# Exploratory research into the feasibility of a hydrogen fuel-cell tractor semi-trailer in long-haul freight road transport, now and in the future

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**Abstract**

Hydrogen as an energy carrier is seen as an important option to reduce the $CO_2$ emissions in the transport sector. However, limited research and experience are available on the drivers and barriers of using a hydrogen truck in freight road transport. This article deals with the following question: *Under which techno-economic boundary conditions a hydrogen fuel-cell tractor semi-trailer (hereafter called: hydrogen truck) is a feasible option for long-haul freight road transport in Europe?* In this article, the Total cost of ownership (TCO) is determined for different scenarios varying in routes for the production, distribution and refuelling and investment costs for a hydrogen fuelled truck. This article concludes that it can be an economically feasible option in the future under the given assumptions. The most influential factors on the TCO are the hydrogen price and the hydrogen truck cost. Insights from this study can be used to assist in the creation of policy measures to increase the uptake of zero-emission freight transport in the overall fleet.

**Keywords:** Hydrogen, fuel-cell electric vehicle, freight transport, TCO, zero-emission

## 1. Introduction

Heavy-duty road transport accounts for more than 4% of all GHG emissions. A large reduction potential is given by using different energy carriers and improving vehicle efficiency (Cuelenaere et al., 2014; Hill, Hazeldine, Einem, Pridmore, & Wynn, 2009).

Amongst other, bio-diesel, battery- and hydrogen-electric vehicles are potential candidates to replace diesel fuelled vehicles. Although bio-diesel can be Well-to-Wheel (WTW) zero-emission, the local (TTW) emissions will always remain. Electric vehicles have the advantage of being TTW zero-emission. The WTT emission depends on the method of electricity and/or hydrogen production. If renewable energy sources are used, the WTW is zero-emission. Battery-electric vehicles generally face range limitations. Hydrogen is a promising alternative to overcome these limitations. However, hydrogen trucks are not yet broadly available and at a less developed technological stage. Although being technically feasible, hydrogen fuelled heavy-duty vehicles still face many challenges to overcome before it can reach a large scale

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Current research and policies on 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 hydrogen refuelling station (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). The current HRS are not equipped with high flow refuelling equipment, which is often used by heavy-duty vehicles (Rijkswaterstaat, 2019). The same problem applies to the production of hydrogen vehicles. The Hyundai Nexo and Toyota Mirai are the only passenger vehicle models available in the Netherlands. 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).

The stage of deployment of HRS and hydrogen vehicles influence the costs. In the Netherlands, multiple permits for building an HRS are granted, however, they are not built due to limited demand for hydrogen (Schaap, 2019). The price of a refuelling station and indirect the price of hydrogen can decrease when large quantities of hydrogen are being sold. 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; Moultak, Lutsey, & Hall, 2017). At this moment, this is one-off production. In the future, with mass production, the price is expected to decrease, but it is uncertain to which extent, and when this will happen.

The current literature considering, on both technological and economic perspective hydrogen trucks as well as hydrogen as an energy carrier need to develop to be able to compete with a diesel truck. This study focussed on the following research question: *Under which techno-economic boundary conditions a hydrogen fuel-cell tractor semi-trailer is a feasible option for long-haul freight road transport in Europe?*

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

This article uses a TCO analysis to identify the boundary conditions for the feasibility of a hydrogen truck. While looking into the cost components of the TCO and comparing this with a diesel truck, the conditions for feasibility arise. Identifying these boundary conditions is important as it assists in creating policy to achieve the climate agreement.

The following section describes the TCO method used in this study and how the components are filled in. Section 3 describes the use case that is used. Section 4 discusses the components of the TCO for both the diesel and hydrogen truck. Section 5 discussed the results of the TCO analysis. Section 6 reflects on how the assumptions influenced the results. Section 7 provides the conclusion and policy recommendations.

## 2. Methodology

This article uses a TCO method to analyse the affordability of a hydrogen truck now and in the future. Literature reviews and expert interviews were used to fill in all the components of the TCO. Figure 1 shows the generic TCO framework, this consists of 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 (Bubeck, Tomaschek, & Fahl, 2016). In this study, the component costs and future projections of component costs were determined for both diesel and hydrogen fuelled trucks in order to make a direct comparison between both.

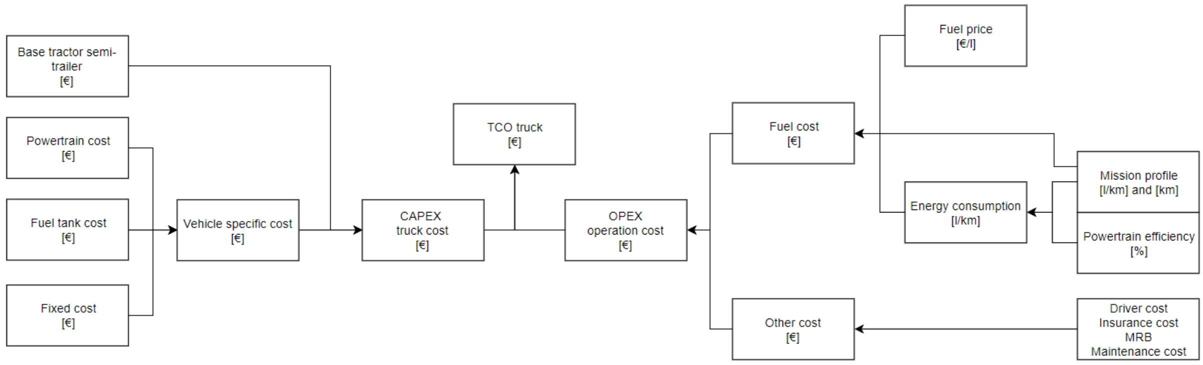


*Figure 1 Generic TCO framework*

A literature review was used to get a first estimate of the component costs and dependent variables. Semi-structured interviews were used to check the outcome of the literature review with experts in the field. The interviewed experts included scholars, civil servants, truck manufacturers.

