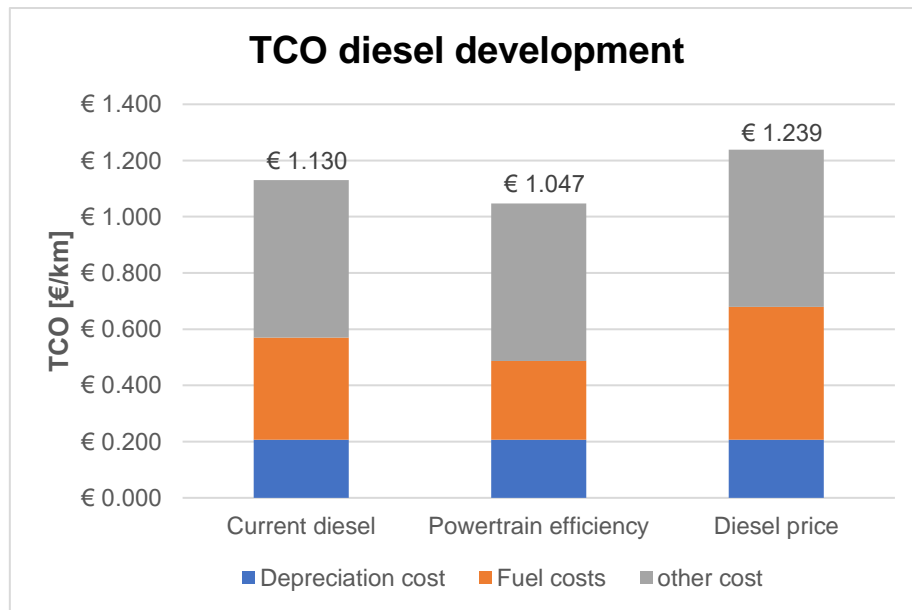


Figure 13 TCO diesel current and possible scenarios

3.6. Conclusion

This chapter provided the evaluation framework that is used to analyse the TCO of the hydrogen truck and the diesel truck. The TCO of the diesel truck is already known and calculated. In contrary to the hydrogen truck that requires more explanation, this is done in chapter 4 and 5. Chapter 6 calculates the TCO of the hydrogen truck and compares this with that of the diesel.

4. Hydrogen fuel price

The previous chapter discussed the TCO framework of a hydrogen truck. This chapter looks into how the hydrogen fuel price is built-up. The analysis is done in two steps. Firstly, section 4.1 analyses the cost of each of the steps of the supply chain. Secondly, section 4.2 combines the steps of the supply chain into so-called 'hydrogen supply routes' (after this called 'routes').

4.1. Supply chain analysis

To determine the hydrogen price, each part of the supply chain needs to be analysed, see Figure 11. Before hydrogen can be refuelled at a refuelling station, it first needs to be produced and distributed to the refuelling station. For each of these steps, all sorts of methods can be used. The hydrogen fuel price differs depending on the chosen method. This section examines the methods and developments of these steps and the impact on the fuel price. Section 4.1.1 discusses the production cost, section 4.1.2 discusses the distribution cost and section 4.1.3 discusses the refuelling cost.

For each of the steps, the cost is given. At the end of each section, two values of costs are selected for possible development in modest and strong improvement situation.

4.1.1. Production cost

This section researches the production cost of hydrogen. This is the first step in the supply chain. Hydrogen can be produced with all sorts of materials using all sorts of methods, each with different characteristics and cost. Therefore, it is important to look into the production methods before the production cost can be determined. The hydrogen production methods are explained in section 4.1.1.1. If the production efficiency is higher, the amount of feedstock required is lower and with this the production cost, that is why the production efficiency is discussed in section 4.1.1.2. Ergo, the production cost is discussed in 4.1.1.3. The last section provides a conclusion of the production cost in 4.1.1.4. An overview of the literature that is used in this chapter can be found in Appendix A

4.1.1.1. Hydrogen production methods

Hydrogen can be produced using all sorts of methods and energy sources. Table 13 categorises the production methods into production processes, methods and feedstocks. This thesis describes the general production methods, the exact technology that is used or the combination of pressure and temperature that determines the efficiency and output are not considered.

Table 13 Overview of hydrogen production methods

Process	Method	Feedstock
Reforming	SMR	Natural gas
	SMR + CCS	Natural gas
Gasification	Coal	Coal
	Coal + CCS	coal
	Biomass	Biomass
Electrolysis	Central electrolysis	Water
	Local electrolysis	Water
	Import electrolysis	Water
	Wind and sun electrolysis	Water
	High temperature electrolysis	water

Reforming

Steam Methane Reforming (SMR) is the most used hydrogen production method. In this process, natural gas is split into CO and H₂ under high temperature and pressure (Holstein, Gerwen, Douma,

Delft, & Saric, 2018). During this process, so-called grey hydrogen is produced. This means that during the production of hydrogen, GHG emissions are emitted.

The GHG can be captured using carbon capture storage (CCS). This process would produce blue hydrogen. The CO₂ is often stored in old natural gas fields. However, CCS technology lowers the system efficiencies while increasing the costs (Acar & Dincer, 2015; Gigler & Weeda, 2018).

Gasification

The second category consists of gasification methods. Coal gasification is also a fossil fuel method that emits GHG. This method consists of a series of steps. In the first step, the coal is gasified in controlled circumstances with O₂ and H₂O, this is so-called partial oxidation. During the process H₂, CO and CO₂ are created. The mixture of products is separated, and by-products are extracted from the process. In several steps, the hydrogen production is optimised. After that, the hydrogen is purified and can be transported (Stiegel & Ramezan, 2006). Like the reforming methods, it is also possible to use CCS technology in combination with coal. This would reduce CO₂ emissions.

Another form of gasification uses biomass as feedstock. This process is similar to that of coal gasification. The feedstock that is used is mostly corn, palm oil, sugar cane or residual frying fat. Depending on the type of feedstock, the CO₂ emission could be close zero. During the production of biomass feedstock, CO₂ is captured, this is emitted during the gasification. So, on balance, there is only minimal CO₂ emission (Verbeek, Van Zyl, Van Grindsven, & Van Essen, 2014).

Electrolysis

In general, electrolysis consists of putting electricity through water, during this process water splits into hydrogen and oxygen. Two low-temperature electrolyser techniques are commonly used, the alkaline and the proton exchange membrane (PEM) technique. In this thesis, no distinction is made between hydrogen electrolysis production techniques. As can be seen in Table 13, there are different electrolysis methods available: central, local, import, wind & sun and high temperature.

Central electrolysis, local electrolysis and import electrolysis are similar in terms of method. Central electrolysis consists of large-scale hydrogen production, this benefits from economies of scale effects in terms of cost and efficiency. Local electrolysis produces hydrogen on a smaller scale. Although it might not be as efficient as central electrolysis, it could have advantages when it comes to the distribution of hydrogen. Import electrolysis consists of producing hydrogen in another country that has a lower electricity price. This is important as the electricity price accounts for 70% of the production cost. This would result in a lower production cost. However, the transportation cost to import the hydrogen might be very high (van Wijk, 2019; Weeda, 2019). More about this in 4.1.1.3.

Wind and sun electrolysis use solar and wind to generate energy that is used to convert water into hydrogen. This means that this method takes an additional step before electrolysis is used. New technology is being developed that allows for direct conversion of water into hydrogen using wind or solar energy (van Wijk, 2019).

High-temperature electrolysis uses thermal energy and electricity to produce hydrogen. This is done with using high-temperature electrolysers, mostly solid oxide or Molten Carbonate electrolyser are used (Stetson, 2019; Wikipedia, 2019)

The electrolysis process is, in theory, the same as in a fuel-cell, however, in a fuel-cell, hydrogen and oxygen react and energy and water are released. So, this is the reversed reaction in which energy is released. In the fuel-cell section, 8.1.2, the PEM and alkaline techniques are also mentioned. In that case, it is a mobile application instead of the stationary application, which is the case in this section.

4.1.1.2. The efficiency of hydrogen production

The previous section described the production methods. This section describes the production efficiency of these methods. If the production efficiency is higher, the amount of feedstock required is lower and with this the production cost and TCO. As mentioned before, the exact configuration of the methods in terms of pressure and temperature is not considered. That is why the general range of production efficiencies is given.

In this section, the efficiency of the production method is described by dividing the useful energy divided by the total energy input. The Lower heating value (LHV) is used to calculate the production efficiency. The lower heating value of hydrogen is 120 MJ/kg (Waterstofnet, 2010). So, an efficiency of 50% entails that 240 MJ energy is needed to produce 1 kg hydrogen.

Figure 14 shows the efficiency of the production methods. In general, the bandwidth of the efficiency is relatively large for all production methods. This uncertainty is caused by the configuration and size of the production facilities. The fact that fossil fuel methods have a larger bandwidth than the electrolysis options could be explained by the larger amount of references for fossil fuel applications. Each of the feedstock categories as identified in the previous section is discussed. The literature used to construct the figure can be found in appendix A1.

The first category consists of SMR and SMR+CCS. The median of the production efficiency of these methods is approximately 65-75% (Acar & Dincer, 2015; Alazemi & Andrews, 2015). The SMR+CCS method has a slightly lower efficiency, which is in line with Gigler & Weeda, (2018) who mention that the CCS technique lowers the efficiency with around 4 to 7 per cent point.

The coal and coal+CCS methods have similar characteristics as the SMR options. The median of the efficiencies ranges from 60-70% (Alazemi & Andrews, 2015; Stiegel & Ramezan, 2006). Compared to the SMR method, the coal method has a smaller bandwidth than that of the SMR. The coal + CCS shows a similar decrease in efficiency as the SMR+CCS (Stiegel & Ramezan, 2006).

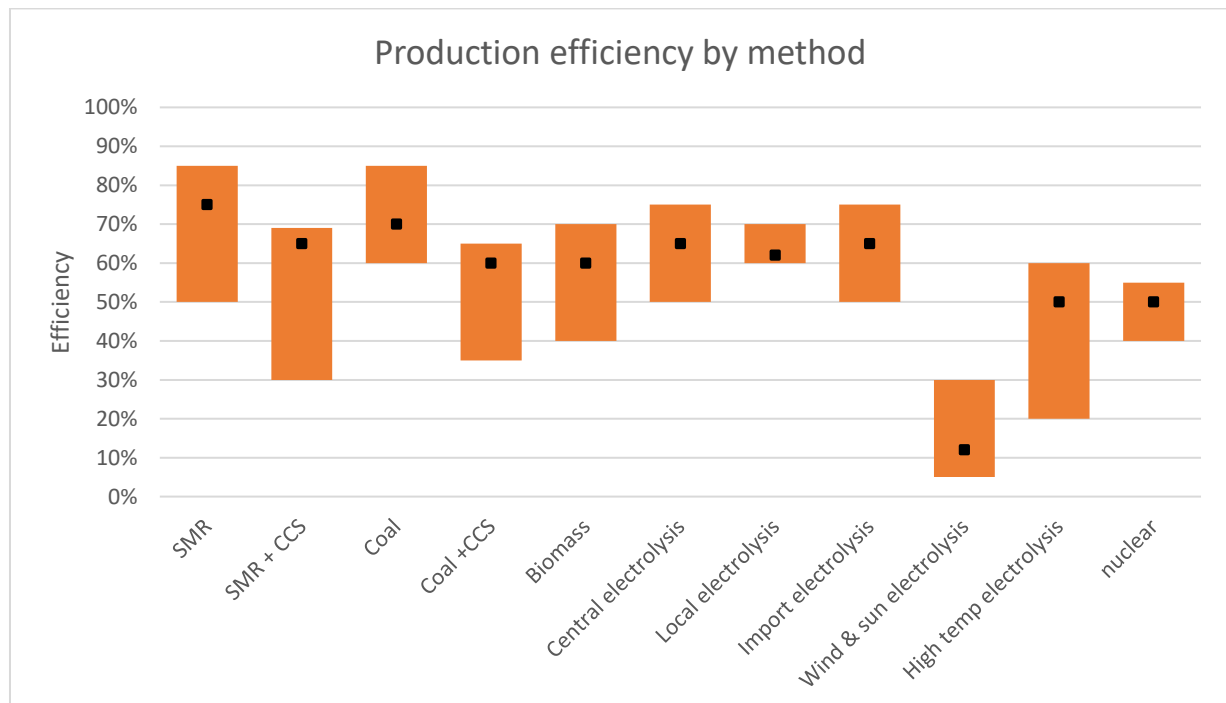


Figure 14 Production efficiency by method, the dots in the figure indicate the median

Biomass gasification uses similar technology as the Coal method hence the similar median of 60%. However, the technology is not as mature as the coal methods, hence the efficiency bandwidth.

The efficiency of the electrolysis methods differs strongly, as can be seen in the last 5 bars of Figure 14. The central, local and import electrolysis options have similar efficiencies of 65 to 70% (Adolf et al., 2017; Dincer, 2012; Holstein et al., 2018). The production scale causes the difference between the options. The wind and solar electrolysis method have lower efficiency in line with solar panel and windmill efficiencies (10-20%) (Alazemi & Andrews, 2015; Dincer, 2012; Verbeek, 2019). This is an additional step beside the electrolysis process. The efficiency of high-temperature electrolysis greatly depends on the configuration of the plant, hence the relatively large bandwidth.

From this section, it can be concluded that the production efficiency of fossil fuel methods (SMR and coal) is high, up to 75%. The central, local and import electrolysis methods are approaching this efficiency with currently around 65%. Biomass gasification reaches an efficiency of 50%.

4.1.1.3. Cost of hydrogen production

The previous section described the characteristics of the production methods. This section describes the cost of the production methods that are found in the literature. However, according to Ad van Wijk, this might not be the best way to find the prices: *“Given the fact that it is a fast-changing and developing technology, literature is often rather conservative”* (van Wijk, 2019). Figure 15 confirms this statement as it shows larger bandwidths for less developed production methods. Given this argument, the results of the literature review are discussed with experts that could verify the current development.

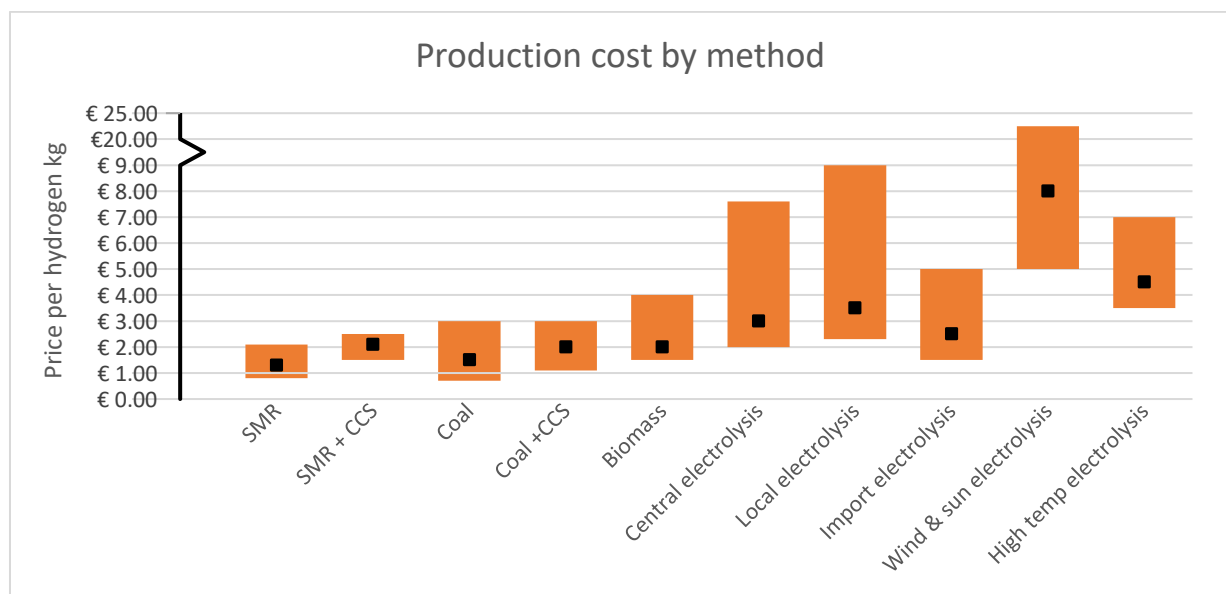


Figure 15 Production cost by method, the dots in the figure indicate the median

Note: The y-axis is broken at the top, the dots in the figure are the most common found values in literature and the bar describes the bandwidth.

Figure 15 describes the cost of production methods. As can be seen, the cost of the SMR methods ranges from €1.50 to €2.50 per kg. The SMR method is already fully developed and economy of scale effects caused the prices to drop. This is also seen from the relatively small bandwidth. The SMR+CCS method has a slightly higher price as this requires extra steps to capture the CO₂. The price of SMR is expected to increase slightly, as the prices of fossil fuels are expected to increase due to scarcity and increasing CO₂-emission cost (Holstein et al., 2018). The price of SMR+CCS is expected to maintain this level as technology improves but the price of the feedstock increases.

The price of coal production methods is approximately €2.00 per kg. This technique is also fully developed. The price of the coal+CCS shows similar characteristics as with the SMR+CCS. The price of using the coal method is expected to remain the same or increase slightly. The price of coal+CCS is

expected to maintain the same level due to an improvement of the technology which reduces the price, but this is nullified by the increase in the cost of the feedstock.

Biomass gasification is a mature developed technique. The price is approximately €2.00 per kg. Based on the interviews, the price of biomass gasification is adjusted to €3.00 per kg in the current situation and €2.30 per kg in the future (van den Hoed, 2019).

The central and local electrolysis techniques are increasing in scale, the cost reduction that accompanies this can be seen in figure 15. The bandwidth is relatively large, but the median value indicates that most of the literature see a price of around €3.00 per kg. The central electrolysis production has a small price advantage compared to local electrolysis given production scale advantages (Adolf et al., 2017; Holstein et al., 2018). In the future, due to among others improvement of technology, the price is expected to decrease towards €2.00 per kg for central electrolysis and €2.30 per kg for local electrolysis (Holstein et al., 2018; van Wijk, 2019; Weeda, 2019).

The production price of import electrolysis could approach €1.00 per kg (van Wijk & Hellinga, 2018). However, this greatly depends on the energy price. Import electrolysis uses inexpensive electricity to produce low-cost green hydrogen. Figure 16 describes the relation between the production cost of hydrogen and electricity prices. In the Netherlands, the tariff of large non-household consumers is around €60 to €70 per MWh (CBS, 2019a). Solar farms that are placed in sub-Saharan countries have up to three times more photonic power potential (kWh/m²) than the Netherlands (SOLARGIS, 2017). This is due to the angle of incidence and more hours of sun per year. This creates large amounts of green energy, which could result in the electricity price to decrease below €20 per MWh and a hydrogen price approaching €1 per kg (van Wijk & Hellinga, 2018). However, this greatly depends on the energy price. Multiple experts indicate that such a drop-in electricity price is not likely. Moreover, import electrolysis brings about other problems like the transportation of hydrogen (van den Hoed, 2019; Weeda, 2019).

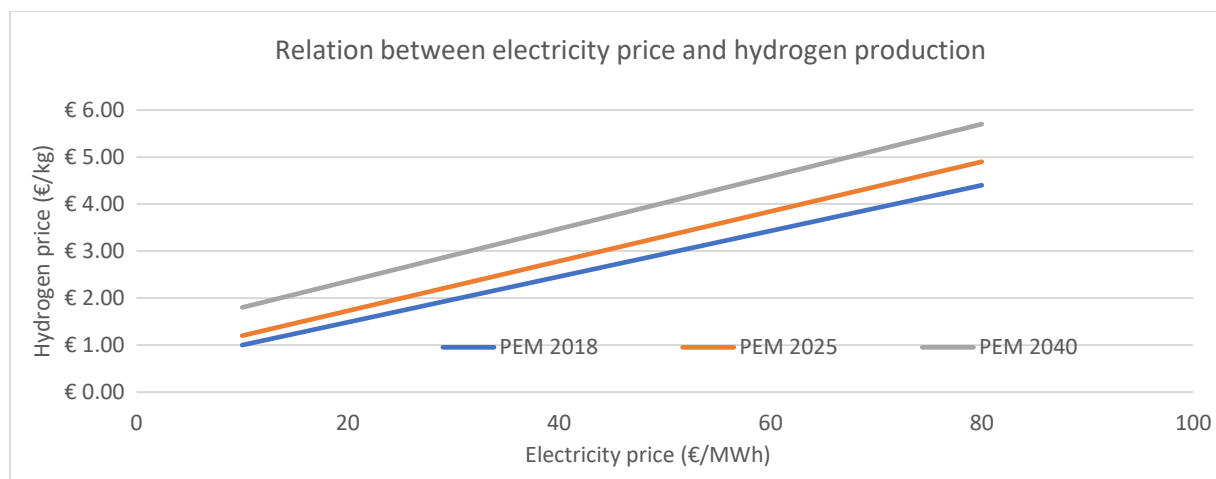


Figure 16 Sensitivity hydrogen production cost using a PEM electrolysis compared to electricity price. Approximately €0.50 for each 10 euro/MWh. Source (Holstein et al., 2018)

The production cost of wind and sun electrolysis is approximately €8 per kg and differs strongly given the bandwidth of €5 to €24 per kg. Given the development of direct conversion of wind and solar energy into hydrogen, the price is expected to decrease to approximately €5.

High-temperature electrolysis has a price of €3.50 to €6 per kg with a median of €4.20 per kg. For this technique, limited price developments are expected (van den Hoed, 2019).

In conclusion, the fossil fuel methods, SMR and coal, are already applied on a large scale resulting in low prices. Electrolysis methods are developing and expanding in scale, but this requires quite some development and effort before it is comparable in terms of cost with conventional production options.

4.1.1.4. Conclusion

This section described potential hydrogen production methods. Table 14 gives an overview of the results of this section. Currently, the total hydrogen price is set to €10 per kg, this includes VAT and exception from excise duty. However, the proportion of production cost in this is unknown.

The prices of the production methods vary quite a lot, the same goes for the expected development. The prices of modest and strong improvement scenario are selected based on the current price and expected development.

*Table 14 Results of hydrogen production methods. *indicates that the current hydrogen price is fixed at €10 per kg, however, it is unknown to which extent this is attributable to production cost*

	Unit	Current*	Future	
			Modest	strong
SMR	€/kg	-	2.00	2.00
SMR + CCS	€/kg	-	2.20	2.00
Coal	€/kg	-	2.50	2.50
Coal +CCS	€/kg	-	2.40	2.40
Biomass	€/kg	-	3.00	2.30
Central electrolysis	€/kg	-	2.50	2.00
Local electrolysis	€/kg	-	2.70	2.30
Import electrolysis	€/kg	-	2.00	1.00
Wind & Sun electrolysis	€/kg	-	8.00	5.00
High temp electrolysis	€/kg	-	4.50	3.50

4.1.2. Distribution cost

The previous section described the production of hydrogen. Before the hydrogen can be refuelled into the hydrogen truck, the hydrogen needs to be distributed to the HRS. This chapter describes the distribution modes and distribution cost. There are multiple distribution modes available to transport hydrogen. Before it is possible to determine the distribution cost, one needs to know how much hydrogen needs to be distributed. This is described in section 4.1.2.1. In section 4.1.2.2, the distribution modes are described together with the technical characteristics. Followed by section 4.1.2.3 that describes the cost of the distribution modes. 4.1.2.4 concludes this section.

4.1.2.1. Demand for hydrogen distribution

The demand for hydrogen transport is based on the demand for hydrogen at the HRS. This is only the hydrogen demand for transport application. Combining the transport of hydrogen for other purposes is possible. However, this is beyond the scope of this thesis. Currently, there are only six small refuelling station, see Figure 17. For instance, the fuelling station at the Helmond automotive campus has a capacity of refuelling 60 kg hydrogen per day; given the fuel tank size of a truck of around 30 to 40 kg, this would mean that only one truck would be able to refuel completely (Bouwman, 2019).

In the literature, the size of refuelling stations ranges from 120 kg/day to 1,500 kg/day (Hydrogen Council, 2017; Isenstadt & Lutsey, 2017; Melaina & Penev, 2013; Ogden, 1999). The largest fuel station size would allow approximately 40 to 50 trucks to refuel per day. Section 5.4 explains more about the refuelling stations.

As can be seen, it is difficult to predict the amount that is required. This thesis assumes that the demand for hydrogen is high enough so each of the transport modes can be used to its full capacity. This causes the prices to drop to marginal cost. In the future, this situation is imaginable if for instance all stations would be refuelled from a central location like the Port of Rotterdam.

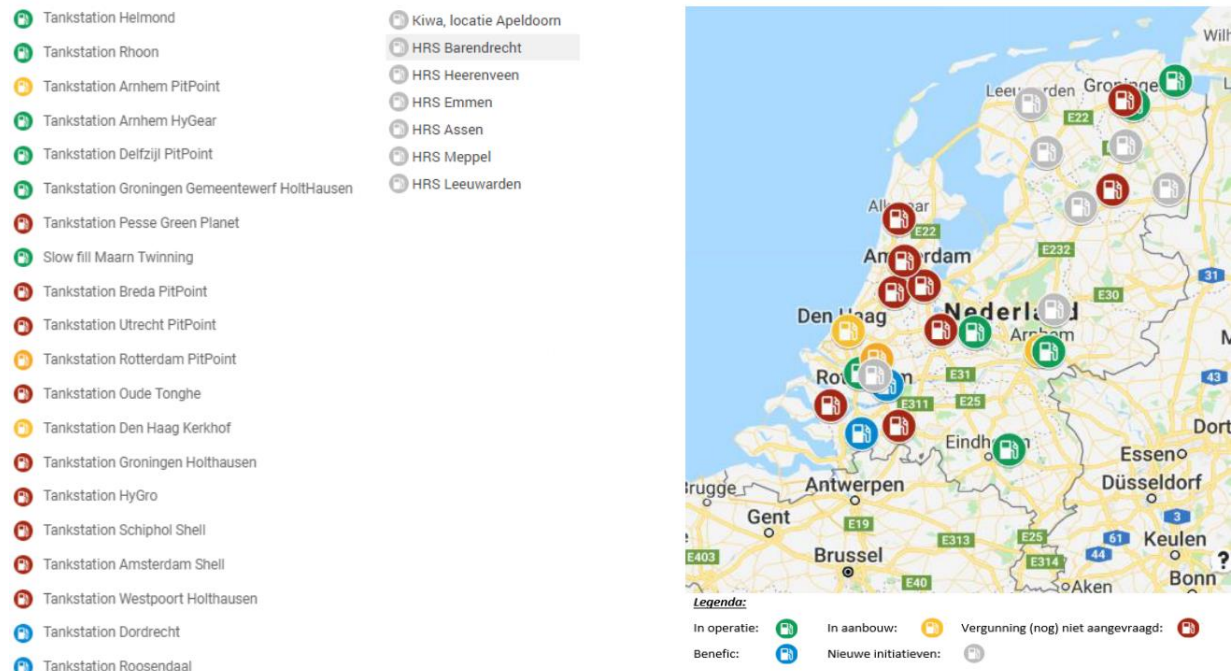


Figure 17 Overview of hydrogen stations in the Netherlands. Green is operational stations, yellow being build, Red permit not yet filled, blue stations from the Benefic project and grey new innitiatives. (Neis, 2019)

4.1.2.2. Distribution mode

Given the demand for hydrogen, a suitable distribution mode can be picked. This section describes the distribution modes together with the technical characteristics of these modes.