## 3. Use case

To compare the cost of two different trucks, it is essential to look at the required performance. The mission profile is used to calculate the average energy consumption per kilometre given the route, tonnage, road type and type of vehicle (Meersman & Van de Voorde, 2016). The energy consumption is one of the components to determine the diesel or hydrogen fuel cost. The mission profile, seen in Figure 2, is created for a tractor semi-trailer combination (GWT 40 ton) that transports 25 ton for 500 kilometres to one destination. Given the different road types and associated speed limits, the average speed is approximately 70 km/h (no slope). 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.

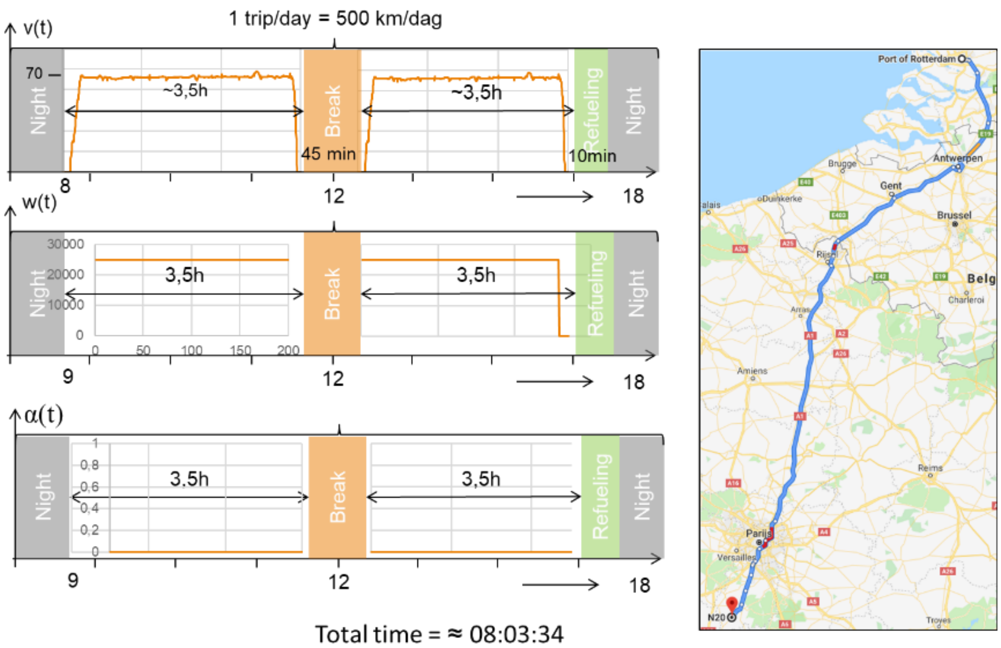


*Figure 2 Mission profile Diesel truck*

## 4. TCO analysis

The TCO of both the diesel and the hydrogen truck is calculated using the TCO framework shown above (Figure 1).

### 4.1. TCO Diesel truck

For the diesel truck, a new euro 6 diesel truck is selected with a 310 kW ICE and a 1,000 L fuel tank. The ICE engine is assumed to cost €65 per kW and the fuel tank €2 per L (Kleiner & Friedrich, 2017). An empty tractor without a power train costs €135.000 (Moultak et al., 2017). In total, the diesel truck cost is approximately €157,200. The residual value of the diesel truck is approximately €30,000. The cost of the diesel truck is assumed to remain the same since it is already fully developed.

The OPEX cost consists of the fuel cost and the other cost. As described in the TCO framework, the fuel cost is calculated by multiplying the diesel price, the diesel energy consumption per kilometre and the yearly mileage. The diesel price is assumed to be 1 euro per litre (CBS, 2019). The diesel energy consumption depends on the diesel powertrain efficiency and the Wheel power demand. The diesel powertrain efficiency is assumed to be 31%, consisting of the brake thermal efficiency of 43% and auxiliary systems efficiency of 72% (Delgado & Lutsey, 2014; Van Zyl, Heijne, & Ligterink, 2017). Give the selected mission profile and the powertrain efficiency, the diesel truck consumes 37 L per 100 km. This is calculated using the dynamic vehicle model developed by TNO (Van Zyl et al., 2017). The other costs are assumed to be €10,000 per year for maintenance and driver salary of €60,000 per year.

In the future, the TCO might change. Uncertain factors are the diesel powertrain efficiency and the diesel price. The diesel powertrain efficiency is assumed to increase to 40% due to the brake thermal efficiency increase from 43% to 50% (Delgado & Lutsey, 2014). Due to $CO_2$ emission regulation, the diesel price could increase towards €1,30 per L. The results of the TCO analysis can be found in paragraph 0.