Conventional fuels are mostly liquid and distributed by truck or by pipeline. The gaseous fuel CNG is mostly distributed by tube-trailer truck or by pipeline. This depends on the location and the infrastructure at hand. For instance, the refuelling station at Rhoo is connected to the hydrogen pipeline that runs from the port of Rotterdam to the port of Antwerp.

Table 15 shows that there are four modes of distribution with considerable differences in terms of throughput. The distribution modes are derived from the literature review, see appendix A2 for used literature. The transport modes can be divided into three categories, pipeline and truck modes and no distribution. The pipeline option has a very high potential throughput (80-100 ton/day) (Brey, Carazo, & Brey, 2018; Demir & Dincer, 2018; Mintz et al., 2007). The downside of this distribution mode is that it requires dedicated pipeline infrastructure. The investment costs of this are very large, which affects the cost per kilo. This thesis does not discuss the investment cost of the pipeline explicitly. However, the effect of this is incorporated in the price per kilo, more about this in the next section.

The two truck options provide batch deliveries of hydrogen. The throughput of the trucks is 20 to 80 times lower than that of the pipeline (Adolf et al., 2017; Brey et al., 2018; Kim, Lee, & Moon, 2008; Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). However, the trucks can use the road infrastructure that is in place. If the hydrogen is produced locally, then there is no need for distribution as the hydrogen is already near the fuelling location. This has the advantage that there is no distribution cost. However, as seen in section 4.1.1, the cost of local production is slightly higher (Adolf et al., 2017; Holstein et al., 2018). Section 4.2 analyses which combinations of methods/modes costs less.

Hydrogen can also be distributed while attached to another material. Formic acid and H₂-fuel are examples of so-called chemical storage techniques or hydrogen carriers (H₂-Fuel, 2016). This has an advantage over other distribution modes as it increases the storage density of hydrogen (kg/m³). This enables a truck to carry a larger quantity of hydrogen using the same size truck. However, due to the disadvantages of the additional required equipment in the truck, these storage techniques are not considered in this thesis, this is further explained in 5.2.2.1. The usage of a chemical storage technique only for distribution purpose can be an option but given the limited development of these techniques it is not seen as an option at this moment.

A pipeline with liquid hydrogen is not an option either. Liquid hydrogen needs to be kept at a -252°C, this requires insulated pipes and cooling equipment throughout the pipeline network. This is costly and might not even be technically possible. Therefore, this option is not considered (Atli-Veltin, 2019).

Table 15 Characteristics of hydrogen distribution modes

	Maximum throughput per day	Infrastructure required	Investment cost
Pipeline (gas)	~80-100 ton	Pipeline	High
Truck (liquid)	~4ton	Road	Low
Truck (gas)	~0.3-0.5 ton	Road	Low
No transport	Production capacity	None	None

4.1.2.3. Cost of distribution

In the previous sections, the demand for hydrogen and the distribution modes were discussed. In this section, the prices of these distribution modes are described.

Figure 18 to Figure 20 describe the prices per kilogram transported hydrogen for the different distribution modes. During the literature review, an average distance of 200 km is taken for roundtrip distribution of hydrogen. This aligns with hydrogen distribution from a central location like the port of Rotterdam. It becomes clear that each of the modes has economies of scale. However, the cost reductions and possible prices differ per distribution mode. This is caused by the scale of throughput, one can clearly see the differences in throughput between a pipeline and a truck option by the values on the x-axis, as mentioned in the previous section. The following prices are found:

- The pipeline mode, seen in Figure 18, has a relatively high price (€2.00 to €4.00 per kg) at low throughput, the price drops to around €0.30 per kg at high throughput.
- The truck liquid hydrogen mode, seen in Figure 19, has a price of roughly €1.50 per kg at low throughput, the price drops to around €0.40 per kg at high throughput.
- The gas hydrogen truck mode, seen in Figure 20, has a price of roughly €2.50 per kg at low volume and €1.20 per kg at high throughput volume.
- The local hydrogen production requires no transport, so the transport cost is zero.

During the expert interview, the prices at maximum throughput were verified. For the truck gas option, the price ranges between €0.60 to €1.00 per kg. The price of distribution by liquid truck ranges between €0.13 to €0.30 per kg (van den Hoed, 2019; Weeda, 2019). As can be seen, the cost of truck modes aligns with the values that are found in the literature.

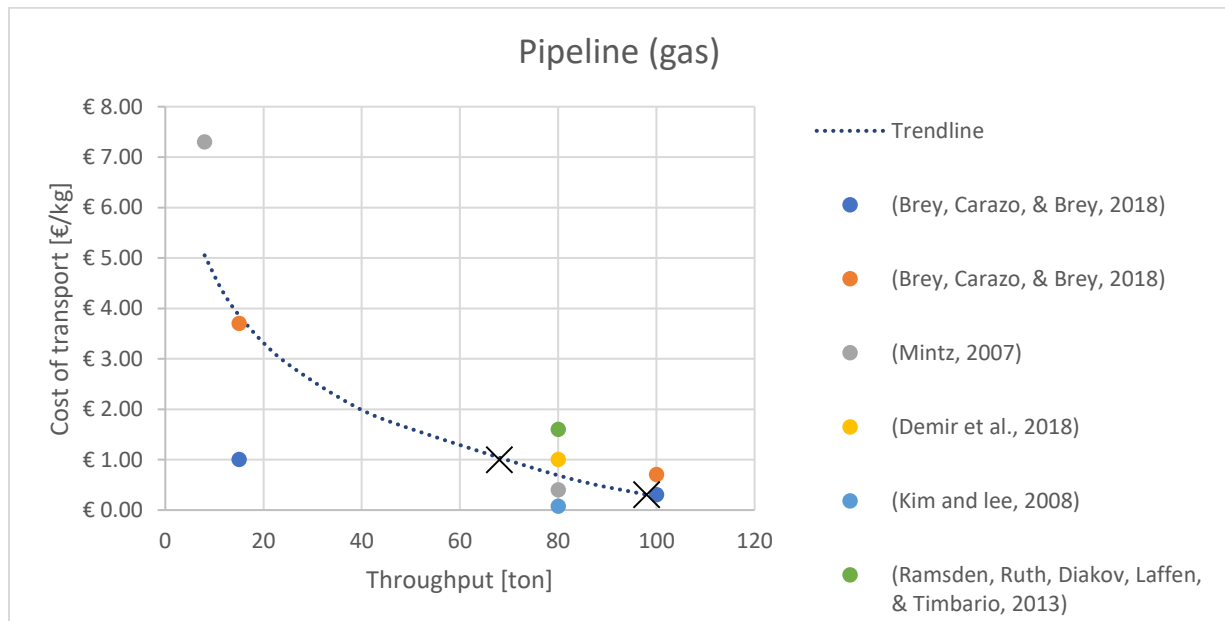


Figure 18 Transport cost per kilogram of using a pipeline with gaseous hydrogen for increasing throughput. The x indicates the selected values for modest and strong improvement scenarios.

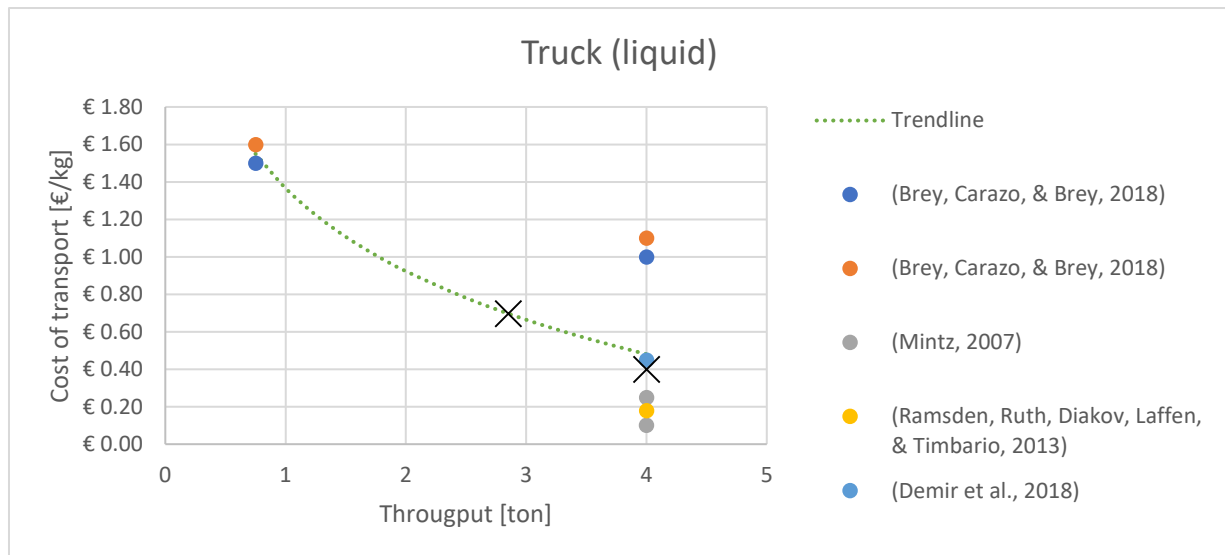


Figure 19 Transport cost per kilogram of using a truck with liquid hydrogen for increasing throughput. The x indicates the selected values for modest and strong improvement scenarios.

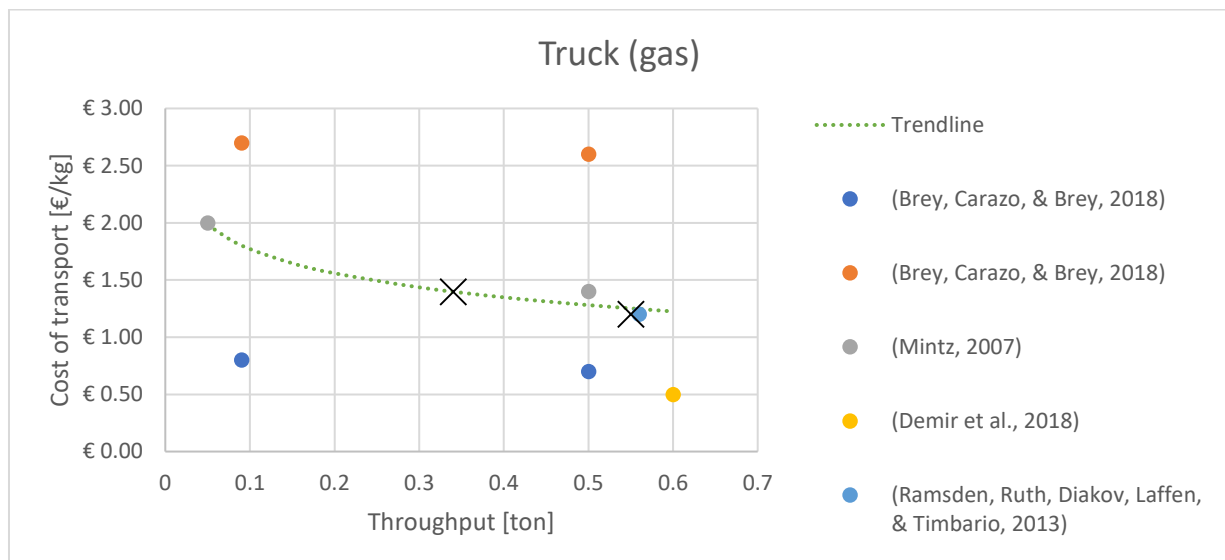


Figure 20 Transport cost per kilogram of using a truck with gaseous hydrogen. The x indicates the selected values for modest and strong improvement scenarios.

4.1.2.4. Conclusion

This section described the potential distribution modes. Table 16 shows that the prices of the pipeline and truck liquid are almost similar, even though the capacity of a pipeline is much larger. This is caused by the large investment costs that are needed for the pipeline option.

Table 16 Results of hydrogen distribution modes. * indicates that the current hydrogen price is fixed at €10 per kg, however, it is unknown to which extent this is attributable to distribution cost

	Unit	Current*	Future	
			Modest	Strong
Pipeline (gas)	€/kg	-	1.00	0.30
Truck (liquid)	€/kg	-	0.70	0.40
Truck (gas)	€/kg	-	1.40	1.20
No transport	€/kg	-	0.00	0.00

4.1.3. Refuelling cost

The previous section distributed the hydrogen to the refuelling stations, the last step in the hydrogen supply chain is refuelling the truck. This section discusses the refuelling process and the refuelling cost. The refuelling cost is among others dependent on the utilisation of the station and the refuelling method. This section starts with the HRS network deployment in 4.1.3.1. The methods are analysed based on fuelling speed in section 4.1.3.2. After which, the refuelling cost is determined in 4.1.3.3. This section finishes with a conclusion in 4.1.3.4.

4.1.3.1. Hydrogen refuelling station network

There are only six HRS operational and another three open in the near future, as can be seen in Figure 17. There are multiple applications for subsidy to build an HRS, all are granted, however, they are not being built. This is due to the limited demand for hydrogen refuelling infrastructure (Schaap, 2019). There are approximately 80 vehicles powered by hydrogen. It is the ambition of the government to increase the number of HRS to 50 and have over 2 million hydrogen-powered vehicles by 2030 (Rijksoverheid, 2019; Rijkswaterstaat, 2019). This means that the utilisation of the current stations is relatively low. Besides that, there are multiple fuelling standards in place. 350 bar is used for hydrogen buses, whereas passenger vehicles use 700 bar. Section 6.3.2 discusses the refuelling standard based on the fuel tank storage method.

To guide the deployment of HRS, the European Parliament and the European Council created the Alternative Fuel Infrastructure Directive (AFID) (European Parliament & European Council, 2014). This directive

- Requires member states to develop national policy frameworks for the market development of alternative fuels and their infrastructure;
- Foresees the use of common technical specifications for recharging and refuelling stations;
- Paves the way for setting up appropriate consumer information on alternative fuels, including a clear and sound price comparison methodology.

With this directive, the deployment of HRS is supported. This thesis assumes that in the future, there are enough HRS along the European Ten-T freight road corridor. Moreover, the utilisation of the HRS is that high that the refuelling costs approach the marginal costs.

4.1.3.2. Refuelling methods

As mentioned in the previous section, there are several refuelling standards. This section describes and compares these refuelling methods based on technical characteristics. The most important technical characteristic of a refuelling station is the refuelling speed.

Ideally, heavy-duty vehicles would like to use high-speed fuelling stations. With diesel, normal fuelling speeds are around 60 litres per minute, whereas high-speed fuelling stations reach fuelling speeds up to 120 litres per minute (AVIA, 2018). Given a fuel tank size of 1,000 litres, this means that the refuelling takes 5-10 minutes. High-speed refuelling is also possible for hydrogen. However, such stations simply do not exist yet.

Table 17 shows the different hydrogen refuelling methods. Currently, the refuelling speed at regular HRS is around 1 to 1.5 kg/min. The fuelling speed of passenger vehicles (Light duty) at 700 bar can go up to 3.6 kg/min according to the SAE J2601 LD protocol. This is a universal safety protocol that dictates the maximum refuelling speed. For trucks, heavy-duty vehicles (HD), the J2601 HD describes that the maximum refuelling speed is limited to 7.2 kg/min at 350 bar (Schneider, 2012).

Table 17 Technical characteristics of hydrogen refuelling methods

	Fuelling protocol	Unit	Refuelling speed current	Refuelling speed future	Source
700 bar light duty vehicle	SAE-J2601 LD	kg/min	1-1.5	3,6	(Schneider, 2012)
350 bar heavy-duty vehicle	SAE-J2601 HD	kg/min	1-1.5	7,2	(Schneider, 2012)
700 bar heavy-duty vehicle	H70HF	kg/min	1-1.5	5-8	(Fuel Cells Bulletin, 2019)

However, the SAE-J2601 does not formulate a fast refuelling protocol for heavy-duty 700 bar. As can be seen in section 5.2.2.1, which discusses the hydrogen storage techniques for truck application, the 700 bar option is an important option to consider as the storage density (kg/m^3) is 1.5 times larger than 350 bar. In March 2019, a coalition of Air Liquide, Hyundai, Nel, Nikola Motor, Shell, and Toyota published plans to develop a new refuelling protocol called H70HF. This is a 700 bar heavy-duty protocol that is created to refuel 40-ton trucks. With this new standard, heavy-duty trucks should be able to refuel in 10 minutes (Fuel Cells Bulletin, 2019).

Nikola, which is part of this coalition, advocates that the refuelling time is approximately 10 to 15 minutes this would mean that the refuelling speed would be somewhere between 5 and 8 kg/min. The Nikola TRE truck type has a driving range of 500 to 1,200 km (Nikola, 2019b). If an energy consumption of 7-15 kg/100 km is taken into account (Navas, 2017). This suggests that 500 kilometres is the range when fuel consumption is high (15 kg/100km) and 1,200 km if fuel consumption is low (7 kg/100 km), this gives a fuel tank capacity of approximately 80 kg. On the website, Nikola claims that the refuelling time is between 10 to 15 min, meaning that the refuelling speed is roughly 5 to 8 kg/min

section 4.1.2 takes the option of liquid hydrogen into account. However, with refuelling, this is not an option due to additional cooling systems that are required. Section 6.3.2 will describe that given the required equipment and the limited space in a truck it is not possible to store liquid hydrogen in the fuel tanks. A refuelling standard needs to be developed in close connection with the automotive industry. Vehicles need to be developed that are compatible with the fuelling standards of the refuelling stations and vice versa. The same goes for chemical storage techniques like H₂-fuel.

4.1.3.3. Cost of refuelling

The previous section described the refuelling methods. This section discusses the prices of the refuelling methods. The size of a refuelling station strongly influences the price of hydrogen, because of economy of scale effects. As the hydrogen price is currently fixed to €10 per kg and there are no examples of fully utilized hydrogen fuelling stations, it is difficult to determine the refuelling cost. Hence, the analogy with diesel is made together with an expert interview to approach the refuelling cost of hydrogen.

Over the last five years, the diesel price fluctuates between €1.20 to €1.40 per kg (CBS, 2019b). The retailer site cost and profit margin only account for 7% (Shell, 2019). That means that the station cost is less than €0.10 per L. With diesel, it is important to be aware that it is produced at large scale with economy of scale effects decreasing the price per kilogram.

In literature, the capacity of refuelling stations ranges from 120 kg/day to 1500 kg/day (Hydrogen Council, 2017; Isenstadt & Lutsey, 2017; Melaina & Penev, 2013; Ogden, 1999). The largest fuel station size would allow 30 to 40 trucks to refuel a day. The literature does not extensively discuss the price of the fuelling station.

From interviews, it has become clear that the price of the fuelling station is expected to decrease as the utilization and capacity of the HRS increases. Robert van den Hoed, (2019) estimates that the price

could decrease to below €1.00 per kg. According to Weeda (2019), it can approach €0.50 per kg if fully utilized and €1.00 per kg in a less ideal situation. This is in line with a report from the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), which mentions prices of below 1 euro (McKinsey, 2010).

4.1.3.4. Conclusion

In this section, the refuelling methods are described. Given the limited availability of literature describing heavy-duty refuelling and the early stage of HRS roll-out, it is difficult to predict the characteristics of future refuelling stations. Table 18 shows the refuelling price and Table 19 the refuelling speed. The optimal refuelling speed of 8 kg/min, but 7 kg/min is more likely to occur as an average refuelling speed, so this is selected in the TCO analysis.

*Table 18 Results of refuelling methods of hydrogen. * indicates that the current hydrogen price is fixed at €10 per kg, however, it is unknown to which extent this is attributable to refuelling cost*

	Unit	Current*	Future	
			Modest	strong
Price 350 bar	€/kg	-	1.00	0.50
Price 700 bar	€/kg	-	1.00	0.50

Table 19 Refuelling speed of methods

	Unit	Current	Future	
			Modest	strong
Refuelling 350 bar	kg/min	1	4	7
Refuelling 700 bar	kg/min	1	4	7

4.2. Hydrogen supply routes

Section 4.1 described the steps of the hydrogen supply chain. This section gives an overview of the possible routes. After which, a selection is made of the routes that are analysed in the TCO analysis of chapter 6. The routes are selected based on the criteria of transport companies that are operationalized as a list of requirements, see Table 2. Besides that, further selection is made based on expert opinions.

Table 20 shows an overview of all the methods or modes for each of the steps of the hydrogen supply chain. From this, one could theoretically create ten times four times two equals 80 options. However, not every method can be combined, there are several reasons for not considering a certain method.

Table 20 List of methods for each of the steps of the hydrogen supply chain

#	Production	#	Distribution	#	Refuelling
1	SMR	1	Pipeline (gas)	1	Gas 350 bar
2	SMR + CCS	2	Truck (gas)	2	Gas 700 bar
3	Coal	3	Truck (liquid)		
4	Coal +CCS	4	No transport		
5	Biomass				
6	Central electrolysis				
7	Local electrolysis				
8	Import electrolysis				
9	Wind and sun electrolysis				
10	High-temperature electrolysis				

The production methods coal and SMR are not considered options as they use fossil feedstock, which emits CO₂, to produce (grey) hydrogen. Nevertheless, SMR+CCS is considered as fossil fuel, this method is the most used production method and captures the CO₂. Although Coal+CCS can also capture the CO₂, this method is not considered in this thesis. Wind and sun electrolysis and high-temperature electrolysis are not considered because it is expected that they do not reach competitive cost levels of €2.00 to €2.50 per kg in the future scenarios.

From the four distribution modes, only one is not considered. The truck gas option is not considered as it has limited storage capacity per truckload. Due to the limited capacity, the cost per kilogram is two to three times higher than other options.

The 700 bar refuelling method is preferred over the 350 bar method. This is due to the fuel tank capacity in the hydrogen truck. As can be seen in section 5.2.2.2, there is limited space in a hydrogen truck to store hydrogen. Therefore, a higher pressurised storage method is chosen.

Besides the fact that methods are not considered, it is also possible that a combination of methods is not possible — for instance, the production method “Import electrolysis”. The cost of production is low. However, the hydrogen needs to be imported to the Netherlands by ship or long-distance pipelines. The business case for importing is being made, however, this is not finished at this moment (van Kranenburg, 2019). Therefore, the production method “Import electrolysis” is also not considered (Verbeek et al., 2014; Weeda, 2019).

In total, seven routes are selected to be analysed in chapter 6. Six routes require distribution: SMR+CCS, central electrolysis and biomass with two possibilities for distribution, gas pipeline and truck liquid. The last route consists of local electrolysis and does not need any distribution. Table 21 gives the selection of routes. Table 22 shows that the cost of the routes. As can be seen, the cost does not differ that much between routes in strong improvement scenario, all around €3.00 per kg. Compared to the current hydrogen price, there is a large decrease of up to 70 percent.

The hydrogen price is used as input for the OPEX cost of the hydrogen truck TCO, see chapter 6

Table 21 Selected routes based on the requirements and expert interview selection.

	Production	Distribution	Refuelling
Route 1	SMR + CCS	Pipeline (gas)	Gas 700 bar
Route 2	SMR + CCS	Truck (liquid)	Gas 700 bar
Route 3	Biomass	Pipeline (gas)	Gas 700 bar
Route 4	Biomass	Truck (liquid)	Gas 700 bar
Route 5	Local electrolysis	-	Gas 700 bar
Route 6	Central electrolysis	Pipeline (gas)	Gas 700 bar
Route 7	Central electrolysis	Truck (liquid)	Gas 700 bar

Table 22 Hydrogen price development for selected routes in modest and strong improvement scenario.

	Unit	Current	Future	
			Modest	Strong
Route 1	€/kg	10.00	4.20	2.80
Route 2	€/kg	10.00	3.90	2.90
Route 3	€/kg	10.00	5.00	3.10
Route 4	€/kg	10.00	4.70	3.20
Route 5	€/kg	10.00	3.70	2.80
Route 6	€/kg	10.00	4.50	2.80
Route 7	€/kg	10.00	4.20	2.90

4.3. Conclusion

This chapter discussed the hydrogen fuel price. This was analysed using the hydrogen supply chain. It became clear there are multiple methods for each of the steps of the hydrogen supply chain. Table 22 shows that 7 routes are defined, the TCO contribution of these routes is compared in chapter 6. Moreover, it became clear that the current hydrogen price is fixed to €10 per kg and this could develop towards €3 per kg in strong improvement scenario depending on the route.

5. Hydrogen truck cost

The previous chapter discussed the hydrogen fuel price consisting of the steps of the supply chain. This chapter discusses the cost of a hydrogen truck.

Currently, there are no hydrogen trucks commercially available. To determine the cost of a hydrogen truck, three steps are taken. Firstly section 5.1 identifies the components of a hydrogen truck. Secondly, section 5.2 analyses the cost, using a component-based analysis. Thirdly in 0, the components are combined to determine the hydrogen truck cost. The analysis in this chapter is structured according to the TCO framework mentioned in the Theory, see Figure 9.

5.1. Studied hydrogen truck concept

This section describes differences and similarities between a battery-electric truck, a hydrogen fuel-cell truck and a ranged extended electric truck. There are commonalities: the hydrogen truck can be considered as an extended version of the electric truck (Koffrie & Hommen, 2017). The difference is the size of the battery and the use of the battery.

A battery-electric truck uses batteries to power an electromotor (EM) which is used for propulsion. The driving range of a Battery electric truck is determined by the capacity of the battery (kWh) and the energy consumption (kWh/km).

A hydrogen truck has some additional components. The additional components are the fuel-cell system, the hydrogen fuel tank and the DC/DC converter. Each component is explained in the next sections. In a hydrogen truck, the following process is executed: hydrogen is injected into the fuel-cell. In the fuel cell, the hydrogen reacts with oxygen in an electro-chemical process into water and electrical energy. This energy is then used to power the electromotor which provides propulsion to the wheels. Before this can happen, the voltage needs to be increased using a DC/DC converter, so it aligns with the operating voltage of the electromotor.

In this case, the battery is not used to power the electromotor. However, this is also possible, for instance, in the prototype truck that VDL has built for the European Interregio 2.0 project. In this case, the hydrogen tanks and fuel-cell system act as a 'mobile charging station' that charges the battery while driving. This application is called a range-extended electric vehicle (Bouwman, 2019).