### 4.2. TCO hydrogen truck

In contrary to the cost of the diesel truck TCO, the hydrogen truck TCO is not easily defined. This section dives into the cost components of the hydrogen truck. Four elements of the hydrogen truck TCO require more explanation. Section 4.2.1 determines the hydrogen truck cost (CAPEX) using a modular build-up of components. After that, three sections discuss the build-up of the OPEX with the hydrogen fuel price, the vehicle efficiency and the extra refuelling time. To accommodate for the uncertainty of cost, this article considers both a modest improvement and a strong improvement scenario for the hydrogen truck.

#### 4.2.1. 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. Three important component categories can be distinguished, namely, hydrogen truck components, electric truck components and other components.

The electric truck components consist of the battery and the electromotor. The battery price is assumed to be €280 per kWh and develops towards €184 and €120 per kWh in modest and strong improvement scenario (IFLScience, 2018). The electromotor price is assumed to be €18 per kW and develops towards €14 and €12 per kW (Fulton & Miller, 2015; Moultak et al., 2017). The other cost consists of the 'empty tractor' €135,000 (same as diesel tractor) this is assumed to remain the same in the future (Moultak et al., 2017). The DC/DC converter costs approximately €20,000 and decreases towards €12,000 and €8,000 in the future scenarios (Bouwman, 2019). Fixed electric truck costs are €5,000 and fixed hydrogen truck cost is €10,000, in the future, this decreases to respectively €3,000 and €5,000.

#### 4.2.1.1. Hydrogen truck components

Figure 3 shows the hydrogen truck components: the fuel-cell stack, balance of plant and the hydrogen fuel tank. The balance of plant and fuel-cell stack are combined in the fuel-cell system. For each of the components, multiple technologies are available, each with a different cost.

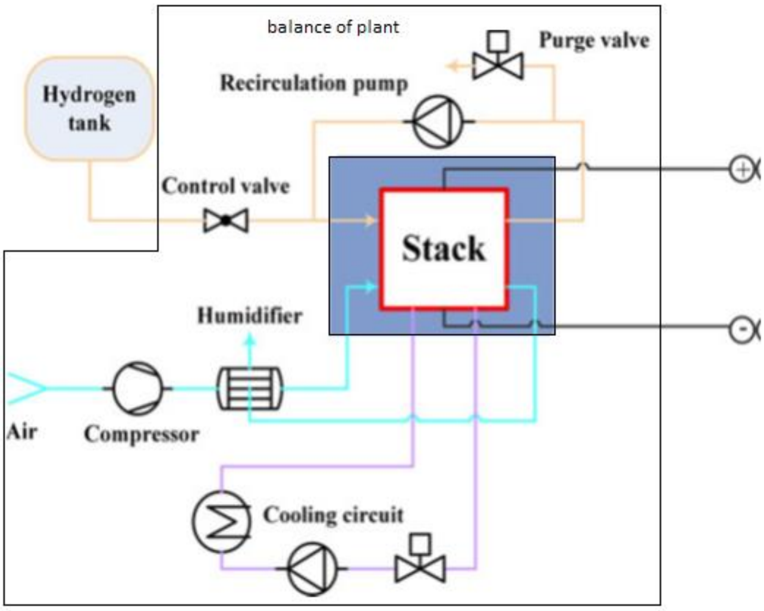


*Figure 3 Schematic overview of the hydrogen truck components: fuel-cell stack, balance of plant and hydrogen tank* (Koffrie & Hommen, 2017).

*Fuel-cell system*

The fuel-cell system consists of the fuel-cell stack and the balance of plant. In the fuel-cell stack, the electro-chemical process occurs whereas the balance of plant makes sure that the fuel-cell stack maintains ideal conditions in terms of among others, temperature and pressure.

The Proton-electric membrane (PEM) is the dominant fuel-cell technology. Other fuel-cell types are not suitable due to required maintenance, operating temperature (Department of Energy, 2011; Wikipedia, 2019). Figure 4 shows the fuel-cell stack cost, the current purchase price is assumed to be around €800 per kW (Bouwman, 2019). Due to economy of scale and more experience, the price decreases towards €50 to €160 per kW in the modest and strong improvement scenario.

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 and development towards €800 per kW (Bouwman, 2019). Steven Wilkins indicated that the balance of plant cost could decrease towards €200 to €600 per kW (Wilkins, 2018). As the fuel-cell system is an expensive component in the calculation of the total hydrogen truck, a conservative choice is made to assume €1,200 per kW and €650 per kW in a 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.

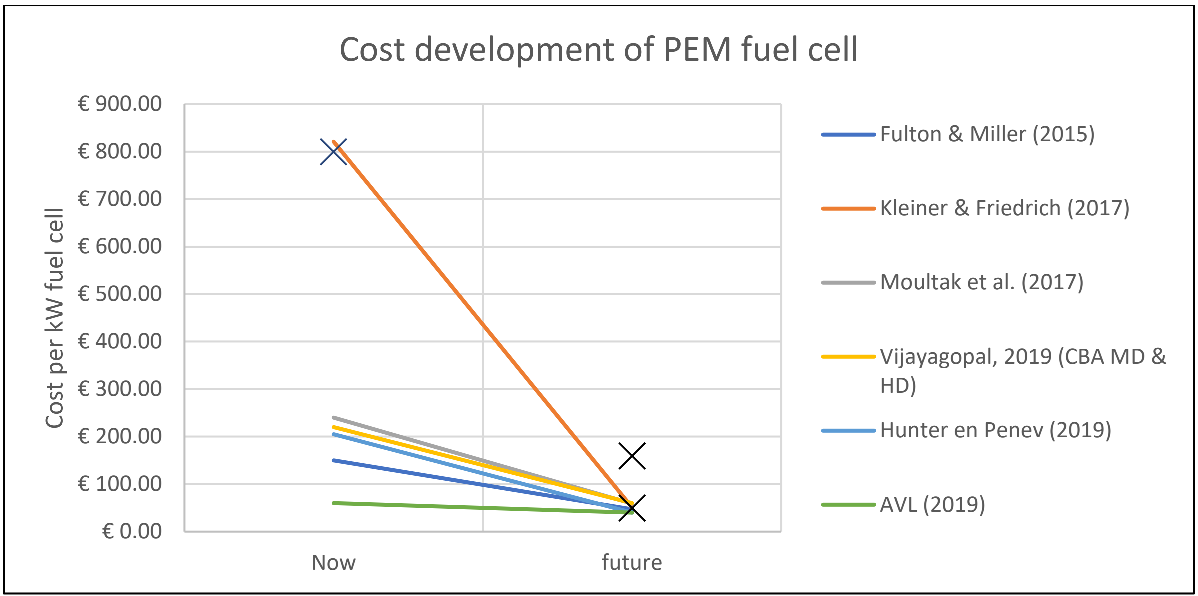


*Figure 4 Fuel-cell stack cost development, crosses indicate selected values for current, modest improvement and strong improvement.*

## *Hydrogen fuel tank*

The previous paragraph discussed the fuel-cell system. This paragraph dives into the storage of hydrogen in a truck. Two topics will be addressed: storage techniques and the cost of the hydrogen tank. There are several storage techniques available, however, not every technique is applicable for the truck application. Table 1 shows six storage techniques, there is a large difference in the storage density of the techniques, see the third column. 37 kg represents the required amount of hydrogen for one day of operation, this is calculated based on the dynamic vehicle model from TNO. This calculates the fuel consumption based on a specific powertrain and mission profile.

*Table 1 hydrogen storage techniques with characteristics. *currently not feasible*

| | **Storage medium** | **Density [kg/m³]** | **Required volume to store 37 kg hydrogen [m³]** |
|---|---|---|---|
| **$H_2$ 1 bar, 20°C** | $H_2$ (g) | 0.09 | 411 |
| **$H_2$ 350 bar 20°C** | $H_2$ (g) | 23 | 1,608 |
| **$H_2$ 700 bar 20°C** | $H_2$ (g) | 38 | 0.974 |
| **$H_2$ liquid -252°C** | $H_2$ (l) | 70* | 0.529* |
| **H2-fuel** | $NaBrH_2$ (s) | 111* | 0.33* |
| **Formic acid** | $Ch_2O_2$ | 53* | 0.70* |

The three storage techniques with an astrix in Table 1 require that much additional equipment that they are not found to be feasible at this moment (Atli-Veltin, 2019; Bouwman, 2019; van Wijk, 2019). So, 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.

Figure 5 describes the development of the hydrogen fuel tank cost. There is no consensus about the cost of the fuel tank. The current price is assumed to be €1,000 per kg and the expected future value fluctuates between €400 and €600 per kg, which is in line with other studies(Bouwman, 2019; Kleiner & Friedrich, 2017; Moultak et al., 2017)

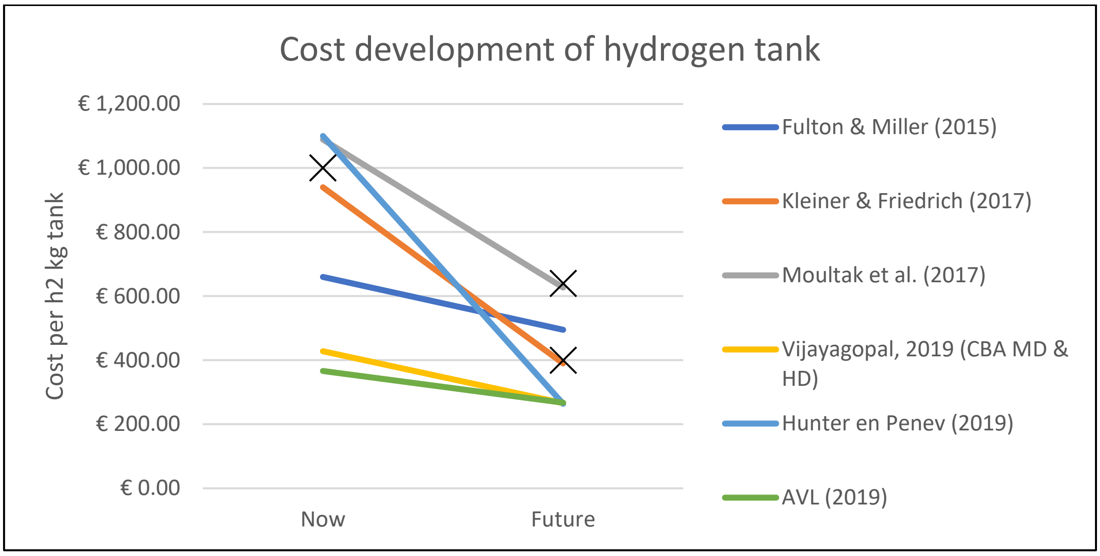


*Figure 5 Fuel tank cost development, crosses indicate selected values for current and modest & strong improvement scenario.*

#### 4.2.1.2. Integral hydrogen truck cost

Until now, all the important components of the hydrogen truck are discussed. Based on the technical specifications of the hydrogen truck shown in Table 2 and the cost estimations of section 4.2.1, the hydrogen truck cost (CAPEX) can be calculated, see Table 3.