This thesis focusses on a hydrogen tractor semi-trailer with hydrogen as primary propulsion technique. This entails that the truck gets all its power from the hydrogen that is converted into electricity using a fuel-cell. There will be a battery in the truck, however, this is only needed for brake regeneration and to power other non-propulsion systems.

5.2. Component-based analysis of hydrogen truck cost

From section 5.1 it has become clear that a hydrogen truck consists of all sorts of components. This section analyses the cost of the most important components.

- Section 5.2.1 discusses the fuel-cell system cost
- Section 5.2.2 discusses the fuel tank cost
- Section 5.2.3 discusses the battery and electromotor cost
- Section 5.2.4 discusses the cost of other components.

5.2.1. Fuel-cell system cost

This section discusses the fuel-cell system. As described in section 5.1, the fuel-cell system converts hydrogen into electrical energy. The fuel-cell system consists of the fuel-cell stack and the Balance of Plant (BoP). Firstly, these components are explained. Secondly, there are several fuel-cell technologies available, these are discussed in section 5.2.1.1. After that, the cost of the fuel-cell system is discussed in 5.2.1.2. Section 5.2.1.3 concludes this topic.

Inside the fuel-cell stack, the electro-chemical process occurs. The fuel-cell stack consists of an assembly of fuel-cells, depending on the required power range (kW). Fuel-stack manufacturers usually have standardised fuel-cell stack sizes (multiple fuel-cells combined into a stack), multiple stacks are put in series or parallel or combination of series and parallel in order to acquire the required power range (Koffrie & Hommen, 2017; Resende, 2019).

The balance of plant, see figure 21 the boxed area (does not include box called “stack”), makes sure that the fuel-cell stack maintains ideal conditions primarily in terms of temperature and pressure. It consists of four auxiliary systems: hydrogen supply system, air supply system, water management system and cooling system. So, the balance of plant connects the fuel-cell stack with all other components in the truck.

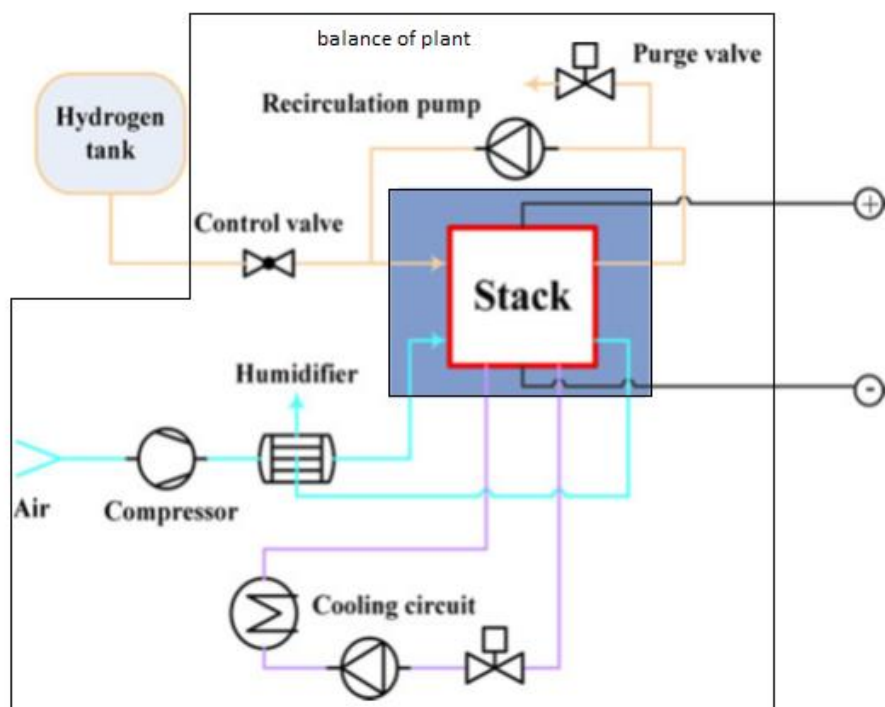


Figure 21 Schematic overview of a fuel-cell system with balance of plant and fuel cell stack (Koffrie & Hommen, 2017).

5.2.1.1. Fuel-cell technology

This section discusses several fuel-cell techniques that are available. After which the characteristics and developments of the dominant fuel-cell technology in automotive application is discussed more extensively.

The different fuel-cell types differ in the electrolyte that is used. This influences the reaction that occurs in the fuel-cell and other characteristics such as temperature and required maintenance. Table 23 (next page) gives an overview of a few common fuel-cell types. However, most of these techniques cannot be used in a mobile application. First of all, the operating temperature of the fuel-cell technique should be below 120°C (Bouwman, 2019; van Wijk, 2019). If the operating temperature is higher, it takes extensive cooling to remove the heat. In column 3 of Table 23, there are several so-called high-temperature fuel-cell techniques like Molten Carbonate fuel-cell (MCFC), Solid-Oxide fuel-cell (SOFC) and Phosphoric Acid (PAFC). These fuel-cell techniques cannot be used in automotive applications.

Secondly, the fuel-cell system should be simple in operation. For instance, the Alkaline fuel-cell (AFC) uses potassium hydroxide in its reaction that needs to be refilled after operation. This is inconvenient as you want a low maintenance system in a truck. In contrary to the Alkaline fuel-cell, the Proton Exchange Membrane (PEMFC) uses simple membranes that require almost no maintenance (Department of Energy, 2011; van Wijk, 2019).

So, from this, it can be concluded that the PEM fuel-cell technique is the only useful fuel-cell technique for mobile application at this moment. This is also mentioned in the interviews (Bouwman, 2019; van Wijk, 2019; Wilkins, 2019). In the rest of this thesis, I focus on the PEM fuel-cell. The rest of this section discusses the efficiency of the PEM fuel-cell and the expected development.

Table 23 Overview of fuel-cell types, adjusted from (Department of Energy, 2011; Wikipedia, 2019)

	Common electrolyte	Operating temperature	Typical stack size	Efficiency (LHV)
Polymer Electrolyte Membrane (PEMFC)	Perfluoro sulfonic acid	<120°C	1 kW–500 kW	50-60%
Alkaline (AFC)	Aqueous potassium hydroxide	<100°C	10kw –2 MW	60-70%
Phosphoric Acid (PAFC)	Phosphoric acid	150°–200°C	<10 MW	40%
Molten Carbonate (MCFC)	Molten lithium, sodium, potassium carbonates	600°–700°C	0.3 MW–3 MW	50-55%
Solid Oxide (SOFC)	Yttria stabilized zirconia	500°–1,000°C	1 kW–2 MW	55-60%

In this thesis, the efficiency is defined as the useful energy divided by the total energy that is put in (Barbir, 2013). When analysing vehicles, it is important to distinguish some efficiencies. Figure 22 distinguishes five sorts of efficiencies (Koffrie & Hommen, 2017). These efficiencies are:

- Fuel-cell system efficiency, the efficiency mentioned in column 5 of Table 23
- Final drive + motor efficiency
- Powertrain efficiency, the combination of fuel-cell system efficiency and drive + motor efficiency
- Battery efficiency, not considered in this thesis
- DC-DC converter, not considered in this thesis.

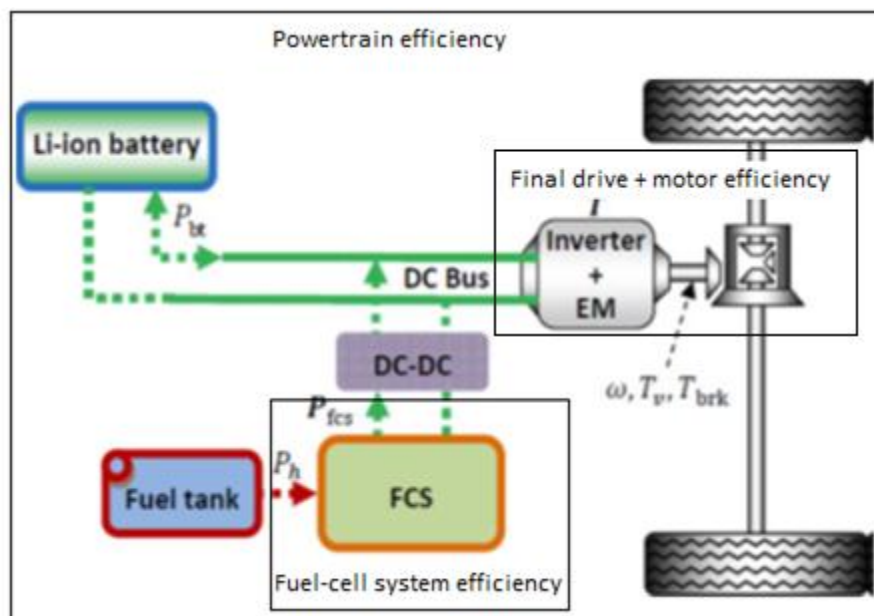


Figure 22 Final drive + motor efficiency, fuel-cell system efficiency and powertrain efficiency. Adjusted from (Koffrie & Hommen, 2017)

The fuel-cell system efficiency is expected to increase in the future, as the application of fuel-cells in vehicles is relatively new, let alone installing it in trucks. Currently, fuel-cell manufacturers use multiple fuel-cell systems from passenger cars to assemble the fuel-cell system of a truck. In the future, fuel-cell manufacturers expect to develop a dedicated truck fuel-cell system (Resende, 2019). Table 24 shows the efficiencies that are found in the literature. As can be seen, the efficiencies found in the literature range from 50-60% at this moment to 60-70% in the future. From the interviews, it became clear that it is difficult to predict how the efficiency will develop. The following values for fuel-cell system efficiency are selected: an efficiency of 50% for the current situation and respectively 60% and 65% for modest and strong improvement scenario.

Table 24 Development of fuel-cell system efficiency, for the efficiency calculation, the lower heating value (LHV) is used.

	Unit	Current (LHV)	Future (LHV)
(Vijayagopal & Rousseau, 2019)	%	60%	70%
(Hunter & Penev, 2019)	%	61%	61%
(Resende, 2019)	%	50%	60%
(Wilkins, 2019)	%	50-55%	60%

The final drive + motor efficiency is related to the electromotor and the final drive. The electromotor converts electrical energy into mechanical energy. The final drive uses the mechanical energy to rotate the shaft, creating motion. The electromotor has an efficiency of 91%, whereas the final drive has an efficiency of 98% (Koffrie & Hommen, 2017). This means that the final drive + motor efficiency is approximately 90% (98% multiplied by 91%). The efficiency is expected to remain the same in the future.

The powertrain efficiency, which is built up of the fuel-cell system efficiency and the final drive + motor efficiency, is approximately 45% in the current situation (50% multiplied by 90%). This is expected to increase to 54% and 59% in modest respectively strong improvement scenario.

5.2.1.2. Fuel-cell system cost

The fuel-cell system cost consists of the fuel-cell stack and the Balance of plant. Figure 23 shows the fuel-cell stack cost development. As can be seen, there is a sharp decrease in cost. Although all the sources agree on the optimal price of €50 to €60 per kW, they do not agree on the current price. The limited uncertainty in the future about the fuel-cell stack cost is a bit surprising as one would expect uncertainty to increase in the future. One reason for this to not happen could be that the future value is the marginal cost or component cost. The large bandwidth at this moment could be the result of the purchase quantity or only material cost (Bouwman, 2019). From the interview with Ruud Bouwman, it became clear that commercial prices are around €800 per kW for the fuel-cell stack of the hydrogen prototype truck (Bouwman, 2019).

The balance of plant cost is difficult to identify as this highly depends on the selected manufacturer, the pressure of the system and the size of the fuel-cell. A rough estimation puts the balance of plant cost around €1,400 per kW (Bouwman, 2019). Steven Wilkins agrees with the complexity of estimating this but could imagine that the balance of plant cost would be around €1,400 per kW. In the future, the balance of plant price is expected to decrease, but it is uncertain to which extent. The prices range from €200 to €600 per kW (Wilkins, 2018). Bouwman, (2019) expects a decrease towards €800 per kW. As this component is important for the calculation of the total price, see section 5.3, a conservative choice is made to select €1,200 per kW and €650 per kW in modest and strong improvement scenario.

The total fuel-cell system cost becomes €2,200 per kW in the current situation. This is expected to develop to €1,360 per kW in modest and €800 per kW in strong improvement scenario. This means that the fuel-cell system cost is greatly dependent on the balance of plant. Limited information is

available on this topic, additional research is needed to provide more certainty about the price reductions.

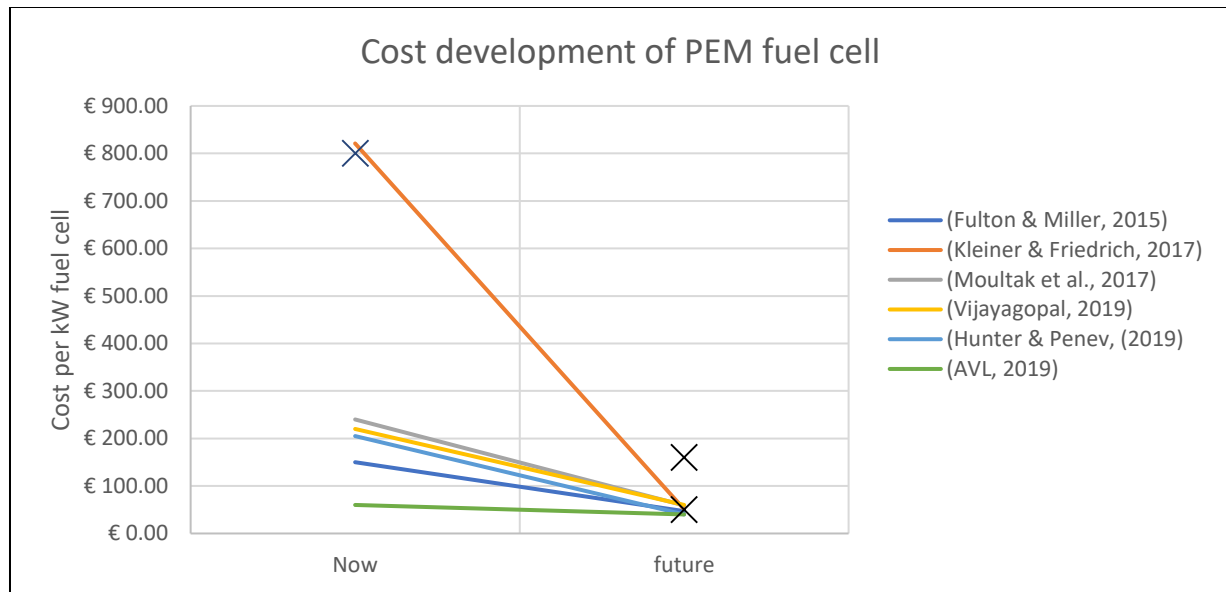


Figure 23 Fuel-cell stack cost development, crosses indicate current, modest and strong improvement scenario.

5.2.1.3. Conclusion fuel-cell system

This section described the fuel-cell system techniques and characteristics. Table 25 shows the efficiencies. The powertrain develops from 45% towards 59%. Table 26 shows that the price of the fuel-cell system is expected to decrease. However, there is uncertainty to which extent the price will decrease.

Table 25 Hydrogen truck efficiency components

	Unit	Current	Future	
			Modest	strong
Fuel-cell efficiency	%	50	60	65
Final drive and motor efficiency	%	90	90	90
Powertrain efficiency	%	45	54	59

Table 26 Selected fuel-cell system cost

	Unit	Current	Future	
			Modest	strong
Fuel-cell cost	€/kW	2200	1360	800

5.2.2. Fuel tank cost

The previous section looked at the fuel-cell system. Another important cost component in the hydrogen truck is the fuel tank. There are several techniques to store hydrogen. These techniques are discussed in this section. Section 5.2.2.1 starts with calculating the required size of the fuel tank and possible storage techniques. Section 5.2.2.2 determines the position of the fuel tank and the calculates the space that is available for placing the fuel tank. Followed by, the cost of the fuel tank in section 5.2.2.3. Section 5.2.2.4 concludes this section with an overview of the selected values.

5.2.2.1. Hydrogen storage techniques

Usually, hydrogen is stored under pressure; however, this is not necessarily needed. There are also other storage techniques like liquid hydrogen or material carriers. In this section, storage techniques are compared. In this comparison, the size of the hydrogen tanks is calculated based on the amount of hydrogen that is needed for a full day of operation. Therefore, first, the amount of hydrogen that is needed for a full day operation is calculated.

With the use of a dynamic vehicle model of TNO, the energy consumption of the hydrogen truck is calculated (Van Zyl et al., 2017). Table 27 shows the results, as can be seen for this mission profile; one would need roughly 37 kg hydrogen. Compared with 182 L diesel that was found in section 3.5. This difference in quantity is caused by powertrain efficiency (45% vs 31%) and energy density (33.33 kWh per kg vs 10 kWh per L).

Table 27 Output of dynamic vehicle model based on the selected mission profile

	Unit	/km	/total	Comment
Kilometres	km	1	500	Mission profile
Wheel power demand	kWh	1.12	560	Dynamic vehicle model output
Hydrogen fuel	kWh	2.49	1,244	Powertrain efficiency 45% (currently)
Hydrogen fuel	kg	0.075	37.33	Energy density hydrogen 33.33kWh per kg

The next step is to identify hydrogen storage techniques. Table 28 shows a list of common storage techniques for hydrogen. As can be seen in column three, there are large differences in storage capacity of the techniques. If one stored 350 bar compressed hydrogen compared to liquid hydrogen, one would need three times more volume to store the same amount of hydrogen. The line shows the diesel reference.

Table 28 Hydrogen storage techniques with characteristics. *currently not feasible

	Storage medium	Density [kg/m ³]	Required volume to store 37 kg hydrogen or 182 L diesel [m ³]
H₂ 1 bar, 20°C	H ₂ (g)	0.09	411
H₂ 350 bar 20°C	H ₂ (g)	23	1.608
H₂ 700 bar 20°C	H ₂ (g)	38	0.974
H₂ liquid -252°C	H ₂ (l)	70*	0.529*
H₂-fuel	NaBrH ₂ (s)	111*	0.33*
Formic acid	CH ₂ O ₂ (s)	53*	0.70*
Reference Diesel	(l)	840	0.182

Column 4 of Table 28 shows the fuel tank size that is required to store the 37 kg of hydrogen that is needed for daily operation. According to Ruud Bouwman, this is not enough: “currently with 700 bar, I can store around 30 kg hydrogen in a truck. However, ideally, I would like to store 80 kg for long-haul transport. This requires different storage techniques”.

As can be seen from Table 28, the options 3 to 6 storage techniques have a higher storage density of hydrogen. Nevertheless, they still require up to 3 times more space than the diesel reference. This difference is primarily caused by the density as shown in column 3.

It is also important to look into the equipment that is needed to use the storage technique in a truck. The 350 bar and 700 bar storage techniques require compressors to maintain the pressure and the 700 bar storage technique require thicker walls than the 350 bar technique that can withstand the higher

pressure. Whereas a liquid hydrogen tank needs to be kept on -252°C , this requires a lot of cooling and a thick isolating tank wall (Atli-Veltin, 2019).

The H_2 -fuel and formic acid are so-called chemical storage techniques or hydrogen carriers. This entails that hydrogen is bonded to another material which increases the density tremendously and in turn reduces the required volume of the hydrogen tank. However, as hydrogen is bounded to the carrier in the fuel tank you either need to unbind the hydrogen before it goes to a PEM fuel-cell or a dedicated fuel-cell technique that could convert the carrier and the hydrogen into electricity.

Liquid hydrogen, H_2 -fuel and formic acid (see *) require that much additional equipment that they are not found to be feasible at this moment, you would need a chemical plant inside your truck (Atli-Veltin, 2019; Bouwman, 2019; van Wijk, 2019). That is why the 350 bar and 700 bar compressed storage techniques are currently used in vehicles. From these two, the 700 bar seems to be the most promising as there are strict rules concerning dimensions for trucks. More about this in the next section.

5.2.2.2. Position of the hydrogen fuel tank

In Europe, there are strict rules on dimensions for trucks. Fixed height, width and length. Length includes the tractor maximum length, trailer maximum length as well as the maximum total length of the combination of tractor and trailer (Larsson, 2009). These rules make it challenging to incorporate the components in the tractor as one needs, among others a fuel-cell, a fuel tank, a battery, an e-motor and other components.

Placing the fuel tank in the hydrogen truck is a challenge. Given the density of hydrogen, the tanks will be relatively large. One needs roughly 1m^3 to store 39 kg hydrogen at 700 bar or approximately 1.6m^3 to store the same amount at 350 bar. Moreover, it is important to keep in mind that only 90% of the capacity of a tank can be used; this is to make sure the tanks remain pressurised. In the current concept hydrogen trucks, there are three options for this problem.

1. Placing the H_2 -tanks directly behind the cabin like in Figure 24. This requires multiple smaller H_2 -tanks of approximately 5 kg stacked behind the cabin. The total fuel tank capacity of the Coop truck is 34 kg. The Coop truck that is developed by Esoro, the Toyota project portal and the Nikola One are using this technique (Esoro, 2019; Nguyen & Lindström, 2017; Nikola, 2019a; Yokoo, 2018).



Figure 24 Positioning of the hydrogen fuel tanks in the tractor of the Coop truck behind the driver (Esoro, 2019)

2. Placing the H₂-tanks in the side pods. This would entail that the H₂-tanks are positioned between the front and back wheel axles. This is the same place as the conventional diesel fuel tank. As can be seen in Figure 25, there is space for this. Using the side pots, you would be able to place H₂-tanks of roughly 0.45m³ at each side. This gives the possibility to store around 30 to 35 kg on 700 bar.

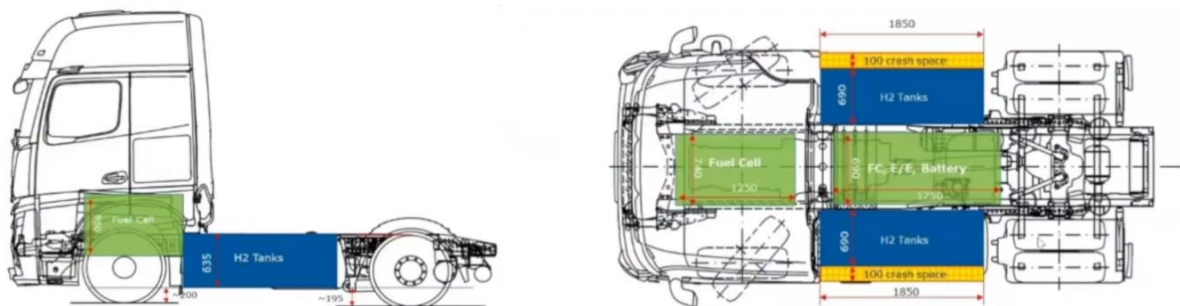


Figure 25 Schematic overview of truck and hydrogen fuel tank in the side pods (Resende, 2019)

3. Placing the H₂-tanks in the trailer. This is a prototype truck that is developed by VDL for the project Waterstofregio 2.0. The project consists of creating a 44-ton electric tractor semi-trailer with a hydrogen range extender. The truck can drive 100 kilometres on its battery, with the hydrogen range extender the driving range can be extended to 400 kilometres. Figure 26 shows that the range extender is positioned in the trailer. In the trailer, four hydrogen tanks, the fuel-cell system and the DC-DC converter are located. This means that the hydrogen is converted into electricity in the trailer. This is used to charge the battery of the truck. So, this prototype does not use hydrogen as primary propulsion technique.

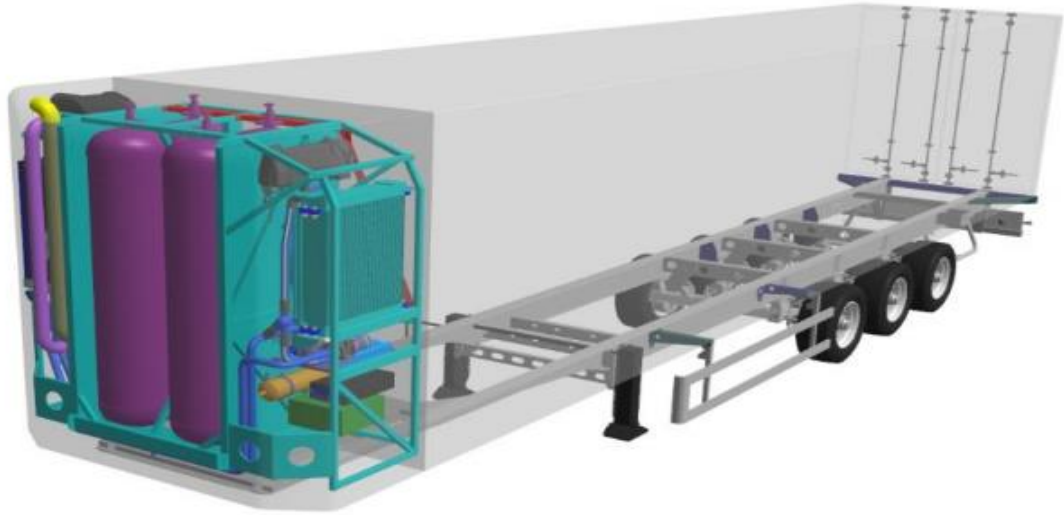


Figure 26 Schematic overview of the trailer and hydrogen components (Bastiaansen, 2017)

As can be seen, consensus about the fuel tank position and the storage technique has not (yet) been reached. In the future, it might be possible to store hydrogen using alternative storage techniques removing the problem of positioning the fuel tank. However, this is beyond the scope of this thesis.

5.2.2.3. Cost of the fuel tank

The hydrogen fuel tank costs are calculated based on the energy storage capacity. To provide a clear overview of the cost of the fuel tank, the cost of the fuel tank is converted into euro per kilogram fuel tank provided. Figure 27 shows the cost developments according to literature. There is no consensus about the cost of the fuel tank. The values of around €1,000 to €1,100 per kg are similar to the costs seen by Ruud Bouwman, (2019). The expected future value fluctuates between €400 and €600 per kg. The crosses indicate the selected prices for current and future scenario, modest and strong improvement scenario.