*Table 2 Technical specification of the hydrogen truck*

| | Unit | Current | Future | |
|---|---|---|---|---|
| | | | Modest | strong |
| **Size of E-motor** | 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 |

*Table 3 Capex component analysis of the hydrogen truck*

| | | 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 fuel-cell truck | € | 284,000 | 183,960 | 110,600 |
| Tractor | € | 135,000 | 135,000 | 135,000 |
| Total electric truck cost | € | 23,423 | 16,500 | 12,051 |
| Total hydrogen truck cost | € | 284,000 | 183,960 | 110,600 |
| CAPEX hydrogen truck | € | 442,423 | 335,460 | 257,651 |

#### 4.2.2. Fuel price

Currently, the hydrogen fuel price is fixed to €10 per kg in the Netherlands, this includes BTW and exemption from excise duty. In the future, this is expected to decrease. This section examines the hydrogen price by looking into the cost of the components. The hydrogen price is divided into three components, namely, production, distribution and refuelling. For each of these steps, all sorts of methods can be used. The hydrogen fuel price differs depending on the chosen method.

In total, seven routes are selected to be analysed using the TCO. 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 4 gives the selection of routes. Table 5 shows the cost of each route, as can be seen, the cost of the routes does not differ that much in strong improvement scenario, namely around €3,00 per kg.

*Table 4 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 5 Hydrogen price development for selected routes.*

| | 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 |

### 4.2.3. Vehicle efficiency

The vehicle efficiency is an important factor in the calculation of the required amount of hydrogen. When analysing vehicles, it is important to distinguish some efficiencies. This article defines efficiency as the useful energy divided by the total energy that is put in. Figure 6 distinguishes five sorts of efficiencies. These efficiencies are:

- Fuel-cell system efficiency
- Final drive + motor efficiency
- Powertrain efficiency, the combination of fuel-cell system efficiency and drive + motor efficiency
- Battery efficiency, not considered in this article
- DC-DC converter, not considered in this article

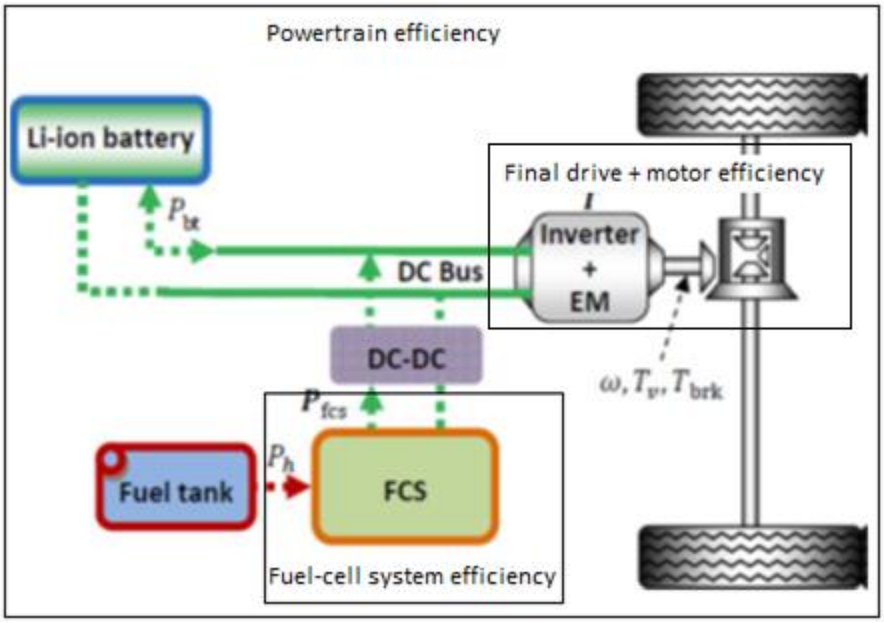


*Figure 6 Final drive + motor efficiency, fuel-cell system efficiency and powertrain efficiency. Adjusted from* (Koffrie & Hommen, 2017)

The fuel-cell system efficiency is currently assumed to be 50% (Bouwman, 2019; Wilkins, 2019) this is expected to increase in the future. Fuel-cell manufacturers use multiple fuel-cell systems from passenger cars to assemble the fuel cell system of a truck, this changes towards a dedicated truck fuel-cell system (Resende, 2019). Table 6 shows the efficiencies that are found in the literature. As can be seen, the efficiencies found in the literature range from 60-70% in the future. This article assumes that fuel-cell system efficiency increases towards respectively 60% and 65% for modest and strong improvement scenario.

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

*Table 6 Development of fuel-cell system efficiency*

The final drive + motor efficiency is related to the electromotor and the final drive. The electromotor is assumed to have 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 a build-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 a respectively modest and strong improvement scenario.

#### 4.2.4. Extra refuelling time & hydrogen truck mission profile

The mission profile of the hydrogen truck differs from the diesel truck due to the extra refuelling time. This has two causes: the fuel tank capacity and the refuelling speed of the HRS. Figure 7 shows there are two refuelling moments per day, whereas the diesel truck only refuels once (Figure 2). Given that approximately 37 kg hydrogen is needed for daily operation 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 assumed to be longer than that of the diesel truck, 18 minutes, compared to the 10 minutes (Figure 2). 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 1.5kg /min refuelling speed ≈ 18 minutes

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.

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.

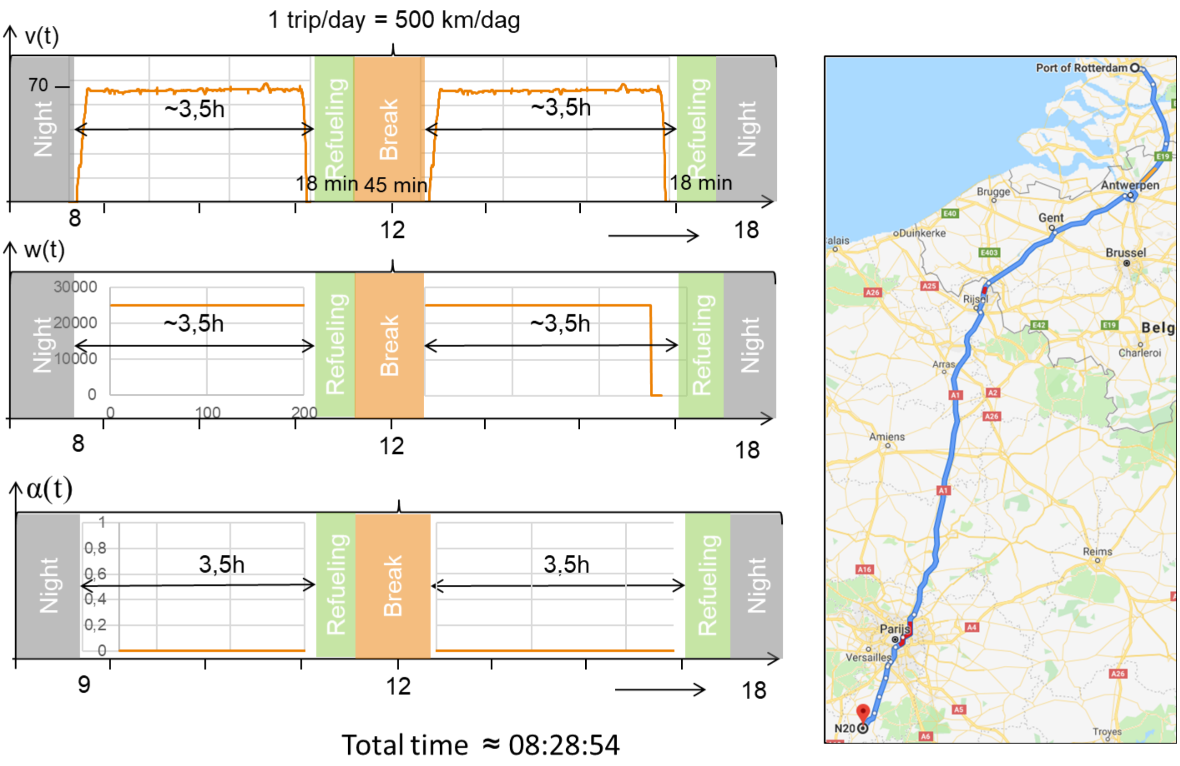


*Figure 7 Mission profile hydrogen truck*

### 4.3. Model setup

This section discusses the general assumptions that are used to calculate the TCO, see Table 7. The TCO is measured in €/km, this 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 deprecating the truck cost. Given a lifetime of 6 years, a purchase price, a residual value and an interest rate of 6%, the depreciation cost per year can be calculated using the PMT formula. This gives 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 euros 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).

*Table 7 Overview of fixed variables*

| | Unit | Value |
|---|---|---|
| **Years of operation** | years | 6 |
| **Interest rate** | % | 6 |
| **Driver salary** | €/year | 60,000 |

## 5. Results

### 5.1. Diesel truck TCO

The first bar of Figure 8 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. Table 8 shows two scenarios and the effect of it on the diesel TCO price. These scenarios can also be seen in Figure 8, the first bar. While discussing the development of the TCO of the hydrogen truck, the diesel truck scenarios act as possible bandwidth for the diesel reference truck.