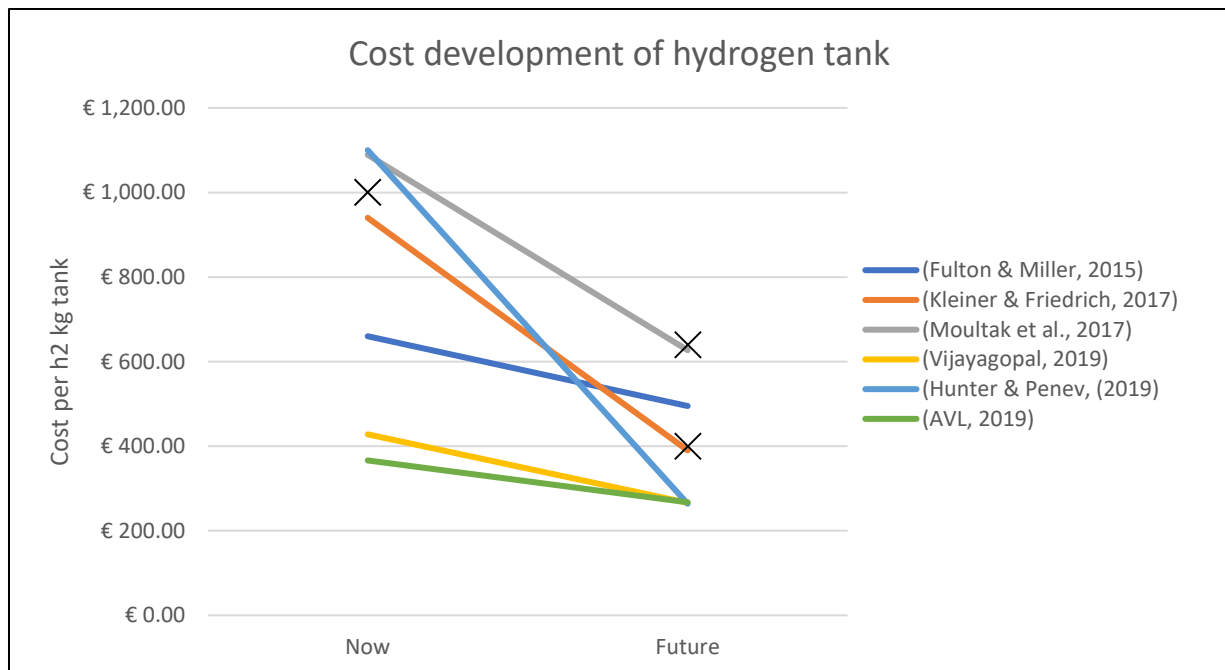


Figure 27 Fuel tank cost development, crosses indicate current, modest and strong improvement scenario.

5.2.2.4. Conclusion hydrogen fuel tank

In previous sections, the hydrogen fuel tank techniques and characteristics have been discussed. Table 29 shows that currently, the hydrogen truck has 350 bar fuel tanks, whereas, in the future scenarios, this is 700 bar. The Fuel tank size is 34 kg currently, subtracting the 10% that cannot be used one ends up with approximately 30 kg storage hydrogen capacity. In the modest and strong improvement scenarios, this is extended to 44 kg with an effective capacity of around 40 kg. Table 30 shows the price development of the fuel tank, starting from €1,000 per kg and decreasing to €640 per kg in modest improvement to up to €400 per kg in strong improvement scenario.

Table 29 Selected fuel tank characteristics

	Unit	Current	Future	
			Modest	Strong
Storage technique	bar	350	700	700
Fuel tank size	kg	34	44	44

Table 30 Price development of fuel tank

	Unit	Current	Future	
			Modest	Strong
Fuel tank cost	€/kg	1,000	640	400

5.2.3. Battery and electromotor cost

This section discusses the cost of the battery and electromotor. Figure 28 shows the cost development of the battery component. Batteries are rapidly developing, hence the relatively large bandwidth. The selected values for the battery price cover the bandwidth that is seen in the literature.

The price of the electromotor is selected to be €18 per kW in current situation, this develops to €14 and €12 per kW in respectively modest and strong improvement scenario (Moultak et al., 2017; TNO, 2019). Table 31 shows the price development for the battery and electromotor.

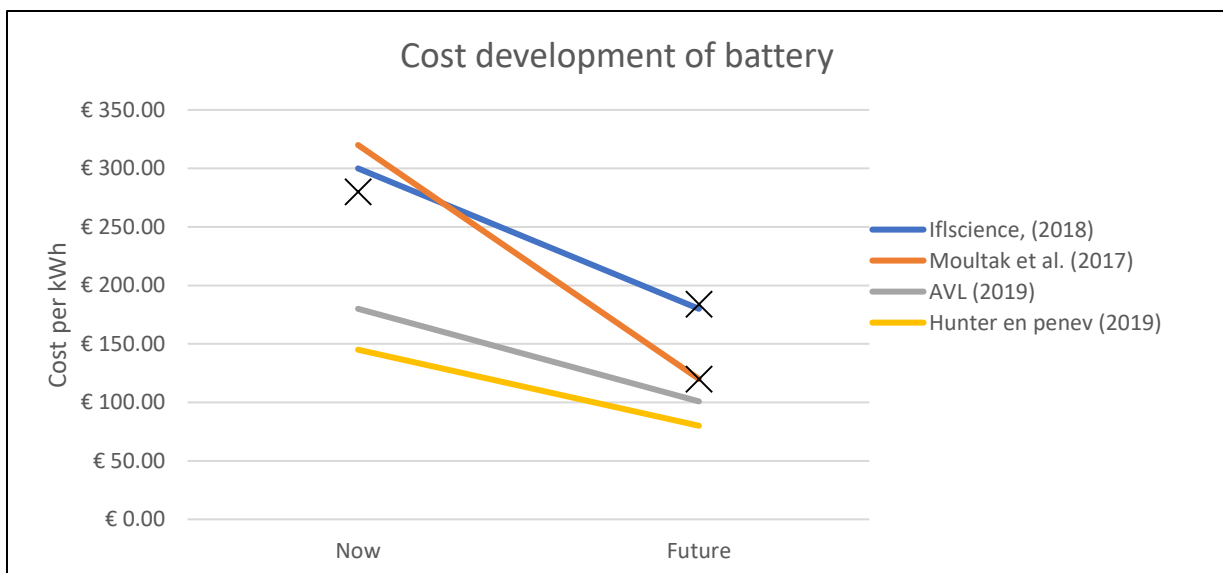


Figure 28 Cost development of battery, crosses indicate current, modest and strong improvement scenario.

Table 31 Overview of price development of battery and electromotor components

	Unit	Current	Future	
			Modest	Strong
Battery	€/kWh	280	184	120
Electromotor + inverter	€/kW	18	14	12

5.2.4. Other cost of hydrogen truck

Besides the specific fuel-cell components such as the fuel-cell system and the hydrogen fuel tank. There are also other components in the truck, such as a DC/DC converter, 'empty tractor' (tractor without powertrain), fixed electric vehicle cost and fixed hydrogen truck cost. Table 32 shows the cost development of these components (Fulton & Miller, 2015; Hunter & Penev, 2019; Moultaq et al., 2017; Resende, 2019; TNO, 2019). Except for the tractor, all components decrease in price, this is in line with assumptions from literature (Moultaq et al., 2017; TNO, 2019)

Table 32 Overview of price development of other components

	Unit	Current	Future	
			Modest	Strong
DC/DC converter	€	20,000	12,000	8,000
Tractor	€	135,000	135,000	135,000
Fixed electric vehicle cost	€	4,923	3,800	3,051
Fixed fuel-cell vehicle cost	€	10,000	7,800	5,000

5.3. Integral analysis of hydrogen truck cost

Until now, the components of the truck are discussed and the cost of these components. In this section, the specifications of the truck are described together with the CAPEX of the hydrogen truck for current situation but also modest and strong improvement scenario.

Table 33 Technical specification of the hydrogen truck

	Unit	Current	Future	
			Modest	strong
Size of electro motor + inverter	KW	250	250	250
Size of battery	kWh	50	50	50
Size of fuel-cell	kW	100	100	100
Size of fuel tank	kg	34	44	44

Based on the Capex framework displayed in Figure 9 of the theory, the cost of the truck can be composed. Table 34 shows the calculation of the hydrogen truck. This is built-up from the component cost analysis of section 5.2 and the technical specifications of the hydrogen truck as described in Table 33.

Table 34 Capex component analysis of the hydrogen truck

	Unit	Current	Modest	Strong
Tractor	€	135,000	135,000	135,000
Electro motor + inverter	€	4,500	3,600	3,000
Battery	€	14,000	8,400	6,000
Fixed electric truck	€	4,923	3,800	3,051
Total electric truck	€	23,423	16,500	12,051
Fuel cell system	€	220,000	136,000	80,000
fuel tank	€	34,000	28,160	17,600
DC/DC converter	€	20,000	12,000	8,000
Fixed hydrogen truck	€	10,000	7,800	5,000
Total hydrogen truck	€	284,000	183,960	110,600
Tractor	€	135,000	135,000	135,000
Total electric truck	€	23,423	16,500	12,051
Total hydrogen truck	€	284,000	183,960	110,600
CAPEX hydrogen truck	€	442,423	335,460	257,651

If the Capex values are compared with literature, similar values can be found. These mostly concern American studies based on Class 8 long haul, which is similar to 40-ton trucks. In Table 35, the current and future prices are given. In most of the literature, milestones of 2040 or 2050 are used.

Table 35 Capex values from the literature

	Price current [€]	Price future [€]	Year
(Moultak et al., 2017)	300,000	207,000	2030
(Vijayagopal & Rousseau, 2019)	316,000	175,000	2050
(Hunter & Penev, 2019)	492,000	184,000	2040

5.4. Conclusion

This chapter researched the components of a hydrogen truck. It became clear that large cost reduction is possible if the components are produced at large scale, this is especially the case for fuel-cell systems and hydrogen fuel tanks. The total truck cost will be used hydrogen truck TCO calculation presented in chapter 6.

6. Economic assessment of hydrogen truck vs diesel truck

Until now, all elements of the TCO framework of the hydrogen truck, see Figure 9, were discussed. This chapter calculates the hydrogen truck TCO for the different routes and compares this to the TCO of the diesel truck. Before this can be done, two topics need to be discussed. Firstly, the mission profile of the hydrogen truck is discussed as this differs from the diesel truck mission profile. Secondly, the TCO current hydrogen truck is calculated.

6.1. Mission profile hydrogen truck

The mission profile of the hydrogen truck differs from the diesel truck due to the longer refuelling time. This has two causes: the fuel tank capacity and the refuelling speed of the HRS. Figure 29 shows there are two refuelling moments per day, whereas the diesel truck only refuels once (Figure 12). Given that approximately 37 kg hydrogen is needed for daily operation (Table 11) and the fuel tank can only hold 30 kg hydrogen, there is a need for an extra refuelling stop.

The refuelling time of the hydrogen truck is also longer than that of the diesel truck, 18 minutes, compared to the 10 minutes (Figure 12). This is caused by the relatively low refuelling speed of 1.5 kg/min. 19 kg is refuelled during each refuelling stop; this is half the amount needed for daily operation. The total refuelling time equals: 5 minutes initial refuelling time + 19 kg divided by 1.5 kg/min refuelling speed \approx 18 minutes

In the future scenarios, the mission profile is the same as that of the diesel truck. This is due to the development in fuel-cell efficiency and the larger fuel tank.

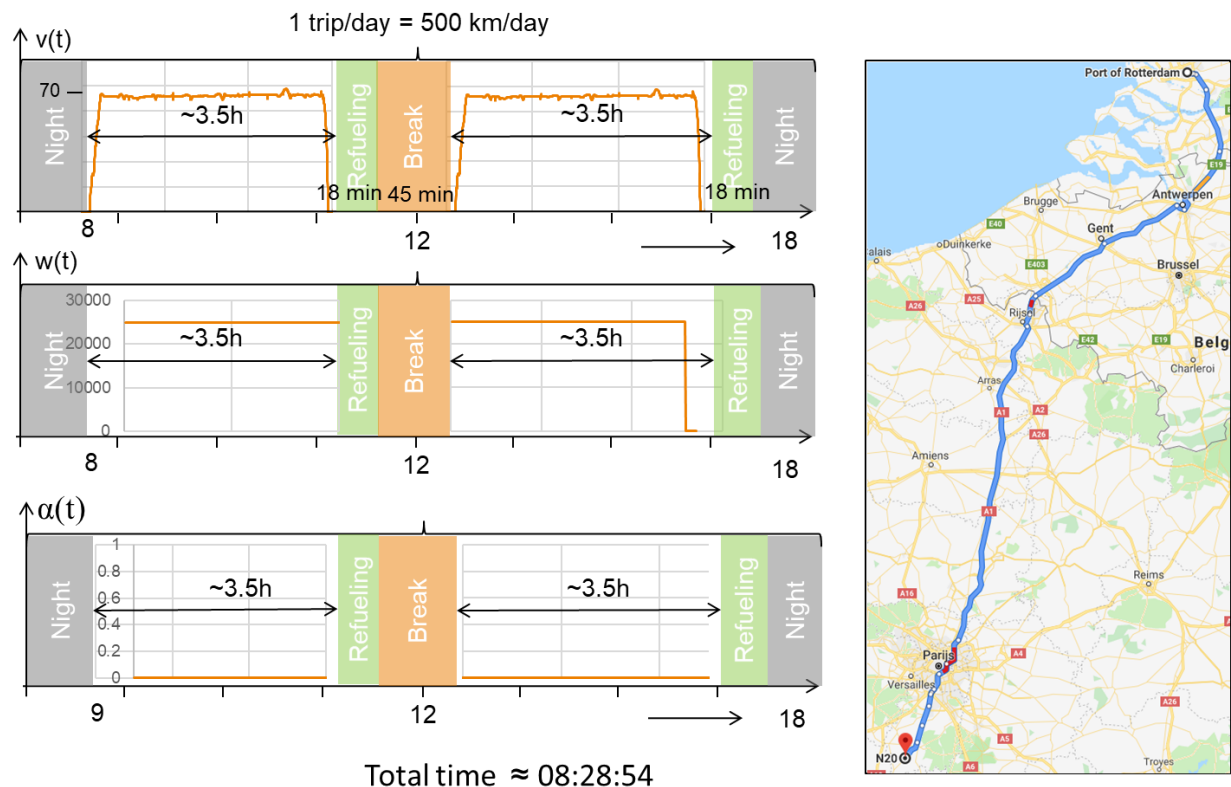


Figure 29 Mission profile hydrogen truck, speed profile, tonnage profile and slope profile. 1 trip of 500 kilometres driven in two periods of 3.5 hours

6.2. TCO current hydrogen truck

In the previous sections, the mission profile is selected, and the cost components are explained, so the TCO can be calculated. Following the framework from the Theory, the TCO consists of CAPEX and OPEX.

The Capex cost is derived from section 5. Currently, the hydrogen truck costs roughly €442,000. Trucks depreciate based on 6% interest, 6 years of operation and a residual value of €50,000.

The OPEX consists of fuel cost and other cost. The fuel cost is calculated by multiplying the hydrogen price, hydrogen fuel consumption and the yearly mileage. Currently, the hydrogen price is fixed to €10 per kg, the powertrain efficiency of 45% and a yearly mileage of 125,000 kilometres.

The other cost consists of the driver salary and maintenance. The driver salary is fixed to €60,000 per year; however, due to the additional time spent during the refuelling, the driver cost increases. The difference in daily operation time between diesel truck and hydrogen truck, 8:03:34 hours compared to 8:28:54. The delta of this is multiplied by the driver salary. The hydrogen truck daily operation time takes roughly 5% longer, so driver salary becomes €60,000 times 1.05 equals €63,000.

Table 36 TCO hydrogen truck current state input

	Unit	value
H2 fuel price	€/kg	10.00
vehicle cost	€	442,423
Hydrogen truck residual value	€	50,000
Driver salary	€	63,000

Figure 30 shows the results of the TCO analysis for the current situation. The size of the blue bar, the depreciation cost, accounts for a much larger portion of the cost compared to that of the diesel truck. Whereas, the fuel cost accounts for the largest portion of the TCO cost. In the modest and strong improvement scenarios, the TCO decreases due to developments in uncertain factors, more about this in section 6.3. As can be seen, the proportion of fuel cost decreases tremendously.

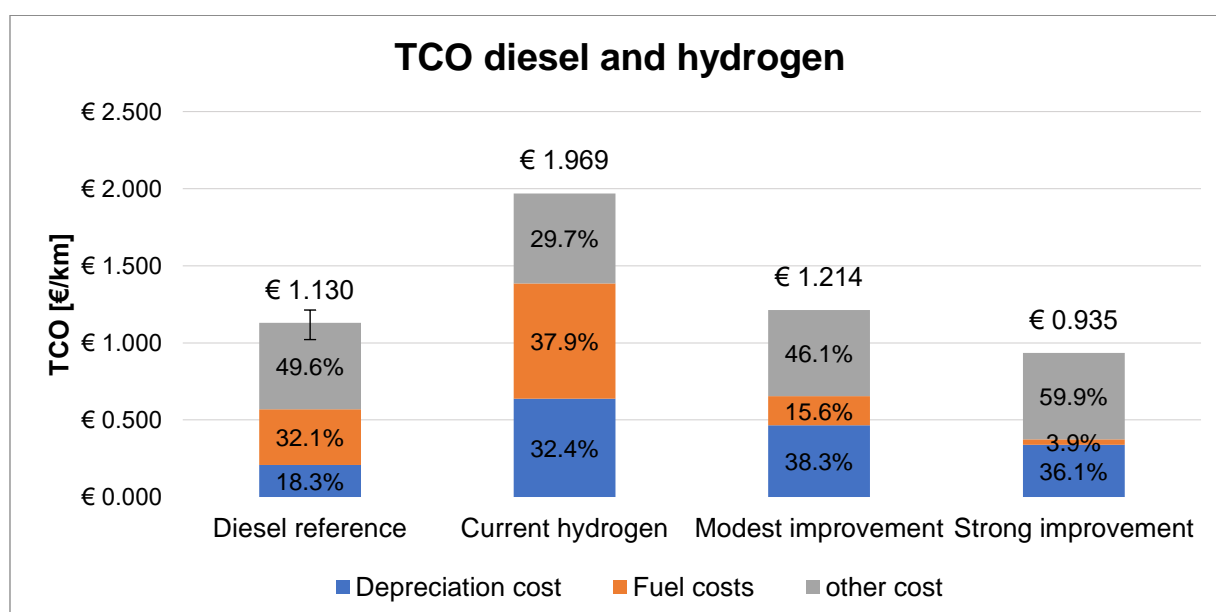


Figure 30 TCO of diesel and hydrogen truck. Diesel truck with uncertainty margin of approximately €0.10. Hydrogen truck with current, modest improvement and strong improvement situation.

6.3. Impact of different hydrogen supply routes on TCO

The TCO of the hydrogen truck develops in the future. Based on the uncertainty analysis of appendix B, the following four factors are identified as being the most uncertain and having the most impact on the TCO:

- Capex cost
- vehicle efficiency
- Extra refuelling time
- Hydrogen price

The first three uncertain factors are the same for each of the route, whereas the hydrogen price (the last factor) differs. Hence, the first three factors are discussed in general and the hydrogen price is discussed for each route. The order of the first three factors is determined by impact on the TCO (highest to lowest). As an illustration for discussing the results, the TCO of route 1 is displayed in Figure 31. The TCO of route 2 to 7 can be found in Appendix C. Table 37 shows the hydrogen supply routes.

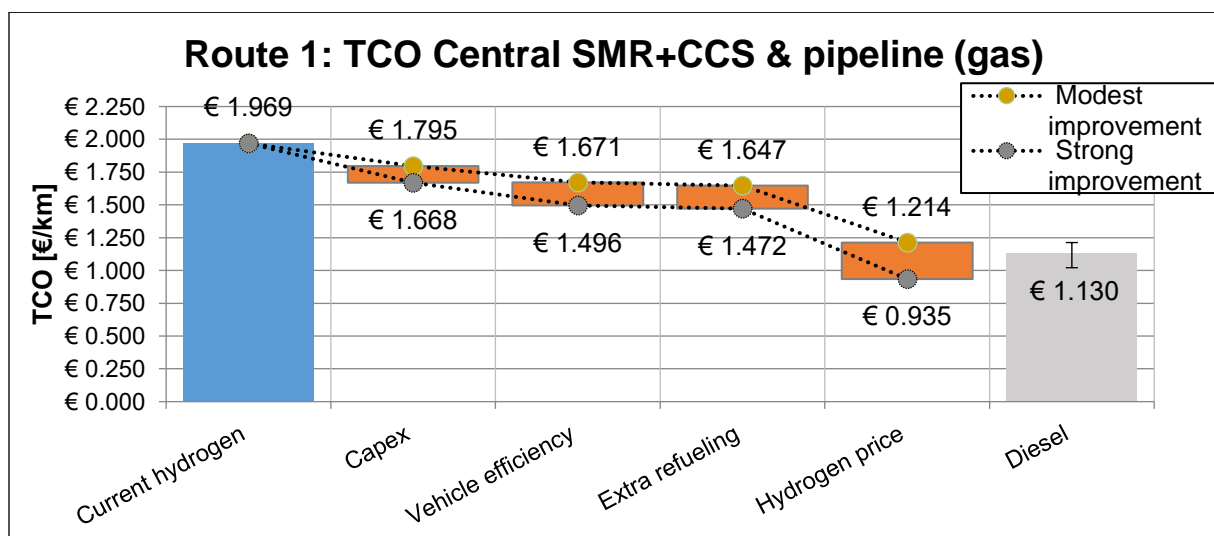


Figure 31 TCO analysis of route 1, with effect of development of 4 uncertain factors

Capex cost

The hydrogen truck cost reduction causes a TCO price reduction of €0.174 to €0.301 in respectively modest and strong improvement scenario (Figure 31). The CAPEX cost is the depreciated hydrogen truck cost. The development of the hydrogen truck is discussed in chapter 5. Due to the development of the fuel-cell system and fuel tank, the hydrogen truck price decreased from €442,000 towards €335,000 in modest improvement scenario and €257,000 in strong improvement scenario.

Vehicle efficiency

The increased vehicle efficiency causes a TCO price reduction of €0.124 to €0.172 per km in respectively modest and strong improvement scenario (Figure 31). The vehicle efficiency is part of the OPEX and influences the fuel cost. The vehicle efficiency improvement is discussed in section 5.2.1.1. Due to the development of the fuel-cell efficiency, the powertrain efficiency increases from 45% towards 54% in modest and 59% in strong improvement scenario.

Extra refuelling time

The development in refuelling speed and capacity of the fuel tank causes a TCO reduction of the extra refuelling of the hydrogen truck causes a TCO price reduction of €0.024 per km in both scenarios. The extra refuelling time has an influence on the daily operation time which influences the driver salary. In the current situation the difference in daily operation time 5%. In the future, the refuelling speed

increases and the fuel tank capacity increases. The required second refuelling stop per day is no longer necessary and the remaining stop takes the same time as that of a diesel truck.

Hydrogen price

As can be seen in Figure 31, the TCO reduction of the hydrogen price causes the largest TCO reduction. Currently, the hydrogen price is fixed to €10 per kg, in the future, this is expected to decrease towards €3 to €5 per kg in strong respectively modest improvement scenario. This results in a TCO reduction of €0.37 per km (ranging from €0.25 to €0.54). Table 37 shows the selected hydrogen supply routes, Table 38 shows the impact of the decreasing hydrogen price on the TCO. There is only a slight difference in price reduction between the routes, the next section provides an analysis of this.

Table 37 Selected routes with combination of methods/mode for production, distribution and refuelling

	Production	Distribution	Refuelling
Route 1	SMR + CCS	Pipeline (gas)	Gas 700 bar
Route 2	SMR + CCS	Truck (liquid)	Gas 700 bar
Route 3	Biomass	Pipeline (gas)	Gas 700 bar
Route 4	Biomass	Truck (liquid)	Gas 700 bar
Route 5	Local electrolysis	-	Gas 700 bar
Route 6	Central electrolysis	Pipeline (gas)	Gas 700 bar
Route 7	Central electrolysis	Truck (liquid)	Gas 700 bar

*Table 38 Improvement of the TCO of routes by development of hydrogen price, * currently fixed*

	Unit	Hydrogen price (Current)*	Hydrogen price (modest)	Hydrogen price (strong)	ΔTCO (modest)	Δ TCO (strong)
Route 1	€	10	4.20	2.80	0.433	0.538
Route 2	€	10	3.90	2.90	0.455	0.530
Route 3	€	10	5.00	3.10	0.373	0.515
Route 4	€	10	4.70	3.20	0.396	0.508
Route 5	€	10	3.70	2.80	0.470	0.538
Route 6	€	10	4.50	2.80	0.411	0.538
Route 7	€	10	4.20	2.90	0.433	0.530

6.4. Comparing the routes

The previous section discussed the TCO results of the routes. This section compares the routes and tries to identify an optimal route. Figure 32 shows an overview of all the routes after the price development of the CAPEX, hydrogen price, vehicle efficiency and extra fuelling. From the results in section 6.3, it can be concluded that all of the routes are within the bandwidth of the diesel reference alternative and that there is hardly any difference in the TCO values between the routes. Furthermore, the following things are found:

- The routes that use truck distribution are slightly more expensive than the routes that use pipeline distribution. As can be seen from the difference between the strong improvement scenario of route 1 and route 2 (same for routes 3 and 4 or 6 and 7).
- The Biomass production (routes 3 and 4) are slightly more expensive than SMR+CCS (route 1 and 2) or central electrolysis (route 6 and 7) options. SMR+CCS and electrolysis show the same results in strong improvement scenario, however, SMR+CCS is expected to be slightly better in modest improvement scenario
- The central electrolysis routes (route 6 and 7) do not differ that much from the local electrolysis route (route 5). The additional cost of producing the hydrogen locally are roughly the same as central production but having to distribute using a pipeline. The truck liquid (route 7) option is slightly more expensive.

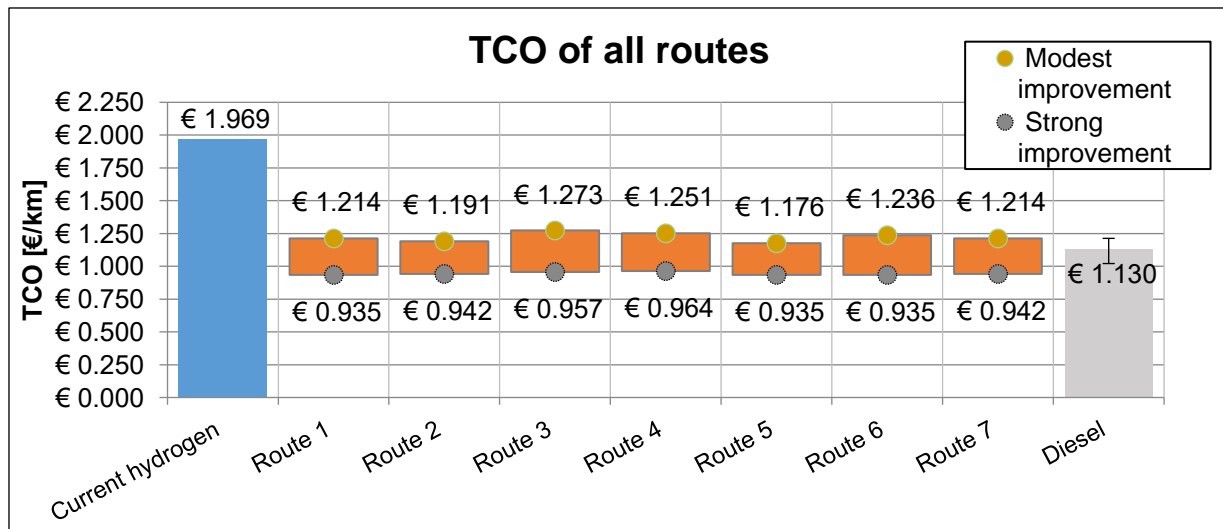


Figure 32 Overview of results of all routes

Concluding, all hydrogen supply routes have approximately the same TCO. This means that from a financial point of view, there is no preferred route. However, from an environmental point of view, the biomass and electrolysis routes are preferred over the SMR+CCS routes.