*Table 8 Scenarios diesel reference, these values provide the uncertainty bandwidth of the diesel truck TCO in the further TCO analysis of the hydrogen truck.*

| | **Current** | **Future** | **Effect on TCO diesel** |
|---|---|---|---|
| **Diesel powertrain efficiency** | 31% | 40% | - €0.083 |
| **Diesel price** | €1,00 | €1,30 | +€0.109 |

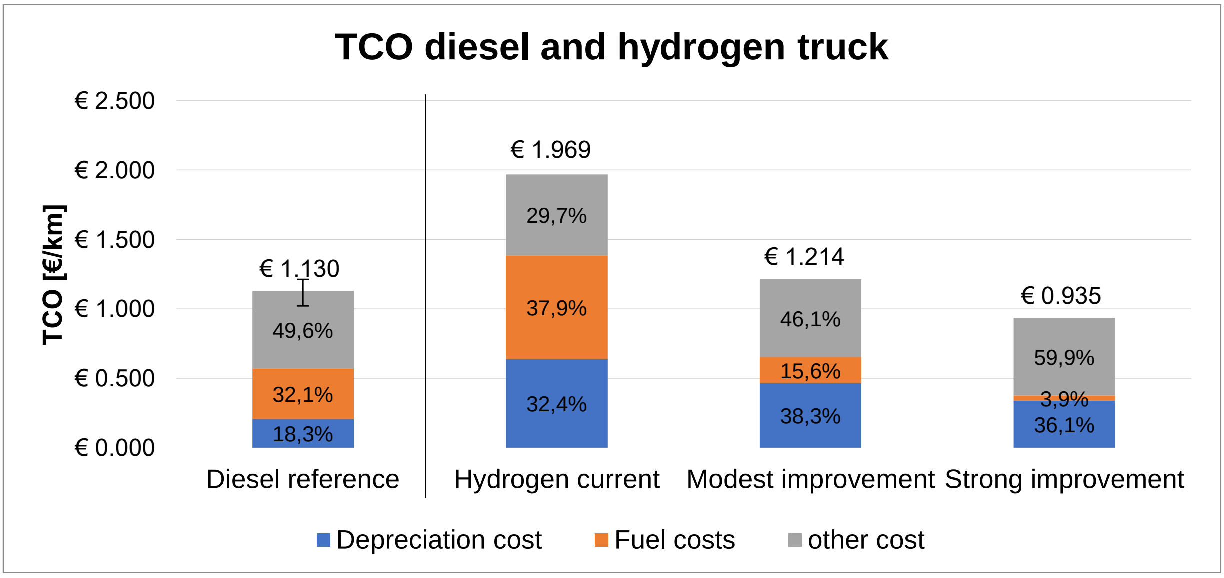


*Figure 8 TCO of diesel and hydrogen truck. Diesel truck with uncertainty bandwidth. Hydrogen truck with current, modest improvement and strong improvement situation. The prices of hydrogen supply route 1 are used for this example*

### 5.2. Hydrogen truck TCO

Figure 8 shows the results of the TCO analysis of 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 a larger portion of the TCO cost.

The TCO of the hydrogen truck develops in the future, the uncertain factors are discussed in 4.2 The Factors following four factors are identified as being the most uncertain and having the most impact on the TCO:

- Truck cost
- Hydrogen price
- Vehicle efficiency
- Extra refuelling time

The first three uncertain factors are the same for each of the route, whereas the hydrogen price differs. Hence, the first three factors are discussed in general and the hydrogen price is discussed for each route. The TCO of the first route is displayed in Figure 9.

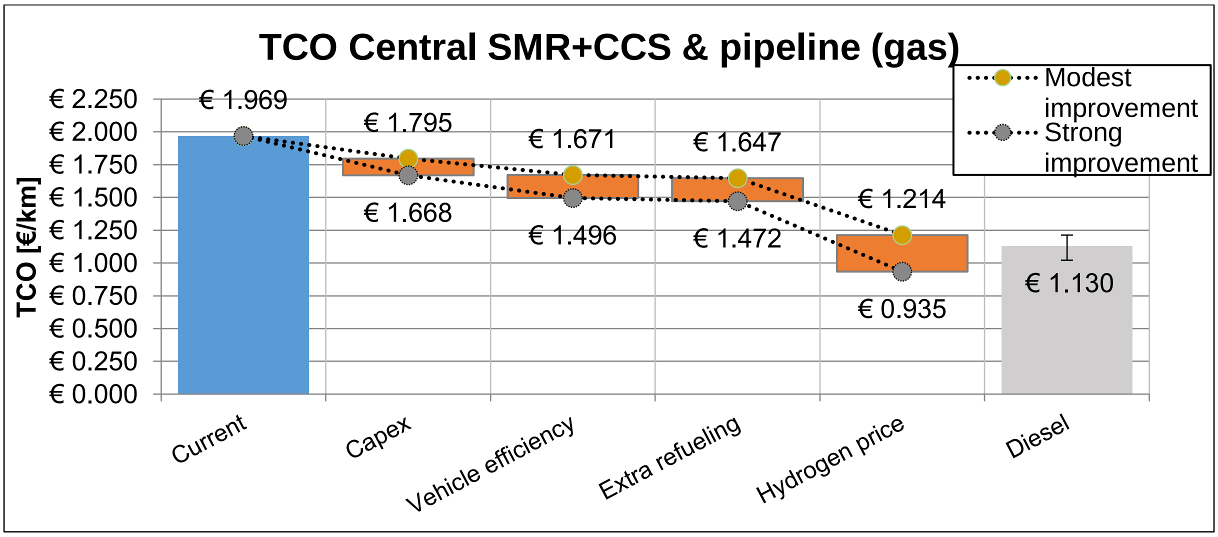


*Figure 9 TCO analysis of route 1*

*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 9). The CAPEX cost is the depreciated hydrogen truck cost. 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 9) The vehicle efficiency is part of the OPEX and influences the fuel cost. Due to the development of the fuel-cell efficiency, the powertrain efficiency increases from 45% towards 54% in modest and 59% in a 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 influences 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*

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 a strong respectively modest improvement scenario. This results in a TCO reduction of €0.37 per km (ranging from €0.25 to €0.54). Table 9 shows the impact of the decreasing hydrogen price on the TCO for the selected hydrogen supply routes. There is a difference in price reduction between the routes, more about this in the next paragraph. Figure 9 indicates that the TCO reduction of the hydrogen price is the largest.

| | 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 |

*Table 9 Improvement of the TCO of routes by the development of hydrogen price, * currently fixed*

*Comparing the routes*

Figure 10 shows that all routes are within the bandwidth of the diesel reference alternative. This means that there are scenarios in which the TCO of the hydrogen truck is lower than the diesel truck.