All the options are within the bandwidth of the diesel option. In modest improvement scenario, the hydrogen truck TCO is almost the same that of the diesel truck. In strong improvement scenario, the hydrogen truck is even cheaper. However, it is important to put this into perspective. In section 6.3, the TCO analysis showed 4 steps of uncertain variables that are improving in the future. All these variables need to develop to achieve an equal or lower TCO. Chapter 7 continues the discussion of the feasibility of the hydrogen truck while answering the sub-questions and in the end answering the research question.

7. Conclusion

Hydrogen as an energy carrier is seen as an important option to reduce the CO₂ emissions in freight road transport. However, not so much research has been done into the possibilities of using a hydrogen truck in freight transport. This thesis aimed to provide more insight into the boundary conditions that are needed to determine the feasibility of a hydrogen truck in long-haul freight transport. The aim of this study can be translated into the following core research question.

Under which techno-economic boundary conditions is a hydrogen fuel-cell tractor semi-trailer a feasible option for long-haul freight road transport in Europe?

The hydrogen fuel-cell tractor semi-trailer can be an economically feasible option under certain boundary conditions. Section 7.1 elaborates on this answer and provides these boundary conditions. Whether the hydrogen truck innovation will succeed depends on many factors and requires a broader perspective, this is discussed in 7.2.

7.1. Feasibility of a hydrogen truck

Given the boundary conditions used in this thesis, a hydrogen truck can be economically comparable to a diesel truck in a modest improvement scenario and can be cheaper in a strong improvement scenario. The hydrogen price and the hydrogen truck are identified as essential but unknown factors that are needed to reach these scenarios. In the rest of this section, a short recap is given of the approach and current and future TCO values after which the identified factors are explained and what is needed to allow the development to occur.

Feasibility is analysed in this thesis from the perspective of the end-user, the transport companies. It becomes clear that the cost-effectiveness is the most important decision variable while availability and robustness in operation are considered important boundary conditions, which are preconditional. A TCO analysis is used to analyse the cost-effectiveness of a hydrogen truck in comparison with a diesel truck.

Currently, the hydrogen truck TCO is approximately €2.00 per km and a reference diesel truck TCO is around €1.10 per km. TCO of the hydrogen truck decreases to around €1.25 per km in modest improvement and €0.95 per km in strong improvement scenario.

Hydrogen price

The current hydrogen price is fixed to €10 per kg by the government, independent of how it is produced. This price includes VAT and exception from excise duty. This thesis identified seven hydrogen supply chain routes (a combination of method/mode for production, distribution and refuelling). The prices of these routes are approximately €3.00 per kg (ranging from €2.80 to €3.20 per kg) in strong improvement scenario and €4.50 per kg (ranging from €4.00 to €5.00 per kg) in modest improvement scenario. From the small bandwidths around the prices, it can be concluded that it is not needed to focus on one particular route from a cost perspective. From an environmental perspective the 'green hydrogen' routes with electrolysis and biomass are preferred. In order to reach the mentioned prices in modest and strong scenario, the components of the hydrogen supply chain need to decrease.

The hydrogen production price is the largest cost component for the hydrogen price. It turns out that two factors are important to consider. Firstly, the hydrogen needs to be produced using sustainable energy to make sure there is no emission polluted and so-called 'green hydrogen' is produced. Hydrogen is seen as a zero-emission alternative for diesel, if conventional energy is used to produce the hydrogen, this benefit is remitted, and hydrogen should no longer be seen as an alternative.

Currently, hydrogen is produced at large scale for other industries using predominantly SMR as production method which uses natural gas as feedstock. Secondly, the production capacity of sustainable hydrogen needs to be expanded to ensure lower production cost. The fossil fuel methods, SMR and coal, are already applied on a large scale resulting in low prices. Electrolysis and other green methods are developing and expanding in scale, but this requires quite some development and effort before it is comparable in terms of cost with conventional production options.

The hydrogen distribution price is less important than production and refuelling cost for two reasons. First, the distribution modes for hydrogen are known already and being applied to other sectors to distribute hydrogen. The distribution cost decreases sharply if the capacity of the distribution mode is utilised. However, the capacity differs strongly, so it is important to decide which mode is used. Collaboration between HRS and/or other sectors could be beneficial to ensure the capacity is utilised completely.

The hydrogen refuelling price is important to consider as it is the least developed of all elements of the supply chain. There are several reasons for this. For instance, there is no consensus about the refuelling standard (350 or 700 bar). For heavy-duty transport, that prefers the 700 bar, there does not yet exist a high-flow refuelling protocol. Moreover, there are only a few HRS in the Netherlands which all are relatively small (<150 kg per day). To get the required cost reduction, large stations (1000+ kg per day) with high utilisation are needed. This is difficult to accomplish as the deployment of HRS is linked to the size of the hydrogen vehicle fleet, this can be seen as a typical chicken-egg problem. The government would like to prevent this from occurring by stimulating both the deployment of HRS and the hydrogen vehicles.

Hydrogen truck

Currently, there are no hydrogen trucks commercially available. However, there are several prototype hydrogen trucks available. To determine the cost of a hydrogen truck and the developments that are expected, a component-based analysis is used. A hydrogen truck costs at this moment around €440,000. In the future, given the developments of the components, large scale production of hydrogen trucks and further development of components, the truck price could decrease to about €335,000 or even €260,000 in modest respectively strong improvement scenario. During the analysis, the hydrogen truck components are identified as the most important factor which accounts for €284,000 of the current price and for €110,000 in strong improvement scenario. The hydrogen components consist of the fuel-cell system and the hydrogen fuel tank.

The fuel-cell system consists of the fuel-cell stack and the balance of plant. The fuel-cell stack technology is developing, and the price is expected to decrease. The extent of these developments is quite known and often researched. In contrary to the development of the balance of plant which is less known. The balance of plant consists of four auxiliary systems: hydrogen supply system, air supply system, water management and cooling system. It is difficult to estimate the cost of balance of plant as this highly depends on the selected operating temperature and pressure which influences the size of the auxiliary systems. Moreover, the configuration of other components like the fuel-cell stack, fuel tank, electromotor and battery also influence these systems. To make sure that the price development, as mentioned above, can occur, two steps need to be taken. Firstly, more research is needed to get a better understanding of the balance of plant and come to standardised fuel-cell systems. Secondly, the standardised components need to be produced at large scale, so prices can decrease.

The size of the hydrogen fuel tank is limited due to regulations, so the selected hydrogen storage technique is an important factor as it determines the quantity of hydrogen that is stored in the fuel tanks which influences the driving range. Two categories of storage techniques can be identified, physical storage and chemical storage. From the analysis of these techniques, it becomes clear that only 350 and 700 bar physical storage are currently feasible solutions. Other techniques required too

many additional systems for either pressurising, cooling or converting. 700 bar is preferred over the 300 bar, given that it can store more 1.5 times more hydrogen (kg/m³).

In conclusion, three categories of boundary conditions are identified. The most influential affordability conditions are the hydrogen price and the hydrogen truck. The most stringent availability conditions are the deployment of the HRS and the hydrogen truck. The most important conditions for robustness in operation are the hydrogen storage techniques and the refuelling speed.

7.2. Broader perspective

The previous paragraph answered the research question of this thesis and provided the boundary conditions for economic feasibility but to determine if a hydrogen truck will succeed in becoming the preferred alternative of the diesel truck, it is needed to look at the alternative from a broader perspective. As mentioned in Geels (2002), whether an innovation succeeds depends on the factors of the system of interest and the actors that influence this system. This section discusses three topics that are needed to determine if this innovation can succeed. Firstly, the important factors that influence whether an innovation succeeds besides the three boundary condition categories. Secondly, the actors and roles they can play in adopting the innovation. Thirdly, a time window is established to give an idea when the hydrogen truck can be adopted.

7.2.1. Factor

In the theory, multiple factors have been mentioned that influence the feasibility of an innovation in the freight road transport sector, this includes but is not limited to social, political, economic, technical and environmental factors. This thesis focusses on the techno-economic factors, but the other factors are also important to give an indication whether the innovation will succeed.

Social factors are important as it involves the perception of people towards an innovation, this involves topics like safety. It is important to demonstrate that a new vehicle type is safe in almost all regular situations for both the users and the environment it operates in. The users must know how to operate the new vehicle type and be able to trust that the new technology is safe in operation. The people that come into contact with such a vehicle should perceive it as a regular vehicle that requires no additional attention.

Political factors relate to broader values like societal cost-benefit, environment and safety. The political factors are often influenced by other factors and actors. As discussed in the government section in 7.2.1, the government has multiple instruments to encourage and discourage innovations but needs to create an agenda for this based on knowledge from industry and research. Based on the 182 times hydrogen is mentioned in the climate agreement, it becomes clear that the current political factors would like to use hydrogen in policies in various sectors (Rijksoverheid, 2019).

The environmental factor is important to consider, this is a fundamental assumption in this thesis. The whole reason that hydrogen is considered to be an interesting option is based on its possibility of being a zero-emission energy carrier.

7.2.2. Actors

Government

The government plays an important role in stimulating innovations. In the climate agreement, the government describes that it would like to reduce the emissions in the transport sector. To stimulate this, all sorts of instruments can be used such as Demonstrations Climate Technology and Innovation (DKTI) projects. This thesis identified the most stringent factors that need to be addressed before a hydrogen truck can be a feasible option. In the case the government decides to commit to hydrogen

based vehicles for freight road transport or simply wants to continue stimulating hydrogen, the following topics should be focused on.

First of all, stimulate the research and development of components of the hydrogen truck and the elements of the hydrogen supply chain. For the hydrogen truck, this can be made specific by focussing on the configuration of the balance of plant in relation to other components (fuel-cell stack, electromotor and battery) and settings (operating pressure and temperature). Moreover, stimulate the development of chemical storage techniques for fuel tank storage inside a truck. For the hydrogen supply chain, it is important to focus on stimulating the development of a high-flow 700 bar refuelling protocol.

Secondly, stimulating the usage of hydrogen truck and hydrogen as an energy carrier. The previous paragraph pointed out that there is a chicken and egg problem with the deployment of HRS and increase of the hydrogen vehicles. The government can stimulate the production of hydrogen vehicles by subsidising the vehicles and asking governmental institutions to consider it in their vehicle fleet replacement, so it would be leading by example. Moreover, stimulating the use of hydrogen vehicles in a particular area improves the business case for a new HRS. Besides stimulating the purchase of hydrogen vehicles, one could also discourage conventional vehicles by implementing flanking measures such as time windows, emission norms and (additional) excise duty for conventional vehicles.

From this, it becomes clear that the government plays an important role in each step towards more sustainable vehicles, starting from the research and development phase and not stopping at the deployment phase.

Original equipment manufacturer (OEM)

The OEMs develop all sorts of vehicles, hydrogen is only one of these categories. OEMs are often large companies that have invested billions in research and development. This means that a change towards zero-emission vehicles needs to be well considered and carefully planned. This thesis provides insight into the perceived boundary conditions of transport companies. If OEMs would like to stimulate the usage of hydrogen trucks, the following topics should be addressed.

The availability of hydrogen trucks is the most important point that is identified in this thesis. Currently, there are only a few prototype trucks being developed and tested. To reach the price reduction as seen in chapter 5, the components of the hydrogen truck should be further developed, and the hydrogen trucks should be produced at large scale. The further development of the hydrogen components is needed as currently multiple standardized passenger components are used in a truck, this applies in particular for the fuel tank and fuel-cell system. For example, a truck has multiple passenger fuel-cell stacks which are combined in order to provide the required power. Dedicated truck components would create standardisation which leads to reduction of cost. Mass production causes the prices to decrease even more, in literature price reduction of 80% are seen when switching towards mass production (Fulton & Miller, 2015; Moultak et al., 2017).

Hydrogen industry

The hydrogen industry consists of all the parties using hydrogen in any part of their business; all parties from production to usage, not limited to the supply chain as defined in this thesis. The government has created numerous DKTIs that provides subsidy for sustainable projects. This thesis has formulated multiple boundary conditions that can be converted into the following recommendations for the hydrogen industry.

Firstly, to reduce the hydrogen price, the following points need to be addressed. First of all, economy of scale effects should be used to full potential. This means that large users of hydrogen should look into possibilities to combine the distribution of hydrogen towards location and consider changing from truck distribution towards pipeline distribution. This allows for much larger throughput. Furthermore, the production scale of sustainable hydrogen needs to be expanded by developing and investing in larger electrolyzers. Current electrolyzers have a capacity of less than 10MW, though the first research is started on the feasibility of a GW electrolyser. A larger sustainable hydrogen production is beneficial for a variety of sectors which mention hydrogen as a means to an end in reaching the climate goals stated in the climate agreement (Rijksoverheid, 2019). Given the ambition of the government to have 50 HRS and 2 million hydrogen vehicles by 2030, there is a large need for sustainable produced hydrogen (Rijkswaterstaat, 2019).

Secondly, at this moment, hydrogen trucks are being developed and prototypes are being tested. The next step is to evaluate these tests in an industry wide discussions to establish standards for heavy-duty vehicles. For instance, the fuel tank storage technique. Currently, there are pilots with both 350 and 700 bar fuel tanks. This thesis showed that given the limited space available in a truck and the preference of a large driving range, the 700 bar seems to be the ideal option until more advanced (chemical) storage techniques become feasible for truck application. Building forward on the previous point, a 700 bar high-flow refuelling protocol needs to be established to ensure standardisation of refuelling stations. This assists in the deployment of the HRS network that is also suitable for truck refuelling.

7.2.3. Time horizon

This thesis has not mentioned a timeline for the developments that should occur before it can be an economically feasible option. This section discusses the timeline of the steps that are needed to approach the modest and strong development scenario. This is done by looking into the readiness of components that are identified as boundary conditions. The following components are discussed: hydrogen truck, balance of plant, HRS, refuelling protocol, hydrogen price.

To reduce the hydrogen price and fulfil the demand for hydrogen at HRS, the production of hydrogen needs to be increased and become completely sustainable. The price decreases as the production scale increases. To produce large quantities of 'green hydrogen', very large electrolyzers are needed which require large quantities of sustainable energy. Electrolyser manufactures can already provide installations that produce 8 ton of hydrogen per day (Nel, 2019). However, given that every sector requires sustainable energy, the availability of sustainable energy for converting to hydrogen is difficult to estimate. With electrolyzers at a scale of 4 to 40 tons, the hydrogen production price could decrease towards €2 per kg (Gigler & Weeda, 2018). This means that the installations of Nel already start approaching such prices.

The hydrogen trucks are currently in prototype and demonstration phase in the Netherlands. Further development of the balance of plant is expected to occur in the next years as the first large orders for trucks are placed in the US and Switzerland. In the US, beer brewer Anheuser-Busch ordered 800 Nikola hydrogen trucks, delivered from 2020 (Fuel Cells Bulletin, 2018) and 1600 trucks for primarily the Swiss transport sector, delivered between 2019-2025 (Carrie Hampel, 2019). The literature on hydrogen truck cost describes that the cost reduction occurs towards 2030 to 2040, but it is imaginable that due to further uptake in hydrogen truck sales this might be sooner (Fulton & Miller, 2015; Hunter & Penev, 2019; Moultak et al., 2017).

There are two steps needed regarding the refuelling of hydrogen trucks. Firstly, the deployment of the HRS, this is planned to happen before 2030. In the climate agreement, the ambition is indicated to

have 50 HRS by 2025. Secondly, the need for a high-flow refuelling protocol for heavy duty vehicles. The previous refuelling protocol took 12 years to develop, given the increased attention for this topic, it is expected that this takes less than 12 years (Schneider, 2012). This means that towards 2030, the boundary conditions associated with the HRS are resolved.

In conclusion, 2030 seems to be a good estimation for most of the boundary conditions to be resolved. The most important factors appear to be the price reduction of the hydrogen truck and the availability of sufficient hydrogen. The last one is important as sustainable energy is used for almost all sectors and hydrogen is mentioned in multiple sectors as a path towards zero-emission.

8. Reflection, contribution of this thesis & future research

During this thesis, assumptions needed to be made to define the scope and ensure the research question can be answered within a specific time frame; section 8.1 reflects on these decisions. Section 8.2 discusses the contributions of this thesis. Section 8.3 gives ideas to continue the work of this thesis and suggestions for future research.

8.1. Reflection

The assumptions that are made concerning the theory that is followed are discussed in section 8.1.1. Section 8.1.2 reflects on the methods that are used. Section 8.1.3 discusses the assumptions that are made to come to a good comparison in TCO between a diesel and a hydrogen truck.

8.1.1. Theoretical framework

This thesis used the theory of Geels, (2002) as a starting point for developing the theoretical framework. This paragraph reflects on this decision and discusses if this approach was suitable for this application.

The line of reasoning and scope of this thesis is guided by the theoretical framework that is created in chapter 2. The innovation framework of Geels, (2002) is used to identify important factors and actors of the freight road transport system. After that, the perspective of transport companies is selected, and their decision criteria are identified. This resulted in the theoretical framework with availability, affordability and robustness in operation.

Given that this thesis consists of exploratory research, using a theory assists in structuring the analysis and systematically identify important factors. This was particularly useful to analyse the steps of the hydrogen supply chain, first identify what methods are available and then find the cost for each method. The three boundary condition categories provided guidance in identifying the most stringent conditions for feasibility. The robustness in operation conditions ensured that factors needed to perform to such an extent that daily operation is possible. Without this category, factors like refuelling speed and fuel tank capacity would not have been identified as boundary conditions.

Furthermore, the theory assisted in keeping the broader perspective of important factors and actors while focussing on the perspective of transport companies. Due to the demarcation created in the theory, this thesis could focus on the economic feasibility from the perspective of the end user, the transport companies. In the conclusion, the theoretical framework is used to reflect what is possible and needed given the results found in this thesis.

8.1.2. Methodology reflection

This thesis has used three methods to analyse the topic. The TCO analysis which results in the evaluation framework structured this thesis. Literature review and semi-structured interviews are used to fill in all the factors of this framework. This section reflects on the selected methods and applied structure.

The Total cost of ownership (TCO) analysis is a good method to evaluate all the cost associated with a particular truck. The TCO method suggests certain categories of cost which could be defined using a modular build-up, this was particularly useful in estimating the CAPEX cost of the hydrogen truck. Moreover, using the TCO method, the hydrogen and diesel truck could be compared in a transparent way. By defining a general TCO framework and then making this specific for each truck, the transparency is guaranteed. This advantage comes to light when analysing the powertrain efficiency of each of the trucks. The diesel truck efficiency is researched quite often, in contrary to the hydrogen truck efficiency. It turned out that five sorts of efficiencies influence the powertrain efficiency of the

hydrogen truck. In conclusion, the TCO method has supported this thesis in a satisfactory way which has assisted in the creation of a transparent assessment of two powertrain options for a truck.

The literature review is used to identify and explore the methods, techniques and developments of the supply chain of hydrogen and the components of the truck. Especially for exploring the methods and techniques the literature review is useful. Furthermore, the literature gives an indication of prices developments but does not provide a good overview of current and possible developments. This is seen at the production cost and efficiency of electrolysis methods which are already further developed than indicated in literature. This is also mentioned during the interview with Ad van Wijk: *“Given the fact that it is a fast-changing and developing technology, literature is often rather conservative”* (van Wijk, 2019). Overall, the literature review is suitable for identifying the factors and get a sense of the prices and developments. The problem of outdated information is anticipated for by performing the semi-structured interviews.

The semi-structured interviews are used to verify and validate the results of the literature review. During the interviews, the information packages are discussed. The information packages consist of the literature review results and the questions based on these results. From hind side, it becomes clear that due to this approach, the conversation might have been to guide or focussed on the purpose of validating and verifying the information. This might have hindered the gathering of new insights. During the interviews, the two-step verification is used to make sure an unbiased view of the results is presented. Alternatively, instead of performing individual interviews it would have been possible to perform expert discussions per topic. This would result in more interaction between experts and different opinions on a particular matter are discussed. Summarising, the semi-structured interviews successfully verified and validated the literature review results, but more attention could have been given to how the interviews are performed.

8.1.3. Assumptions

This thesis calculated the TCO of a heavy-duty hydrogen fuel-cell tractor semi-trailer. Such a truck simply does not yet exist, and the price of hydrogen is currently fixed to €10. Therefore, all sorts of assumptions needed to be made about current prices but to a greater extent the development of these prices.

The first assumption is made to be able to analyse all the components without restrictions. This thesis assumed that every component is produced, distributed or utilised to full capacity. This is an ideal situation which enables the researcher to mimic a situation of full market penetration for the hydrogen truck and all its components. This can be seen as farfetched and unrealistic, however, in this situation, the hydrogen truck can be compared to the diesel reference alternative. This allows one to analyse if an alternative energy carrier like hydrogen can be an option in the transport sector. It gives an indication of the potential of an innovation given the projections of development. In addition, it provides targets for developments in case the innovation is implemented.

The second assumption concerns the factors that are included in the hydrogen fuel price. In this thesis, the hydrogen price is defined as a combination of production, distribution and refuelling cost. However, this is a simplification of reality. The storage and transfer of hydrogen between the steps mentioned above can also be considered in calculating the fuel price. Moreover, the profit margin of each company in the hydrogen supply chain is not considered. This would increase the hydrogen price and in turn the TCO of the hydrogen truck.

The third assumption deals with the uncertainty of breakthrough innovations. In this thesis, only the methods and techniques are considered that are currently available or announced to become available. However, for instance with the storage of hydrogen, ideally, a hydrogen truck should be able to store 80 kg in its fuel tank (Bouwman, 2019). However, the techniques that are currently available

for this, namely hydrogen in a liquid state and chemical storage, cannot be used in mobile application due to cooling and additional systems required. In the future, these problems might be solved, and such techniques might as well become useful. Depending on the breakthrough, the impact can be large as it could remove a barrier for feasibility. Though one must be aware that breakthrough innovation can occur for each technique or product, so also for competing technologies.

The fourth assumption concerns the scope of this research. The hydrogen demand for transport purpose is completely seen isolated from other applications of hydrogen. By combining multiple applications, like chlorine production at a chemical plant, one could use the 'waste' hydrogen of the chlorine production for transportation purpose. Moreover, the distribution of hydrogen by pipeline or truck (liquid) can be performed at a much larger scale if multiple users of hydrogen combine their distribution. Especially in the case of a pipeline, which is built to distribute very large quantities, this might be beneficial as cost per kg could approach marginal cost. Combining multiple sectors could cause a reduction in hydrogen price, which in turn causes the hydrogen truck TCO to decrease.

The fifth assumption involves the selected mission profile. Given the selected mission profile of 500 kilometres and one stop, a hydrogen truck can be a feasible option under the mentioned boundary conditions. Robust in operation also contains that a hydrogen truck is useable for a variety of mission profiles, as one does not purchase a truck solely for one mission profile (Bouwman, 2019). Therefore, additional research using other mission profiles should be performed before the hydrogen truck could be a robust option.

8.2. Contribution of this thesis

The aim of this thesis was to give more insight into the conditions that are needed before a hydrogen truck is a feasible option. This section describes the contribution of this thesis to literature, end-user and policy.

8.2.1. Scientific contribution of this thesis

This section describes several scientific contributions to enrich existing knowledge.

Firstly, resulting from the conclusion of this thesis; the identification of the boundary conditions of feasibility. As the boundary conditions are known, future research can continue on this point and perform more solution-based research to remove the barriers. Moreover, effect-based research can be used to estimate the impact of the adoption of hydrogen trucks on reaching climate agreement goals.

Secondly, this thesis provides a use case of the TCO method in the application of a hydrogen truck with a long-haul mission profile. This contributes in two ways. It shows that a TCO method can also be used for hydrogen truck applications, whereas, In the literature, it is already known that the TCO method can be used to compare vehicle techniques (Wadud, 2017). Moreover, this provides a use case of a mission profile for a heavy-duty truck driving 500 kilometres performing one stop. This contributes to both the general discussion about the feasibility of hydrogen vehicles and specifically to the discussion if a hydrogen truck is feasible in long-haul transport.

Thirdly, this thesis provides a literature review of the most important components of the hydrogen price and the hydrogen truck. There a clear gap in the literature related to heavy-duty refuelling. Current refuelling literature focusses on passenger transport. However, literature into heavy-duty refuelling protocols for 700 bar is currently missing. This thesis discussed that this is clearly needed for the feasibility of a hydrogen truck. From reviewing the hydrogen truck literature, it became clear that a lot is still unknown about balance of plant. The fuel-cell system is identified as an important component in the hydrogen truck. This consist of the fuel-cell stack and the balance of plant. A lot is written about the fuel-cell stack, in contrary to the balance of plant. The balance of plant controls and manages the fuel-cell stack. This process highly depends on the size of the fuel-cell, electromotor,

battery and the selected manufacturer with preferred operating pressure. All this makes it difficult to pinpoint the impact and cost development of the balance of plant.

8.2.2. End-user contribution of this thesis

This section describes the end-user contributions. In the end, transport companies need to make the decision to purchase a hydrogen truck.

Firstly, this thesis provides insight into the usefulness of a hydrogen truck in freight transport. There is increased attention for zero-emission vehicles, however, multiple options are possible. This thesis provides a clear overview of what is needed before the hydrogen truck can be an option for long-haul freight road transport. This can be used during the decision-making process of transport companies to choose a specific zero-emission truck.

Secondly, it provides insight into the relative price difference between a hydrogen truck and a reference diesel truck. Sceptics often say that zero-emission options are too expensive. This research shows to what extent a hydrogen truck is more expensive and to what extent this price difference remains in the future. This thesis explicitly focussed on hydrogen-powered trucks, but the comparison can be extended to also include electric truck options and hybrid options (REEV). This allows transport companies to compare the two zero-emission truck types: a hydrogen truck and an electric truck.

Thirdly, given that the transport industry is a cost driven industry, this thesis highlights the largest cost components within the TCO of a hydrogen truck and shows how this differs from a diesel truck. For instance, the proportion of CAPEX within the total TCO is larger for a hydrogen truck.

8.2.3. Policy contribution of this thesis

This section describes the policy contributions, specifically to what extent this new technology is useful or relevant to reach CO₂ reduction targets.

Firstly, the Dutch government plays an important role in stimulating the adoption of new technologies. This thesis pinpoints the barriers for implementation of hydrogen trucks. Understanding this helps to steer investments to remove barriers for the adoption of hydrogen trucks.

Secondly, this thesis gives insight in the current and future status of the development of the hydrogen truck and the use of hydrogen as an energy carrier for transport. This thesis calculated the TCO of a hydrogen truck and compared this with a diesel truck. This gives insight into the cost difference (Δ TCO) between the truck options. The development of the components shows to what extent the cost difference is reducing. These insights give information to which extent policy instruments are needed to create a situation in which the TCO's of the trucks are equal.

8.3. Future research

The contributions described the added value of this thesis. From this, interesting new inquiries can be started.

This research is exploratory and has identified the barriers for implementation, the next step would be to perform effect research into the implementation of hydrogen trucks. Possible lines of inquiry include model-based research to identify the most suitable policy measures to lower the barrier for feasibility. Moreover, performing choice experiments to understand the willingness to pay of transport companies when choosing a different sort of truck. This identifies the additional willingness to pay to be zero-emission.

The balance of plant is identified as an important component within the hydrogen truck. Understanding more about the required configuration of balance of plant related to the size of other components in the truck (fuel-cell stack, electromotor and battery). Similar, the impact of preferred settings in terms operating temperature and pressure of the balance of plant on the other components. Moreover, researching the impact of the above-mentioned questions on the price of the

balance of plant. All these questions contribute to knowledge about fuel-cell systems and assist in developing more standardised fuel-cell systems.

This research focussed on the use of hydrogen in the transport sector. All the steps of the supply chain are researched in isolation of other sectors. Research into possibilities to combine sectors would be useful as one could identify additional possibilities to reduce the price. For example, since early 2018 Nouryon supplies hydrogen, which is a by-product of chlorine production, for hydrogen-powered buses in Delfszijl (Nouryon, 2018). Further research could provide more cost reductions.

The hydrogen price analysis can be expanded by including more components. The Factors that could be included, applicable depending on route, are: storage cost, compression cost, liquefier cost, value added tax and profit margin. This is useful as it improves the estimation of the hydrogen price development in the future. One could research which method of distribution is most suitable for a refuelling station. Both gaseous and liquid distribution require cost throughout the hydrogen supply chain.

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Appendix

A. Literature review tables

In this Appendix, the literature review tables are displayed. This is the literature that is used to look into the chapters: production, distribution and hydrogen fuel-cell truck.

A1. Production

While searching for literature The analysis of the literature Ibrahim Dincer is an important author in this field. Table 39 Table 40

- International journal of hydrogen energy a respected journal. Besides that, the international journal of energy research.

Table 39 Literature used to analyse the hydrogen production methods, part 1

	SMR	SMR + CCS	Coal	Coal +CCS	Biomass low
(Acar & Dincer, 2014)		x		x	
(Acar & Dincer, 2015)	x		x		
(Adolf et al., 2017)					
(Alazemi & Andrews, 2015)	x		x		
(Brey et al., 2018)	x				
(Dincer, 2012)					x
(Dincer & Acar, 2014)	x		x		x
(Dincer & Zamfirescu, 2012)		x			x
(EDWARDS et al., 2014)	x				
(European Commission, 2013)	x	x		x	x
(Gigler & Weeda, 2018)	x	x			
(Kelly-Yong, Lee, Mohamed, & Bhatia, 2007)					x
(Ochoa Bique & Zondervan, 2018)	x		x		x
(Sinigaglia, Lewiski, Santos Martins, & Mairesse Siluk, 2017)	x		x		
(Stiegel & Ramezan, 2006)			x	x	
(van Wijk & Hellinga, 2018)					

Table 40 Literature used to analyze the hydrogen production methods, part 2

	Biomass high	Wind & Sun electrolysis	electrolysis low temp	electrolyse high temp	Nuclear
(Acar & Dincer, 2014)	X	X	X	X	X
(Acar & Dincer, 2015)	X	X		X	X
(Adolf et al., 2017)			X		
(Alazemi & Andrews, 2015)	X	X	X	X	X
(Brey et al., 2018)		X			
(Dincer, 2012)	X	X	X	X	X
(Dincer & Acar, 2014)	X	X	X	X	
(Dincer & Zamfirescu, 2012)	X	X			
(EDWARDS et al., 2014)		X			
(European Commission, 2013)		X			X
(Gigler & Weeda, 2018)			X	X	
(Kelly-Yong et al., 2007)					
(Ochoa Bique & Zondervan, 2018)		X			
(Sinigaglia et al., 2017)		X	X	X	
(Stiegel & Ramezan, 2006)					
(van Wijk & Hellinga, 2018)		X			

A2. Distribution

Table 41 Literature used to analyse the methods to transport hydrogen

	pipeline gas	truck liquid	truck gas
(Adolf et al., 2017)	x	x	x
(European Commission, 2013)	x	x	x
(Brey et al., 2018)	x	x	x
(Demir & Dincer, 2018)	X		x
(Miller, 2017)	x		
(Kim et al., 2008)	x	x	x
(Mintz et al., 2007)	x	x	X
(Ramsden et al., 2013)	X	x	x

A3. Hydrogen fuel-cell truck

Table 42 Literature used to analyse the components of the hydrogen tank

	Fuel-cell	Fuel tank	Electromotor	Battery
(Fulton & Miller, 2015)	x	x		
(Kleiner & Friedrich, 2017)	x	x		
(Moultak et al., 2017)	x	x	x	x
(Vijayagopal & Rousseau, 2019)	x	x		
(Hunter & Penev, 2019)	x	x	x	x
(AVL, 2016)	x	x		x
(Abma, Atli-Veltin, & Verbeek, 2019)	x			
(IFLScience, 2018)				x

B. Analysis of uncertainty variables

This appendix discusses the selection of uncertain variables. The uncertain variables need to be analysed to derive a selection of variables that is used in the scenarios. The factors are derived from the TCO framework and the analysis of this in chapter 4 and 5.

- Hydrogen price (€/kg)
- Fuelling speed (kg/min)
- Capacity of fuel tank (kg)
- Powertrain efficiency (%)
- Fuel cell system (€/kW)
- Fuel tank (€/kg)
- Total electric truck components (€)
- Mission profile (km/day)

Table 43 Uncertainty analysis of variables, 20% improvement and the impact of this on the TCO price

	Unit	Possible range	Change (20%)	Δ TCO [€/km]
Hydrogen price	€/kg	3.00 to 10.00	1.40	0.105
Fuelling speed	kg/min	1.5 to 7	1.10	0.009
Capacity of fuel tank	kg	30 to 40	2	0
Powertrain efficiency	%	45 to 59	2.8	0.044
Fuel cell system	€/kW	800 to 2,200	280	0.046
Fuel tank	€/kg	400 to 1,000	120	0.007
Total electric components cost	€	12,000 to 23,000	2,200	0.004

The vehicle components are combined into one variable called CAPEX, the Δ TCO becomes €0.060. The refuelling speed and capacity of fuel tank are combined into extra refuelling time, the Δ TCO remains the same. Based on this analysis results, shown in Table 43, the following variables are selected for the uncertainty analysis of the TCO.

- Hydrogen price
- Capex
- Fuel-cell efficiency
- Extra refuelling time

C. TCO results of routes

Figure 33 route 2 Central SMR+CCS + truck (liquid)

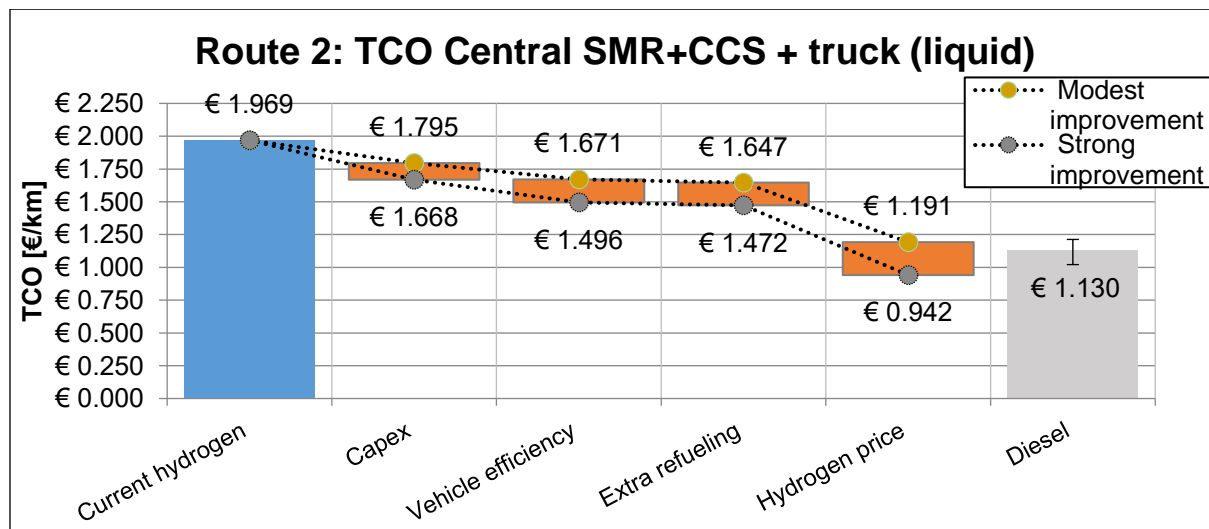


Figure 33 TCO analysis of route 2, with effect of development of 4 uncertain factors

Figure 34 route 3: Biomass + Pipeline (gas)

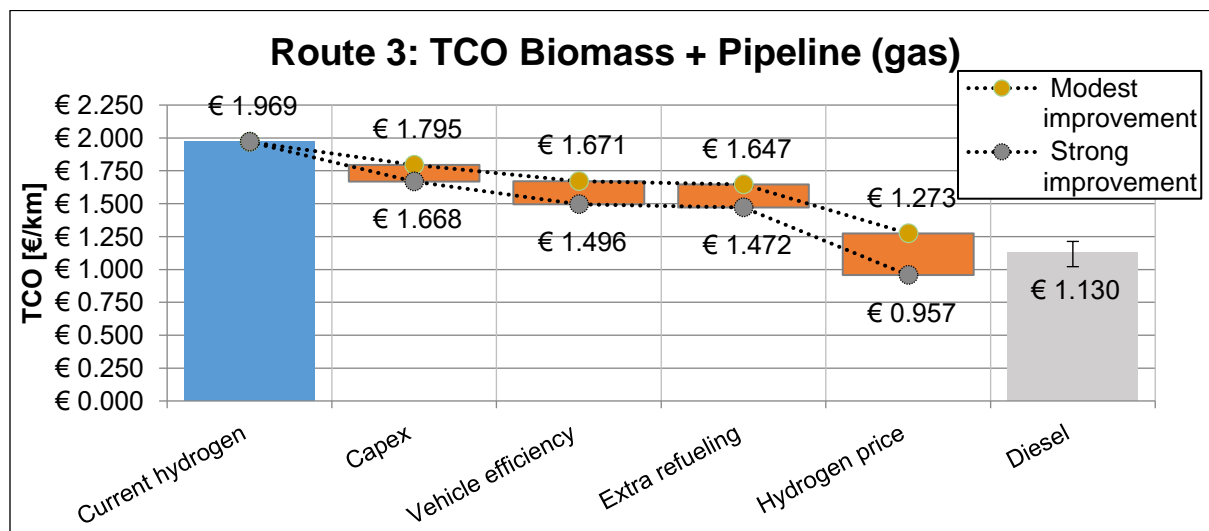


Figure 34 TCO analysis of route 3, with effect of development of 4 uncertain factors

Figure 35 route 4: Biomass + Truck (liquid)

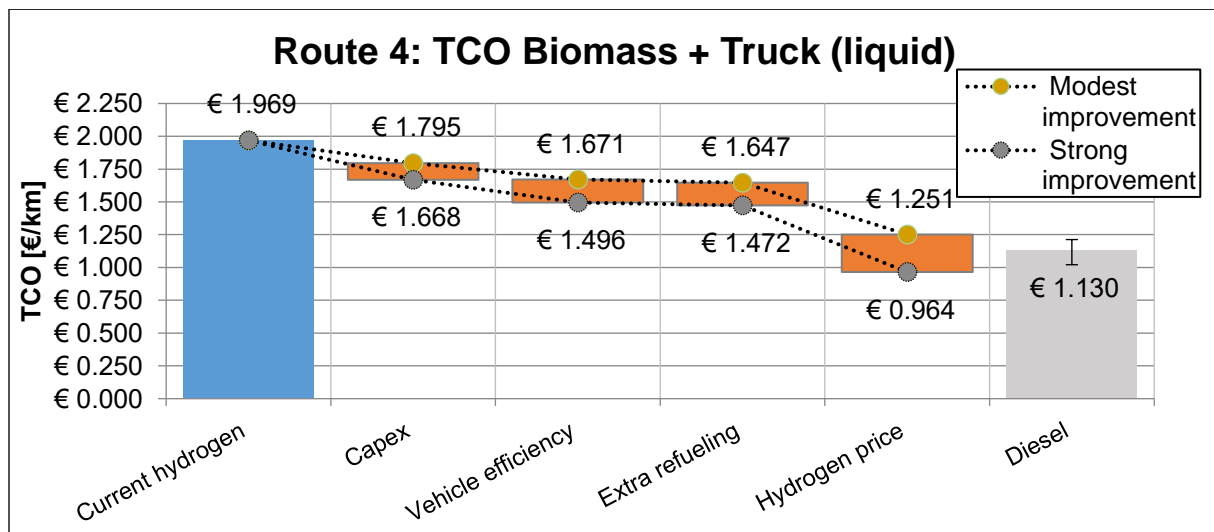


Figure 35 TCO analysis of route 4, with effect of development of 4 uncertain factors

Figure 36 route 5: Local electrolysis

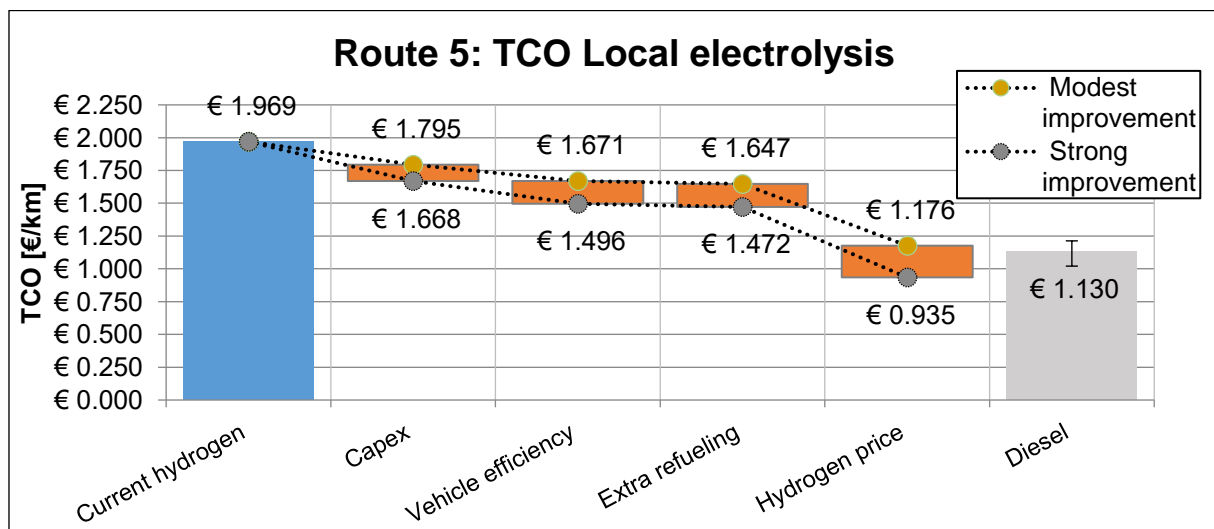


Figure 36 TCO analysis of route 5, with effect of development of 4 uncertain factors

Figure 37 route 6 Central electrolysis Pipeline (gas)

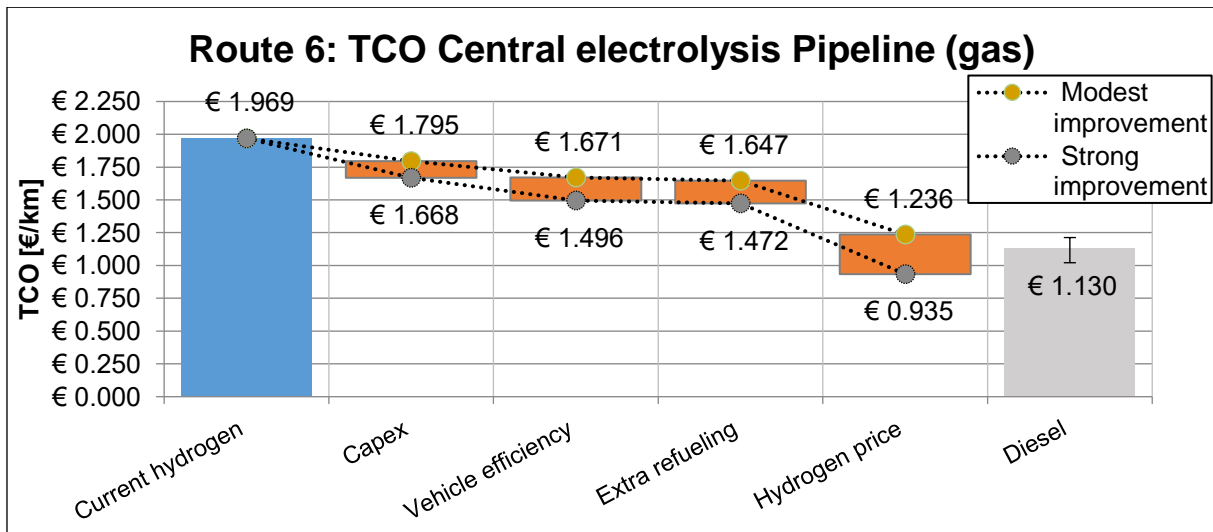


Figure 37 TCO analysis of route 6, with effect of development of 4 uncertain factors

Figure 38 Route 7 Central electrolysis truck (liquid)

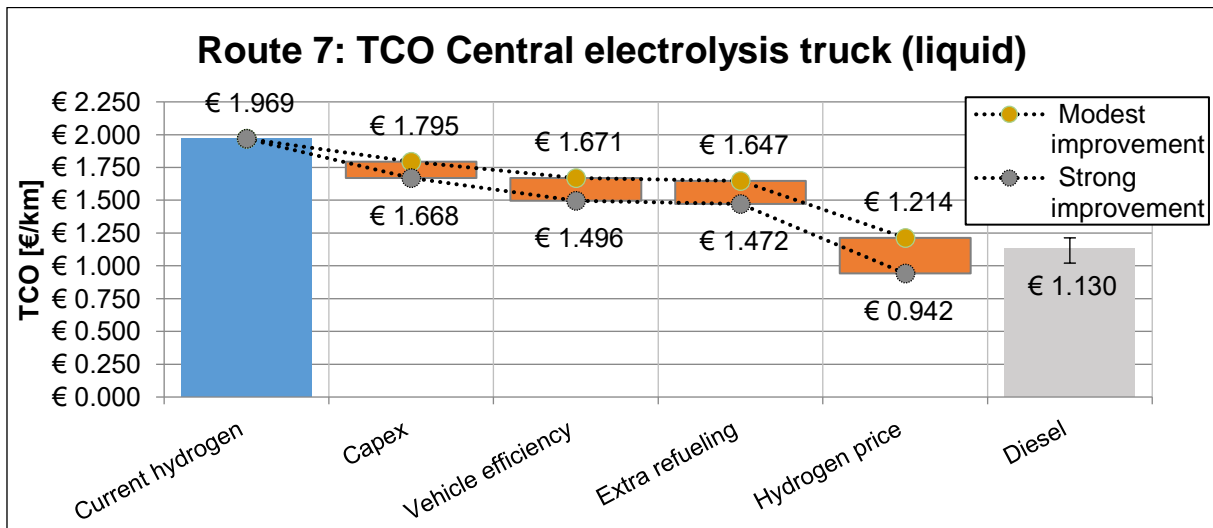


Figure 38 TCO analysis of route 7, with effect of development of 4 uncertain factors

D. Interview information package

I have performed my literature review. From the literature, the following data is extracted. The results are mostly visualised using figures and tables. The questions are mentioned throughout the text and are underlined. Most of the questions concern validating the data that I have found. For each topic the literature that is used is mentioned in the end. On the last page, the full literature list is given.

A short introduction to my thesis:

My research deals with the following question: *Under which techno-economic conditions is a hydrogen fuel-cell truck a feasible option for long-haul freight road transport?*

I will approach this question by comparing the TCOs of a hydrogen fuel-cell truck with a conventional diesel truck. In my thesis, I research the following elements and how they contribute to the TCO:

- The costs of hydrogen for various routes:
 - o production of hydrogen: steam-reforming, coal, biomass, electrolysis
 - o The distribution of hydrogen: pipe-line, truck (liquid) and truck (gas)
 - o The refuelling of hydrogen: 350 bar or 700 bar
- The costs of a hydrogen fuel-cell truck, using component cost analysis

This document consists of the following topics

- Production
- Distribution
- Fuelling station
- Hydrogen fuel-cell truck
- Routes

Production

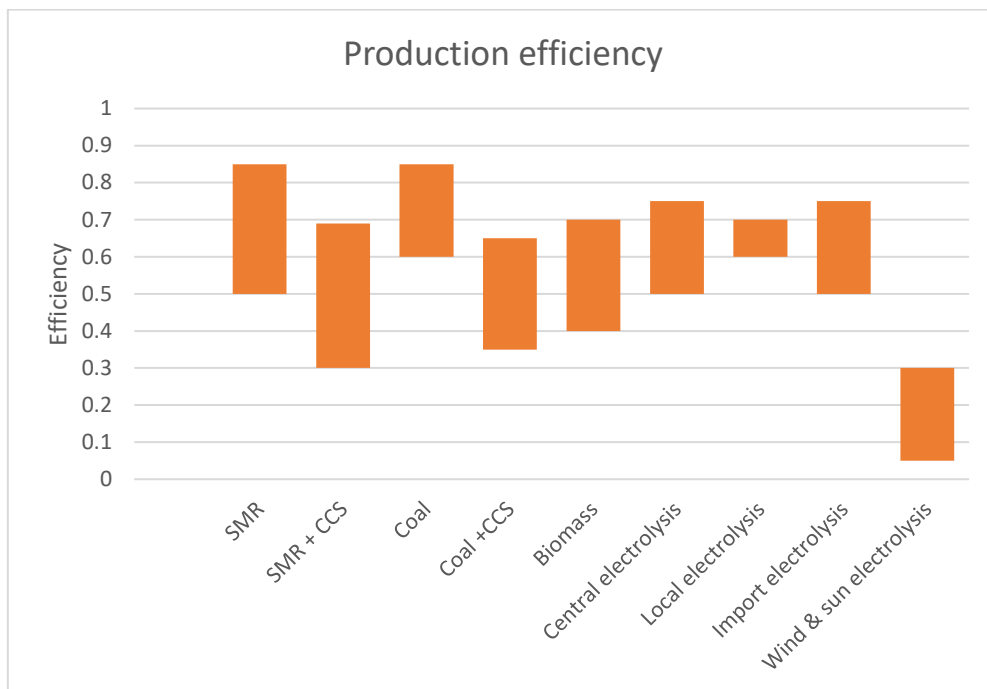


Figure 39 Production efficiency by method

Comment: Based on other interviews, I'm going to split SMR and Electrolysis into local and central. Local having a lower efficiency than central.

From figure 1 it becomes clear that multiple production methods have a relatively high production efficiency. The fossil production methods that are combined with CCS have a lower efficiency.

Question: What is the efficiency of hydrogen production? In the literature, I have found these methods with these bandwidths of efficiencies. How are these expected to develop over the years? What technologies are relevant for improvement?

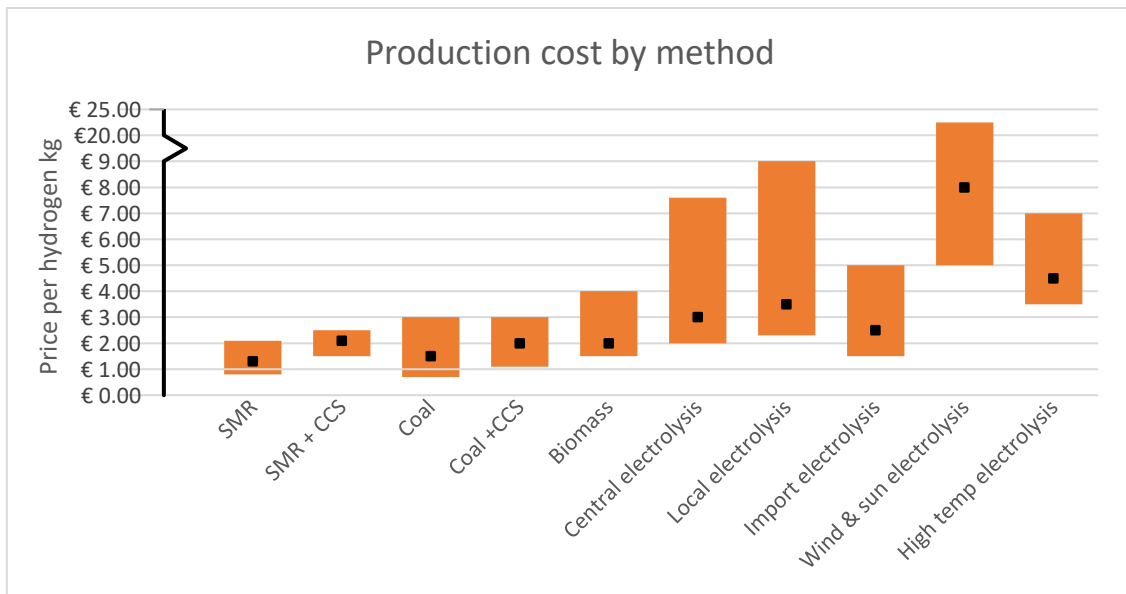


Figure 40 Production cost by method, the dots in the figure describe the most common found value

Note: The y-axis is broken at the top, the dots in the figure are the most common found values and the bar describes the bandwidth.

As can be seen in figure 2, the prices of fossil fuel options are lower than more sustainable options like biomass and electrolysis. Besides that, there is a large bandwidth for the sustainable methods.

Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?

Literature used for this analysis.

(Acar & Dincer, 2014, 2015; Adolf et al., 2017; Alazemi & Andrews, 2015; Brey et al., 2018; Dincer, 2012; Dincer & Acar, 2014; Dincer & Zamfirescu, 2012; EDWARDS et al., 2014; European Commission, 2013; Gigler & Weeda, 2018; Kelly-Yong et al., 2007; Ochoa Bique & Zondervan, 2018; Sinigaglia et al., 2017; Stiegel & Ramezan, 2006; van Wijk & Hellinga, 2018)

Distribution

Table 44 Characteristics of hydrogen transport methods

	Gas pipeline	Truck liquid	Truck gas
Throughput per day	~80ton	~4ton	~0,5ton

From table 1 it becomes clear that there are scale differences in throughput per day.

Main question: How will hydrogen be transported to the fuelling stations? I have found the following method with costs of throughput

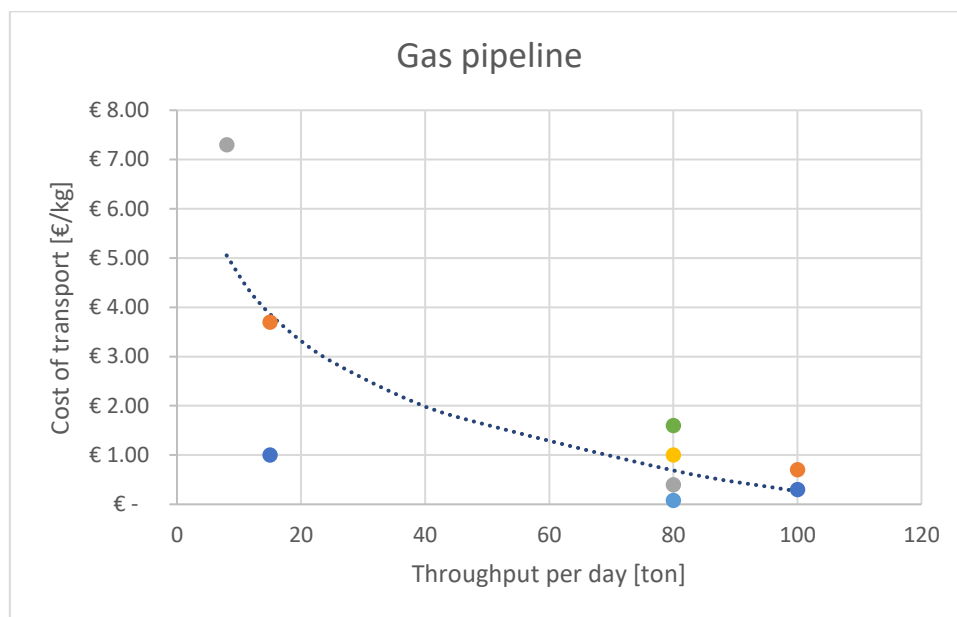


Figure 41 Cost of transport using a gas pipeline

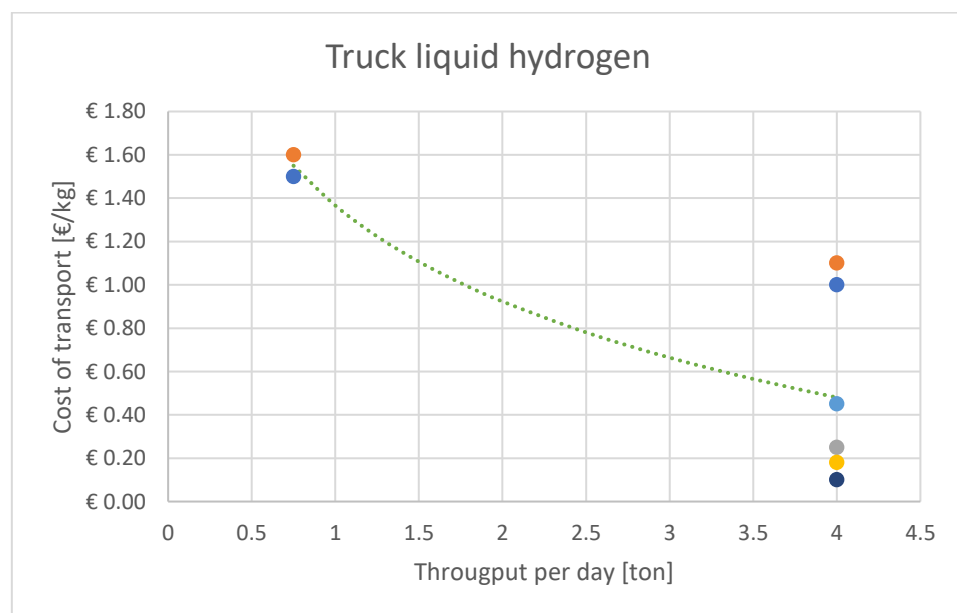


Figure 42 Cost of transport using a truck with liquid hydrogen

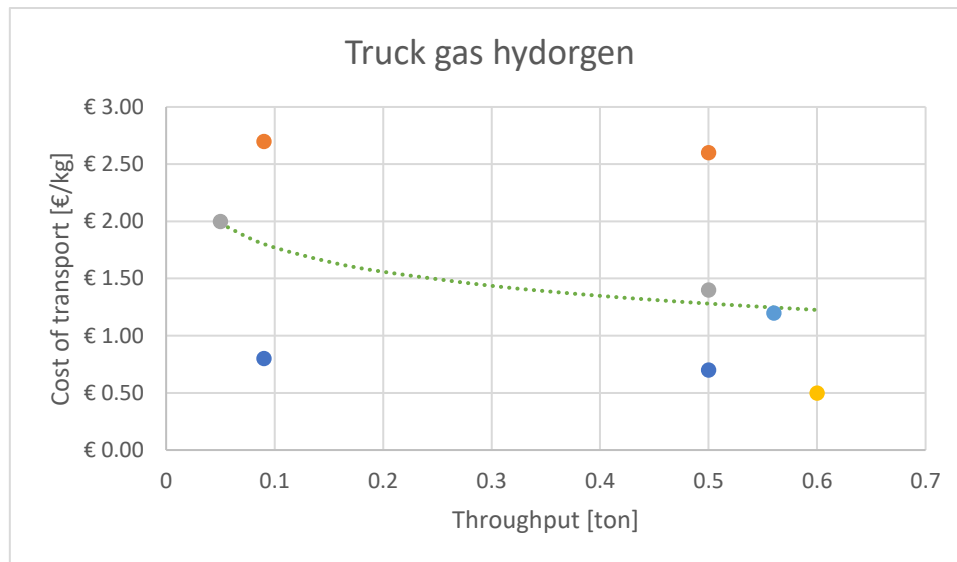


Figure 43 Cost of transport using a truck with gaseous hydrogen

From the figures, it becomes clear that each of the methods has economies of scale. However, cost reductions differ. Moreover, each of the methods operates in a different throughput range. Conventional fuels are all liquid and transported by truck or pipeline. CNG is mostly transported by truck or pipeline.

Question: Currently, most of the hydrogen is transported in a liquid or a gaseous state by truck. Only the station in Rhoon is connected by pipeline. What do you think will be the dominant transport method?

Literature used in this analysis

(Adolf et al., 2017; Brey et al., 2018; Demir & Dincer, 2018; European Commission, 2013; Kim et al., 2008; Miller, 2017; Mintz et al., 2007; Ramsden et al., 2013)

Fuelling station

How will the refuelling of trucks develop? Currently, heavy duty vehicles such as busses and some trucks use 350 bar. However, the new Toyota truck uses 700 bar fuel tanks.

A solution that is still tested is binding hydrogen to a compound such as H_2 -fuel.

Question: What you think about this option?

I found it very difficult to find any literature about heavy duty fuelling station.

As there are currently only a few hydrogen fuelling stations, let alone heavy-duty fuelling stations.

- Current fuelling speed for cars at 700 bar is approximately 1 kg/min. Maximum fuelling speed according to SAE regulation limited to 3,6 kg/min.
- Currently heavy duty is around 1-2 kg/min. SAE states that heavy duty refuelling maximum fuelling speed = 7.2 kg/min at 350 bar.
- Why is the standard for heavy duty not 700bar? This would take less space in fuel tank. Are there other standards for 700 bar than for 350 bar fuelling?
 - o I have read plans for hydrogen 700 bar high-flow (H70HF), stating a speed of 10 kg/min (Fuel Cells Bulletin, 2019)

Question: what do you think will be the fuelling standard for heavy duty vehicles? What developments do you see in the future?

With fossil fuels, the cost component of the fuelling station approaches zero as the utilization and size of the station due to economy of scale.

The literature about the cost component of the hydrogen heavy duty fuelling station is also limited. I'm aware that all sorts of factors influence this price.

- The utilization of the station
- Size of the station
- Mass production

I have found data of the cost component of fuelling station: ranging from 4-10 euros per kg.

Question: How will the price of the fuelling station develop? Does the price component approach zero as well, similar to fossil fuel?

Literature used in this analysis

(Doedijns Group International, n.d.; Melaina & Penev, 2013; Reddi, Elgowainy, Rustagi, & Gupta, 2017; Schneider, 2012; Weeda, 2015)

Vehicle

Fuel cell

In the literature i find numerous fuel-cell methods, but only a few methods are suitable for vehicles: PEM, AFC (and SOFC).

Question: Is there any technique missing in this category?

The efficiency of the PEM fuel cell is around 50% currently. This is expected to develop to 70 % in the future. How about other techniques?

Question: What is the efficiency of a fuel cell (currently available)? How are these expected to develop over the years? What technologies are relevant for improvement?

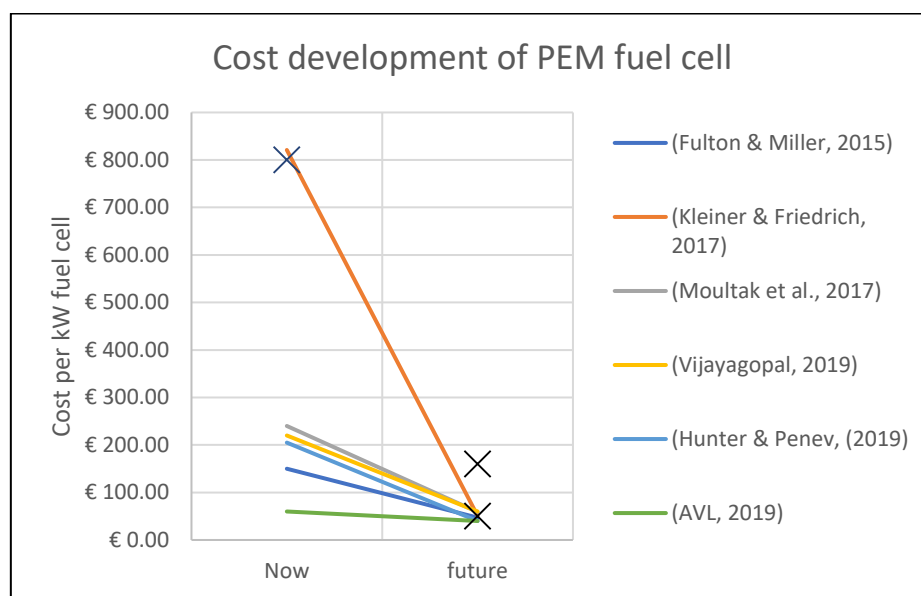


Figure 44 Price development of PEM fuel cell

In figure 44 there is a clear trend, roughly from 250 euro/kW towards 50 euro/kW.

Question: How will the price of fuel-cells develop in the future? For PEM, AFC and SOFC.

Some scholars say that because the efficiency of diesel is still relatively low there is still a lot to improve, compared to an electric engine that has already in >90% efficiency. However, others like Navas (2017): diesel efficiency development is limited so Fuel-cell technology might benefit more from fuel-cell efficiency development.

Question: What is your opinion about this?

Hydrogen tank

How will the storage in fuel tanks of trucks develop? Currently Heavy-duty vehicles such as busses and some trucks use 350 bar. However, the new Toyota truck uses 700 bar fuel tanks. Hydrogen can also be bounded to a carrier which increases the density reducing the required size of the fuel tank. For instance with the concept of “h2fuel” (see attached file)

Question: How will these techniques develop in the future? What will be the dominant technique?

How much impact does the density of compressed hydrogen have on the range of the truck? With diesel, a truck wants to carry enough fuel for a day, this requires a large fuel tank. In my case (500 kg/day) a truck would need 35 kg of hydrogen, this requires a tank of 1.5m³ at 350 bar or 0.9 m³ at 700 bar.

Question: Given the density of hydrogen I don't think it is desirable to carry tanks with a total of 1-1.5m³. The trucks will carry at least enough hydrogen to drive the legal driving time and refuel after the break. During the day the tanks are refueled. What is your opinion about this?

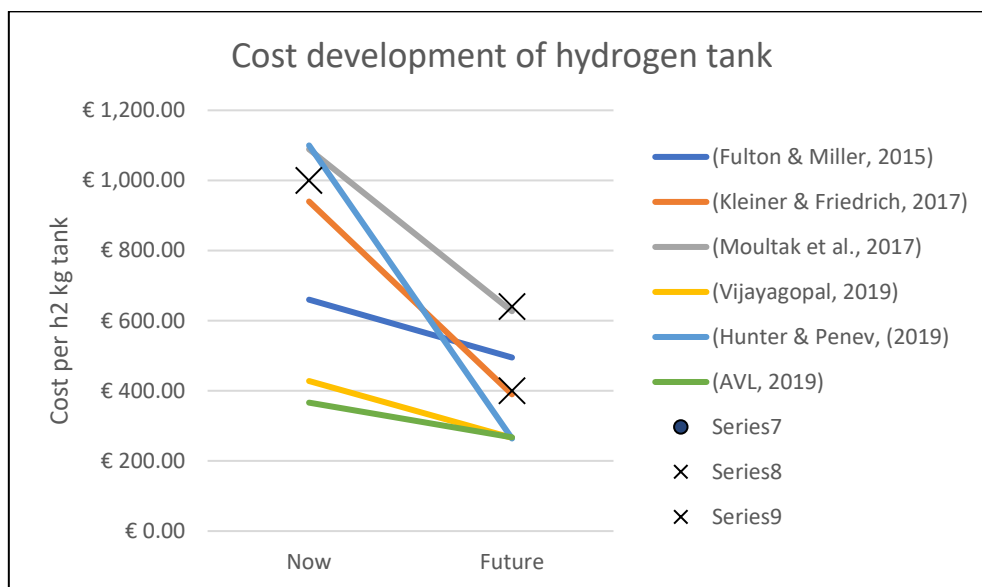


Figure 45 Price development of hydrogen fuel tank technology 350 and 700 bar combined

This includes both 350 and 700 bar tanks. It was difficult to collect data for this topic, that is why I combined it. Storage at 700 bar is roughly a few euros per kWh more expensive than storage at 350 bar.

Question: What price developments are expected for fuel tanks?

General truck questions

Question: What is the additional cost of a hydrogen fuel-cell truck besides the fuel-cell, h2-tank, electro motor and battery?

Currently the hydrogen fuel-cell trucks are created by switching parts of a diesel truck. In the future this will probably change to mass production.

Question: What impact does changing to mass production have on the price of a hydrogen fuel-cell truck? (learning effects)

Literature used for this analysis

(Fulton & Miller, 2015; Hunter & Penev, 2019; Kleiner & Friedrich, 2017; Resende, 2019; Vijayagopal & Rousseau, 2019)

Routes

The final products of my thesis consist of the calculation of the TCO and comparing it with the TCO of a diesel truck. This is done for several hydrogen production routes (a combination of a method for production, distribution and refuelling).

I used three decision variables of transport companies, namely **availability, affordability and robust operation** to assess if they would consider a hydrogen fuel cell truck.

These criteria are operationalized. For availability and robust operation this is difficult, that is why these criteria are represented by a set of requirements. Affordability is measured using the TCO method.

If the criteria are combined, the following situation is created: The requirements from the criteria availability and robust operation create boundary conditions in which routes are evaluated based on affordability.

Question: What do you think of the criteria and operationalization of the criteria?

The requirements are:

Requirement	Definition
Available	
There should be abundant hydrogen available.	There should be enough hydrogen to fulfill the demand of hydrogen of all sectors. For instance: Industry, chemistry and transport sector. Moreover, the production of hydrogen should be large enough, so economy of scale effects can occur.
Renewable energy should be used to produce hydrogen	During the production of hydrogen there should not be any CO ₂ emitted (netto).
The hydrogen production should be energy efficient	
There should be a network of hydrogen distribution	There should be a network in place that could fulfill the demand of the hydrogen fuelling stations.
There should be enough throughput of hydrogen to facilitate the demand	There should be an efficient method to distribute the hydrogen.
There should be a hydrogen fuelling station network	Along the major highways (Ten-T freight road network) there should be a fuelling station every x kilometers that is able to refuel hydrogen trucks with high speed.
The HRS should refuel trucks in a comparable time as diesel fast fuelling stations.	Diesel refuelling time between 5-10 minutes. Similar refuelling times.
There should be a hydrogen fuel-cell truck available at large truck OEMs.	
Robust operation	
The hydrogen tank should be large enough to contain enough hydrogen to drive at least x hours.	Truck drivers must take a break after x hours of driving. The fuel tank should be large enough to be able to drive until the next mandatory break.
There should be a sufficient covering network of HRS.	This entails that trucks should not have to make a detour to reach a hydrogen fuelling station.

Based on this list of requirements several hydrogen production routes are not possible.

Question: what do you think of the list of requirements?

Table of possible options. A theoretical number of options $10 \times 3 \times 2 = 60$ options.

#	Production	Distribution	Refuelling
1	SMR	Pipeline (gas)	Gas 350 bar
2	SMR + CCS	Truck (gas)	Gas 700 bar
3	Coal	Truck (liquid)	
4	Coal +CCS		
5	Biomass low		
6	Biomass high		
7	Wind & Sun electrolysis		
8	electrolysis low temp		
9	electrolyse high temp		
10	Nuclear		

Table of selected routes based on the requirements and selection.

	Production	Distribution	Refuelling
1	SMR + CCS	Pipeline (gas)	Gas 350 bar
2	Biomass high	Truck (liquid)	Gas 700 bar
3	Wind & Sun electrolysis	Pipeline (gas)	Gas 700 bar
4	electrolysis low temp	Truck (liquid)	Gas 350 bar
5	electrolyse high temp	Pipeline (gas)	Gas 700 bar
6	Nuclear	Truck (liquid)	Gas 350 bar

Comment: based on interviews I decided to add a route with Local electrolysis.

Question: What do you think of the routes i selected for my analysis? Do you miss a certain route?

Question: What do you think of the approach that is used to setup this analysis?

E. Interview reports

Multiple interviews are performed to verify and validate the literature that is found with experts. In this appendix the interview reports are presented. The following people are interviewed.

- Bilim Atli-Veltin
- Cemil Bekdemir
- Ruud Bouwman
- Robert van den Hoed
- Karin van Kranenburg
- Dirk Schaap
- Ruud Verbeek
- Marcel Weeda
- Ad van wijk
- Steven Wilkins

The interviews are semi-structured. This means that the experts received the results of literature review together with questions beforehand. The experts are selected based on their expertise of one or more of the topics of my research. That is why, not every question is answered by every expert. The interview reports consist only of the questions and answers the expert could respond to or felt expert on.

Bilim Atli-Veltin
Datum: 6 th of June
General
Bilim Atli-Veltin works at TNO structural dynamics as a scientist researcher. She focuses on composites, crashworthiness, cryogenics, LNG and hydrogen. Structural dynamics focus on testing the limits of materials in terms of among others heat and pressure and safety. A pressurised vessel can be tested on among others ruptures, punctures, heat expansion and permeability.
Hydrogen tank
Question: What are possible storage techniques of hydrogen
<p>There are several options:</p> <ul style="list-style-type: none">- 350/700/900 bar hexagon composite tanks type 4- Cryo-metal tanks- liquid organic storage <p>These are all techniques that are being developed currently. Some are already mature techniques like the 350/700 bar tanks. However, the tank types are still developing, hence the type 4 indication. The type indicates the material of the fuel tank. Type 3 are metallic tanks and type 4 are plastic tanks.</p> <p>Cryogen or liquid hydrogen tanks are kept at -252°C. This impacts the thickness of the fuel tank wall. Moreover, this also requires more equipment for cooling for instance.</p> <p>Liquid organic storage. Hydrogen is connected to a so called 'carrier'. This increases the energy density (kg/m³) allowing to transport more hydrogen using the same size truck. However, this is only in research stage.</p>
Question: Which of these techniques are currently feasible for fuel tank application
The first vehicles use either a 350 bar or a 700 bar gaseous tank. Buses use 350 bar and passenger vehicles use 700 bar.

Liquid hydrogen is currently not an option as it requires large cooling systems to maintain the temperature.

Interesting people to talk to:

- Mark Roeland from process chemistry expert on hydrogen
- Dick Abma did an economic assessment on hydrogen-powered ships

Cemil Bekdemir

Datum: 1st of July

General

Cemil Bekdemir working at TNO Powertrains as a senior scientist specialist. He focusses on thermodynamics, Thermo-physical properties, Combustion Chemistry, Fuels, Combustion Engines and Hydrogen Fuel Cells.

Fuel cell

Question: What is the efficiency of a fuel cell (currently available)? How are these expected to develop over the years? What technologies are relevant for improvement?

Fuel-cell system efficiency is difficult to pinpoint. Fuel-cell stack with the balance of plant components around it. This definitely causes losses. The configuration of the balance of plant in terms of cooling, valves, pumps. The best example of fuel-cell efficiency is the VDL example, they assume 50%.

Future values of 60% efficiency seem realistic.

Question: How will the price of fuel-cells develop in the future? For PEM, AFC and SOFC.

PEM will remain the best options only in the event of other fuel-cell technology breakthroughs, higher efficiencies are possible. This will be mentioned in the discussion.

Question: How will the electromotor efficiency develop in the future

90% is already quite high, so no development is expected.

Hydrogen tank

Question: Given the density of hydrogen I don't think it is desirable to carry tanks with a total of 1-1.5m³. The trucks will carry at least enough hydrogen to drive the legal driving time and refuel after the break. During the day the tanks are refueled. What is your opinion about this?

These techniques develop really slow. For some years there is research to store at a higher density (kg/m³). However, this has not been successful.

Question: What price developments are expected for fuel tanks?

€1000 → €600 per kg. This is similar to the battery price development. That is also expected to decrease tremendously, however there is no consensus to which extent. Desk study indicates different prices than in reality.

General truck questions

Question: What is the additional cost of a hydrogen fuel-cell truck besides the fuel-cell, h₂-tank, electro motor and battery?

Balance of plant component are really dependent on the configuration. High pressure system or low pressure systems.

Current price of fuel-cell system approximately 2,000-3,000 euros per kW.

Important to consider the scale of production. One never buys 1 stack, mostly in bulk.

The prices only drop to this extent if large production scale: 100,000+ stacks.

The balance of plant cost should decrease, all the components are known already. So this can also decrease multiple times. But to which extent is difficult to pinpoint.

Question: What impact does changing to mass production have on the price of a hydrogen fuel-cell truck? (learning effects)

There is not that much experience with this.

The parallels with full-electric trucks. 2 to 2.5 times higher than a regular truck. FC truck 3-3.5 times more expensive.

The size of the FC and electromotor (kW) are depending on the price of the components. If a large decrease in one component (f.e. fuel-cell) , one could choose to pick 250 kW instead of 100kW for the fuel-cell. The electromotor changing the other way around.

Residual value, difficult to say, a lot of components can easily be replaced like valves, pumps etc. Other components like the fuel-cell stack can be restored easily.

Ruud Bouwman

Datum: 20th of June

General

Ruud Bouwman works at VDL Since 1998 I started at VDL Enabling Transport Solutions (ETS) in the strategy department. He works with new development: self-driving, hydrogen, battery electric vehicles.

Multiple projects with hydrogen:

- H2 buses built and now focusing on H2 trucks

Prices, 100% diesel, <100% electric with extra bus logistic, >200% h2. The extra cost of h2 consists of 40% extra fuel and 60% extra system cost (tech, FC+Balance of Plant, tanks, DC/DC and cooler)

If we get it to 120% then there are multiple applications like a coach, regional bus and long-haul truck.

Challenges and requirements for getting the 120% This is possible if the following issues are solved:

1. 2,200 €/kW → <800€/kW
2. H₂ price 10 → 3.5 Euro/kg
3. Volume density h₂
4. Refuelling facilities

Issue 1: cost of the FC system, 700 Euro/kW (stack) in the Toyota Mirai already. the system is first step in th reach to Economy of Scale. The literature describes prices of 50 Euro/kW at 300,000 per year for FC stack which is again 10-20 times cheaper.

Issue 2: the price of hydrogen. Currently it is possible to produce at <2 Euro/kg with solar panels in Australia and Saudi-Arabia. Currently, it is possible to produce blue-hydrogen as waste hydrogen. This is under 3.5 Euro/kg. In the future this is also possible for green hydrogen. Matter of Eco of Scale

Issue 3, Volume: H₂: 350 bar, 1,400 L volume gives you 500kWh ~30 kg h₂~300-400 km (16,5 kWh/kg at 50%) Diesel: 165 L → 500 kWh (3kWh/L 30%)

700 bar is possible, but you can't fuel it back-to-back in large quantities, let alone high speed.

A study from a student from the Fontys at Eindhoven did a study and found 32 types of fuel storage. Options like: 350 bar, 700 bar, methanol, sodium-boron hydride. Potassium-boron hydride, magnesium hydride(s), silicon fuel, hydroxide etc.

Currently I have 30 kg in the tanks I would like to go to 80 kg.

Issue 4: Currently not able to fuel 700 bar in the quantities you need. Now around 1 kg/min and fuelling station @Helmond 60 kg/day. So, 1 truck would be good, however the fuelling time of the second truck would take the rest of the day.

Electric vehicles for regional distribution, 120km range and fast charging at distribution centers
Fuel-cell has 50% loss which is 100% heat, so you require a lot of cooling
Under the cabin of the driver is the climate system.

According to European regulation, you must be able to go downhill without charging your batteries and using the brakes. The problem is that we need to be able to drive a slope of 6% downhill for 6 kilometers without using the brakes, so you need a large cooler and brake resistance. So, the cooler needs to be able to handle this completely

Fuelling station

Question: what do you think will be the fuelling standard for heavy duty vehicles? What developments do you see in the future?

With fuelling the h2 heats up so you need cooling. All sorts of options like overflow using 500 bar H70HF seems interesting and will probably happen.
I don't really see a problem with this. If vehicles are available than fuelling infrastructure will be provided. With the AFID for instance. But if you tell Shell you need x million-ton h2 a year they will probably be happy to provide it for you.

Fuel cell

Question: How will the price of fuel-cells develop in the future? For PEM, AFC and SOFC.

If VDL buys only a stack than it would be probably 800-1,000 Euro/kW. 250-300 might be only material cost (Unknown figures, or only theoretical). 50 Euro/kW seems valid for the future situation.

Currently: 2,200 euro/kw for stack + balance of plant. So roughly 800-1,000 for stack and rest for BoP

Hydrogen tank

Question: How will hydrogen storage techniques develop in the future? What will be the dominant technique?

If liquid or h2-fuel than volume is reduced but weight is increased. With Liquid you can store 70 kg/m³ theoretically but if you consider the storage tank you end up with ~30 kg/m³.

With sodium-Borum hydride you can store much more over 50+ kg/m³ but if you take the chemical plan into account this is much lower.

H2-fuel: You need a chemical plant to extract the h2.

Question: What price developments are expected for fuel tanks?

Indicated prices of 1,000 euros currently, seem valid
Purchases tanks of of 8 kg costs 8,000, however extra cost for safety valves etc. are expensive 10,000 for valves.

From your graphs you can see it something is wrong is not yet clear what it will be, the prices are totally not clear yet.

Lower TRL levels so a lot of guessing, scholars look at industry and vise versa.

General truck questions

Question: What is the additional cost of a hydrogen fuel-cell truck besides the fuel-cell, h2-tank, electro motor and battery?

All sorts of components: 2x cooler, humidifier, filters, compressors, DC/DC, heater. All sorts of valves. All sorts of control units. Compressor is 8k already, Valve of 8k, Special de-ionizing Filter, Most are included in Balance of Plant. If you take a lot of small tanks your additional cost increase as more valves, pumps etc.
Question: What do you think of the routes i selected for my analysis? Do you miss a certain route?
It depends on the situation what the route will be. We clearly don't know how it will be. We haven't decided on the standard, so all options are still open.

Robert van den Hoed
Datum: 7 th of June
General
Robert van den Hoed is a professor energy and innovations at the Hogeschool of Amsterdam (HvA) First, he was an advocate of hydrogen, but this turned and now he is more sceptic. Ten years ago, zero-emission transport should be accomplished with fuel-cell technology. Back then, battery electric vehicles were not an option. Then, the prices of lithium-ion batteries dropped 5-6 times. BEV is improving, and everything is now possible with BEV. The range of BEV is improved tremendously
Most important reason: There has been a fuel-cell price reduction, but not to the extend as the lithium-ion battery.
I'm convinced by the simplicity of BEV, just an iPad on wheels with a large battery. Whereas, the FCEV has: heat exchanger, heat pumps, mechanical parts → more complicated parts.
Could it be possible that this price reduction is still going to happen?
If fuel-cell systems have that much potential, there would already be greater price reductions. Given the price reduction of the last 10 years. On the other hand, we don't really know what will happen and how this will develop.
Production
Question: What is the efficiency of hydrogen production? In the literature, I have found these methods with these bandwidths of efficiencies. How are these expected to develop over the years? What technologies are relevant for improvement?
SMR: 80% efficiency seems a bit high to be honest. Split this into small- and large-scale plants being centrally and locally produced. SMR already standardized, only economy of scale → this will win a few %-point. Electrolysis: maximum of 80% also relatively high? Check if possible. There is a theoretical maximum here. Which forms of electrolysis are included here? Don't think there is much development in this part. Check for high temp PEM
Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?
SMR and Coal seem logical, fully developed techniques. Strange that coal + ccs is relatively cheap. For Electrolysis you need a lot of equipment, relatively high material intensive production plants. I doubt if the prize will be lower than 3-4 euros. If energy prize drops than only electrolysis cost. This would only be comparable price doubles.
Distribution
Question: How will hydrogen be transported to the fuelling stations? I have found the following method with costs of throughput
Compare cost of trucks with each other. The pipeline is a completely different scale. The price differences between truck gaseous and truck liquid makes sense as a liquid truck can carry 8 times more on 1 trip.

The problem with the pipelines is that building the infrastructure costs a lot of money. However, some experts say that the current natural gas network can be adjusted relatively easily to accommodate hydrogen.

Add another production route for local production with Electrolysis in which there is no transportation needed.

Fuelling station

Question: what do you think will be the fuelling standard for heavy duty vehicles? What developments do you see in the future?

Speed of refuelling isn't an issue, if the fuelling speed is 5 or 10 kg/minutes doesn't really matter. 5-10 minutes fuelling time isn't an issue.

Question: How will the price of the fuelling station develop? Does the price component approach zero as well, similar to fossil fuel?

Increasing volumes → price will drop because of economy of scale. Still some expensive parts so not to zero, the prize will probably drop to below 1 euro. Cooling installations will be rather difficult.

Fuel cell

Question: Is there any technique missing in this category?

AFC is outdated, no further development. Same for SOFC, requires a constant operation, high heat. PEM is improved AFC. Only methanol might be an option → check Smart fuel-cell.

The efficiency of the PEM fuel cell is around 50% currently. This is expected to develop to 70 % in the future. How about other techniques? Seems rather high 70%.

Check actual efficiency with tests in the real world.

Question: How will the price of fuel-cells develop in the future? For PEM, AFC and SOFC.

Thought around 200-400 euro/kw.

Check for fuel cell system cost instead of fuel-cell stack only price. System price = fuel-cell stack + initial of fuel cell. The system requires all sorts of hoses and cooling systems, heat exchanger.

Some scholars say that because the efficiency of diesel is still relatively low there is still a lot to improve, compared to electric engine that has already in >90% efficiency. However, others like Navas (2017): diesel efficiency development is limited so Fuel-cell technology might benefit more from fuel-cell efficiency development.

Question: What is your opinion about this?

Diesel will improve a few %-points at most, already 20 years in development and billions of dollars

General truck questions

Question: What is the additional cost of a hydrogen fuel-cell truck besides the fuel-cell, h2-tank, electro motor and battery?

Important to check for complete fuel-cell system, not only the fuel-cell stack. Balancing the system, pressure the system, heat exchanger. Cooling the system.

Routes

Table of selected routes based on the requirements and selection.

#	Production	Distribution	Refuelling
1 <u>central</u>	SMR + CCS	Pipeline (gas)	Gas 350 bar
2	Biomass high	Truck (liquid)	Gas 700 bar
3 <u>central</u>	Wind & Sun electrolysis	Pipeline (gas)	Gas 700 bar
4	electrolysis low temp	Truck (liquid)	Gas 350 bar
5	electrolyse high temp	Pipeline (gas)	Gas 700 bar
6	Nuclear	Truck (liquid)	Gas 350 bar
7	Local electrolysis	No	Gas 700

Question: What do you think of the routes i selected for my analysis? Do you miss a certain route?

Local electrolysis ← has no distribution

local SMR ← will not get CCS so no option in the end. Maybe a column on the right that gives implications of the route.

Karin van Kranenburg

Datum: 13th of June

General

Karin van Kranenburg works at TNO Strategic Business Analysis (SBA) as Expertise Consultant Senior, doing business cases, economic analysis and strategic advice.

The structure of your thesis seems logic. You need to produce-distribute-refuel hydrogen.

When comparing diesel with hydrogen what do you consider? The diesel price consists of a lot of BTW. Really decide how you compare and describe this in detail. You can go all over the place with such analysis.

Really decide and describe your base case.

There are tools to predict end prices after mass production.

Hychain2, Yvonne van Delft of Maria Saric, Solar farms in Sahara in cases for Turkey or Morocco.

Cost model for import of H₂.

- Using an electricity cable
- Gas
- Liquid
- Methanol

Karin got the feeling that the costs wouldn't be that much lower or even a bit higher cost. This will be mentioned in the report.

North sea energy project really doesn't make sense. Really expensive. Cost of electrolysis plant offshore is really costly.

Production

Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?

@Document send by Karin: Prices of production of hydrogen methods. SMR, ATR, PEM and alkaline. Enpuls tech report

@document that sent reports: 1.1 for SMR H₂, 1.4 for SMR+CCS and 2.8 for green H₂

@last 3e report the business case, chemical plant electrolysis. Was based on Nurion (part of AXO) plant in Groningen.

@1e rapport technical and economic characteristics of production methods.

Distribution

Question: Currently, most of the hydrogen is transported in a liquid or gaseous state by truck. Only the station in Rhooen is connected by pipeline. What do you think will be the dominant transport method?

Link Enexis study 'impuls' innovation part: question: can green hydrogen be used to balance the energy system as farmers put their roofs full of solar panels. Transporting this H₂.

The production scale is really important.

Transport cost.

Check the cost I found with the reports I go

Pictures of compression

Pipeline

If electricity price drops than we can go underneath 3 euro. Long term 2 euro if the electricity price really drops. Currently the electricity price is really depended on grey energy sources. If we got more wind energy and less dependent on gas. Than the price can drop even further.

Hydrogen tank

Question: What price developments are expected for fuel tanks?

Tanks are developed for quite some time. So price development should be known. Compare to LPG and CNG tanks. Prices should be similar.

Routes

Question: What do you think of the criteria and operationalization of the criteria?

Your structure is good

Question: what do you think of the list of requirements?

Good list of requirements

Dirk Schaap

Datum: 22th of February

General

Dirk Schaap is a policy advisor responsible for hydrogen in mobility at the Ministry of I&W. This is a sensitive topic at the ministry.

The hydrogen technology is not the problem. The business case and the availability of hydrogen are the problems.

Hydrogen platform, founded by private parties, "waterstofplatform" similar to "waterstofnet" but then focused on the Netherlands. Primary goals: Inform about hydrogen and the possibilities.

<https://opwegmetwaterstof.nl/2018/07/17/waterstof-veiligheid-innovatie-programma/>

Hydrogen is already used in other industries, is there enough hydrogen available for the transportation sector?

Yes, there is more than enough, currently a lot of hydrogen is flared. However, most of the hydrogen is grey hydrogen, hydrogen produced with fossil fuels which cause CO₂ emissions.

We would like to stimulate the usage of hydrogen. Start with using grey hydrogen and change towards green hydrogen with blue hydrogen as an intermediate option.

Why is the refuelling infrastructure not publicly available

One cannot guarantee that you actually get 1 kg, due to limited measuring instruments, temperature and pressure at the refuelling stations. So for consumer protection, they are not public.

There are currently 12 applications for subsidy for building an HRS. However, the HRS is not built due to limited demand for an HRS. One would typically need around 10 buses or 10 trucks to have a solid business case. This can also be accomplished with 70 to 100 passenger vehicles.

The hydrogen price is fixed to €10 per kg. In the future, €4 to €6 per kg is possible, so it approaches the marginal cost.

An important point in the business case remains the economy of scale.

When is the TCO approximately the same?

This is an interesting question for the ministry, Which instruments can the Ministry use to make the TCO comparable.

What kind of learning effects can be expected?

Difficult to say, only 2 trucks currently on the road, for instance the Kenworth hydrogen truck in the harbor of Los Angeles.

One could look into the price reduction of hydrogen buses:

4 years ago 1.5m per bus

Now eu project 8.5

Next 5.8 ton

1,000 buses for 4-5 ton in a French / Norwegian order

Ruud Verbeek

Datum: 8 th of July
General
Ruud Verbeek works at Sustainable Transport and Logistics as a senior technical consultant. In the past Ruud performed a hydrogen feasibility study for the application of a ship.
It is Important to define what kind of heating value you, use. There is something to say to use both LHV and HHV. So explicitly mention what you choose.
Production
Question: What is the efficiency of hydrogen production? In the literature, I have found these methods with these bandwidths of efficiencies. How are these expected to develop over the years?
The efficiencies seem to have a good bandwidth, The wind and solar electrolysis efficiency align with that of solar/wind energy production efficiency. The solar capacity is higher in sub-Sahara countries. One could even say that efficiency is lower due to too much sun intensity.
Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?
Only cents on the kg for distribution for hydrogen using a pipeline when investment cost is fully depreciated.
Distribution
Question: Currently, most of the hydrogen is transported in liquid or gaseous state by truck. Only the station in Rhoo is connected by pipeline. What do you think will be the dominant transport method?
Either gaseous or liquid transport seem to be the best option. A solution that is still tested is binding hydrogen to a compound such as H ₂ -fuel.
Question: What do you think of chemical storage.
Seems a complicated procedure, which is still in the development procedure. This is a complicated process for a relatively simple step.

Marcel Weeda
Datum: 18 th of June
General
Marcel Weeda, senior consultant at ECN part of TNO at the department of Energy transition studies Liquid seems a good option for trucks as they require a lot of hydrogen. → this is not yet possible as very low temperature. This requires a lot of cooling and larger tanks with thicker walls. The liquid option will be mentioned in the recommendations as possible future technology.
Production
@enpuls tech report vs business case report: Why do you use the LHV for the business case but in the tech report you mention that HHV is used for PEM systems.
There is no golden standard, it is important to mention what you use when reporting efficiencies. So with production HHV and for the FC it is often LHV. The efficiency isn't really important. This really depends on the setup. You can take a higher efficiency but lowering the productivity and lifespan. Nuclear is possible, however it is high investment high risk. Locations are assigned but no one wanted to build it and take the risk. Only one new project is known, but they made a deal to get a guaranteed price of above 100 euro/MWh which is really high.
Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?

In Enpuls multiple prices are mentioned however, SMR+CCS large scale isn't considered. I understand that the price of SMR would increase but this wouldn't necessarily mean that the SMR+CCS should increase right?
@report Enpuls: SMR-CCS is 0.5-1 euro more expensive than regular SMR.

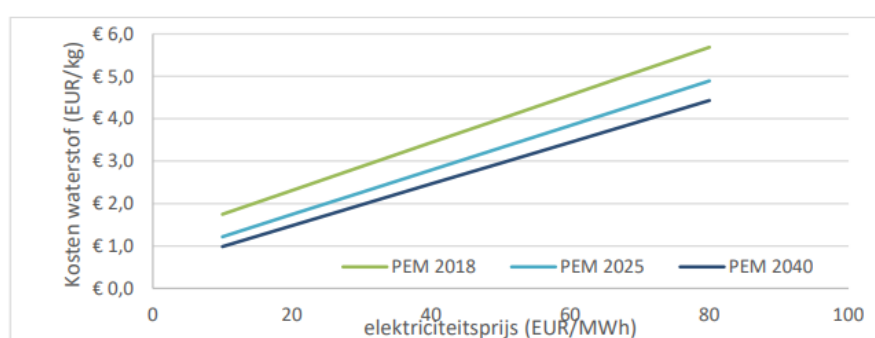
There is a clear connection between electricity price and hydrogen price. To what extent will the electricity price drop?

Do you think it the price will drop? If the energy price is less dependent of grey energy sources. It is possible to that it would drop, However you need to think about a few things:

Balancing the system because of fluctuating supply of energy. Requires extra investment

You need some capacity of adjustable energy supply. This with relatively high cost and low operating time so higher price.

I haven't seen a lot of decreasing energy prices. Take the current energy price and take a bandwidth. The current price of large customers that take a large amount is around 35 euro/MWh. For large scale central production. This means prices of 2.1 - 2.9 in 2050 and 2020



Bron: Enpuls Groene Waterstof Technologiebeoordeling

What do you think of the following prices:

@advanwijk Project with hydrogen Europe with all electrolyser manufactures. We are working on a roadmap 2030. We think that green hydrogen with electrolyser will be produced for 1.5-2 euro. Than it will be comparable with blue h2 (around 2025)

This is always difficult to say. If you take 35 euro/MWh for every 10MWh the price increases 35 cents. So with 35 MWh you quickly come to 2 euro not including the investment cost so you easily reach 2.5 euro. Only if energy price decreases to a minimum you would be able to end up at 1.5 euro.

We can reach 2 euro at the lowest, but 2.5 is more realistic

Distribution

Question: Currently, most of the hydrogen is transported in liquid or gaseous state by truck. Only the station in Rhon is connected by pipeline. What do you think will be the dominant transport method?

Trucks with gas: standard gas tube truck has 200 bar with 300 kilos. However, new tube trucks with composite tanks 500 bar with 1,000 kilo.

If I make assumptions for transport I usually pick 1.5-2.5 euro per km. If we pick a average distribution route from Rotterdam this is approximately 100 km (so trip 200km) $200 \times 1.5 = 300$ / $300 = 1$ euro/kg. So this aligns with your assumptions. If for liquid we take the highest price $200 \times 2.5 = 500$ euros / $4,000 = 0.13$ euro/kilo

Fuelling station

How will the refuelling of trucks develop? Currently, heavy duty vehicles such as busses and some trucks use 350 bar. However, the new Toyota truck uses 700 bar fuel tanks.

A solution that is still tested is binding hydrogen to a compound such as h2-fuel.

Question: How will the price of the fuelling station develop? Does the price component approach zero as well, similar to fossil fuel?

Difficult to say, but if you got fully utilized installations you can reach prices of 0.5-1 euro.

Portfolio powertrains Europe p38-p42 decreasing retail prices. Air liquid: if we can make dedicated stations and know what kind of demand we can expect, than we can do it cost effective. However, if we want to provide enough capacity for potential customers but this is unknown than you will have low-utilization of stations and economy of scale curves like in the p42 of the portfolio powertrain Europe. = higher costs
Fuel-cell
Question: What is the efficiency of a fuel cell (currently available)? How are these expected to develop over the years? What technologies are relevant for improvement?
Seems good, pick a bandwidth and argue for your decision. I usually take 55% efficiency for FC now.
Routes
Question: What do you think of the routes i selected for my analysis? Do you miss a certain route?
SMR with pipeline but also truck liquid. Import electrolysis, we are far away from this. Not in the near future, solar and wind farms need to be developed, converted to hydrogen and transport. From the HYCHAIN2 study they are looking into this. But the factors mentioned before create a relatively high price. Central electrolysis + truck seems logic. Local electrolysis seems possible, in this case the distribution will be zero. Electrolyser is connected to the energy grid. However, the more equipment you got at small scale at a refuelling station creates larger cost. Given lower efficiency.

Ad van wijk
Datum: 13 th of June
General
Part-time Lector Future energy systems at the department of Process Energy from the faculty Chemistry Engineering at the TU Delft. The introduction of hydrogen fuel-cell trucks is stimulated in a particular way. In Switzerland for instance, there is a toll cost for diesel trucks. With some simple calculations you see that hydrogen trucks have a lower TCO. So companies decide to go for these trucks. Economic reason In US, 800-1,000 trucks for Enheuser-busch. I want to distribute my goods CO ₂ neutral. Same in the Netherlands for IKEA and Heineken with green inland vessels. In the port of Rotterdam we are also working on a pollution tax for ships. In a few years there will zero-emission zones so no diesel in cities or kilometer tax. Three options: <ul style="list-style-type: none"> - Prohited - Customers demand it - Due to environmental measures (taxes etc) it is cheaper to take a green option. If you look at the literature available of efficiencies and hydrogen in general. Be aware that with such a fast changing technology the literature is often conservative. Speak with producers of electrolyzers like NEL or Thyssen Kruppe.
Production
Question: What is the efficiency of hydrogen production? In the literature, I have found these methods with these bandwidths of efficiencies. How are these expected to develop over the years? What technologies are relevant for improvement?
At this moment SMR is the dominant technique in the Netherlands. For natural gas + CCS they are looking into ATR. The techniques you use are the most common used techniques. Moreover, electrolysis. Alkaline and PEM, Alkaline is mature technique for production of hydrogen. In terms of efficiency: With the electrolysis the efficiency should be calculaded using the HHV instead of the LHV. @thyssen Krupp : alkaline electrolyzers mostly used to create chloor from salt using electolysis: 20 MW electrolyser has 82% efficiency.

Question: In literature I found the above visualized bandwidths of prices. How do you think this will develop over the years?

The electrolyser in Gronningen uses green energy to power the electrolyser. The rest product of the chlor production is sold to fuelling station for less than 3 euro's. This is green hydrogen.

Electrolysis with PEM and Alkaline nothing about high temp. Not useful as high heat with a bit higher efficiency but this doesn't compensate the extra cost.

Report green hydrogen economy in Noord-Netherlands. Electrolyser and biomass gasification. From the report prices of 2-3 euro are mentioned. However, with current prices of Capex electrolysers the price would be 2-2.5 from alkaline electrolysers.

I'm working with hydrogen Europe on a project with all electrolyser manufactures. We are working on a roadmap 2030. We think that green hydrogen with electrolyser will be produced for 1.5-2 euro. This is comparable with blue hydrogen from natural gas. SMR-CCS. They expect that this price will occur in 2025.

The electrolyser manufactures have published reports. They also check for the full chain of production to refuelling. Check NEL and Thyssen Kruppe.

Wind-hydrogen turbine. Reduces some complexity with integration the electrolyser to the wind turbine. This reduces a step of converting electricity with a AC/DC converter. This way you reduce cost. They say you can produce it for 2.5 euro ← this is local!!

Distribution

Question: Currently, most of the hydrogen is transported in liquid or gaseous state by truck. Only the station in Rhooen is connected by pipeline. What do you think will be the dominant transport method?

Three things are going to happen:

- Local production
- Excess or shortages with trucks. For now it will be gaseous. But in the future this will be liquid as the capacity of the truck is important.
- The small capacity of the gaseous truck will not be sufficient to supply a refuelling station.
- Pipeline, cheapest but not everywhere hydrogen pipelines.

Using gas network for hydrogen, so changing its purpose. 5-10% of the building cost of a new network.

Fuelling station

Question: What you think about this option?

This will definitely be 700 bar.

More about it at vehicle hydrogen tank

Fuel cell

Question: What is the efficiency of a fuel cell (currently available)? How are these expected to develop over the years? What technologies are relevant for improvement?

For Fuel cell techniques it is both Alkaline and PEM. Here PEM is the preferred technique.

Question: Why not Alkaline fuel cell?

To use Alkanline you would have to top up with kaliumhydroxide. For portable fuel-cells you choose a relatively simple membram: the PEM.

Hydrogen tank

Question: How will these techniques develop in the future? What will be the dominant technique?

H₂-fuel, This doesn't seem like a good route, too expensive. Seems far-fetched. This isn't seen as an solution for auto/truck. Maybe in the future for ships as the problem of storing fuel is more significant

This will definitely be 700 bar.

The hydrogen fuel tank was one of the techniques that needed to be developed. The requirements of this tank stipulated that it should be similar weight, dimensions to diesel tanks. Now the ratio

between fuel tank and fuel is reversed. For instance in a car: you refuel 5 to 6 kilos of hydrogen and the tank is around 50-60 kilo. Whereas with diesel you tank 40-50 kg and the tank is a few kilos. All techniques are developed in a modular way. Like the Toyota truck, it has 2 or 3 fuel-cells of the Toyota Mirai. And 7 or 8 of the fuel tanks.

There has been some testing with 350 bar. But this is not reasonable. No OEM tries this.

Routes

Table of selected routes based on the requirements and selection.

#	Production	Distribution	Refuelling
1	SMR + CCS	Pipeline (gas)	Gas 350 bar
2	Biomass high	Truck (liquid)	Gas 700 bar
3 import	Wind & Sun electrolysis	Pipeline (gas)	Gas 700 bar
4 local and central	electrolysis low temp	Truck (liquid)	Gas 350 bar
5 too expensive	electrolyse high temp	Pipeline (gas)	Gas 700 bar
6	Nuclear	Truck (liquid)	Gas 350 bar

Comment: based on interviews I decided to add a route with Local electrolysis.

Question: What do you think of the routes i selected for my analysis? Do you miss a certain route?

Get rid of 350 bar options. This will not be the standard.

High temp electrolysis the efficiency is a bit higher, the extra cost associated with this option isn't compensated with the efficiency increase. Focus on PEM electrolysis (low-temp)

Another obvious route is to import hydrogen from high sun dense/high wind

Electricity price accounts for 60-80% of all cost from electrolysis.

Steven Wilkins

Datum: 20th of June

General

Steven Wilkins works at TNO Powertrains as a senior research engineer. He works on the following topics: hybrid, electric, and fuel cell vehicle systems and powertrain modelling and simulation, and assessment.

1e Truck owner is usually -6 year. Design life 10 years: 1m-1.5m kilometers for a truck – 500*200=100k/year so ~10-15 years. Resale value isn't linear. A steep drop in the beginning and then it plateaus and then drop. If I consider 6 years than need to decide on resale value. The residual value is arbitrary. A safe option is to take 0 at the end of design life. However practical life time increases. With FCEV and BEV it is unknown what their resale value is and whether this will go up. Because in conventional vehicles, you got a lot of moving parts, break wear .

Operation cost: energy, time difference (extra time for refuelling).

The wage of the driver: either western-europe with cost per hour or eastern-europe with cost per kilometre

The 120 kWh is of such a size that it is worth it to plug-in to charge the battery. 50 kWh is the minimum for powering essential systems. However, the question is how you balance it.

How do you remove bias from your research. I give an overview of the numbers that are found. In case of outliers, I try to find at least two unique sources to confirm. After that I give my opinion about it.

Be aware that given the TCO costs are similar with small margins. The technology you choose wins. As generally speaking the more you invest the better your development.

Flexibility is crucial ← battery and fuel-cell. With infra and trucks. If you develop a truck that is only a good truck for 500 kilometer mission profile. That doesn't make sense. What is applicable for regional and urban is going to dominate OEMs and infrastructure and everything else. City and regional is a smaller percentage in vehicles sold.

50% of journeys are below 400 kilometers. Long-haul is an exception.

Currently the OEMs develop a long-haul truck and then they downsize it for shorter journeys.

It is difficult to do such an analysis in total isolation. If for instance h2 passenger cars are sudden becoming more popular you need to distribute much more infrastructure. So the infrastructure problem is kind of sold already.

Fuel cell

Question: Is there any technique missing in this category?

Alkanine, Solid oxide, but PEM is dominant.

Question: The fuel-cell efficiency is expected to develop in the future, to which extent?

Now between 50-55% system efficiency peak efficiency, with a long-haul constant profile. The bigger the battery closer to the peak. The bigger the fuel-cell the larger the efficiency. ~60% system efficiency is a good estimate.

Question: How will the price of fuel-cells develop in the future? For PEM, AFC and SOFC.

With prices it is important to distinguish fuel stack prices, fuel-cell system prices and only material cost. The cost of fuel-cells is going to drop. So the price of 50 euro/kw seems good.

Question: how does the fuel stack price relate to the Balance of plant cost? There are a lot of additional components needed.

The cost of Fuel-cell stacks vs balance of plant, I can see that it would be 800 euro/kW for a stack and 1,400 euro/kw for Balance of plant. In the future prices might drop to 200 to €600 euro/kW

Question: What price developments are expected for fuel tanks?

Moultak is a good source, really modular approach like your work.

General truck questions

Question: What is the additional cost of a hydrogen fuel-cell truck besides the fuel-cell, h2-tank, electro motor and battery?

Tractor and trailer got different life times, 10 years and 20 years.

1/3 is stack cost rest is Balance of plant. However this seems strange for future scenario.