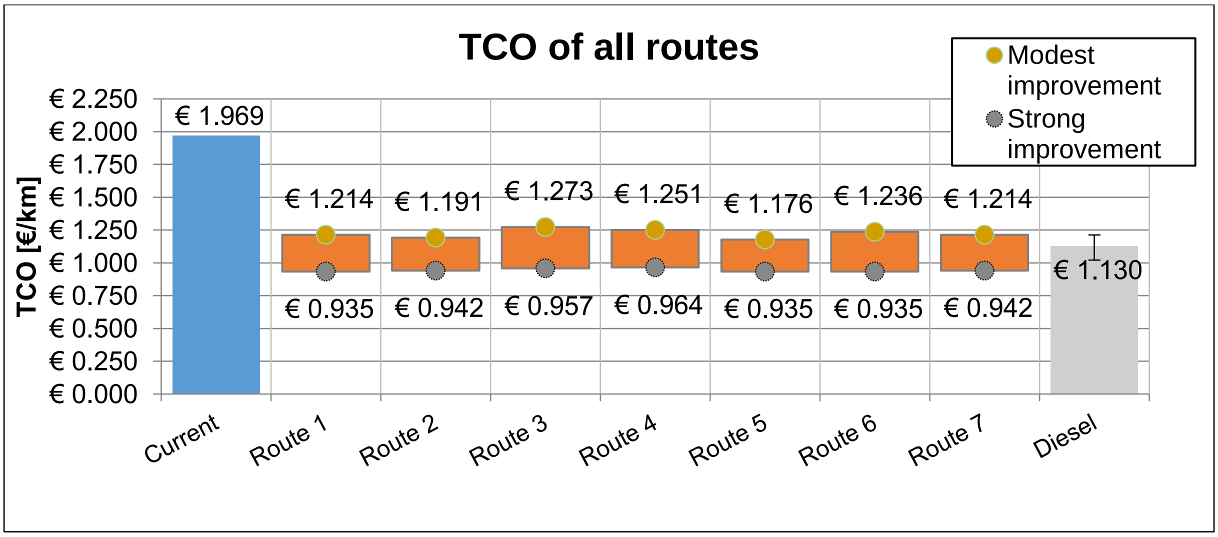


*Figure 10 Overview of results of all routes*

## 6. Discussion

This article 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.

Firstly, 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 is not considered. This would increase the hydrogen price and TCO of the hydrogen truck.

Secondly, dealing with the uncertainty of breakthrough invention. 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 take 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 well be useful. So, knowing this, it is important to keep track of the development of the most critical components of the hydrogen truck.

Thirdly, the hydrogen usage for transport purpose is completely seen isolated from other applications of hydrogen. By combining multiple applications, for instance, combining it with chlorine production at a chemical plant, one could use the 'waste' hydrogen of the chlorine production for transportation purpose. If sustainable energy is used to power the chemical reaction, green hydrogen is produced. 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 for the very large possible throughput of a pipeline, this might be interesting.

Fourthly, the hydrogen truck is under the mentioned boundary conditions a feasible option for the selected mission profile. The mission profile of 500 kilometres and one stop is only one mission profile. Robust in operation also contains that a hydrogen truck is useable for other mission profiles (Bouwman, 2019). This thesis focussed on one mission profile, this can be used as an application case in studies that look into the wider application of hydrogen trucks.

## 7. Conclusions and policy recommendations

Hydrogen as an energy carrier is seen as an important option to reduce the $CO_2$ emissions in the transport sector. However, not so much research has been done into the possibilities of using a hydrogen truck in freight road transport. This article tried to answer 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 was analysed from the perspective of the end-user, the transport companies. It became clear that the cost-effectiveness is the most important decision variable while availability and robustness in operation were considered important boundary conditions, which are preconditional. 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. In order to reach the above-mentioned price reductions, it is important that sustainable hydrogen becomes available at a large scale. For the refuelling of hydrogen it is important that the large hydrogen refuelling stations (HRS) become available and utilised so prices could decrease.

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. It is important to get more insight in the configuration of the balance of plant related to the size of other components like fuel-cell stack, electromotor and battery. This helps to standardise the fuel cell system which allows easier mass production. For the fuel tank it is important to develop better hydrogen storage techniques as the fuel tank capacity is around 30 to 40 kg, however, ideally the tank capacity is 80 kg. This allows the hydrogen truck to be used for other mission profiles as well.

This article identified the most important boundary conditions for feasibility of a hydrogen truck. From this, interesting inquiries can be started.

- Perform effect research into the implementation of hydrogen truck, what is the impact of lowering certain barriers that are identified.

- The high flow 700 bar refuelling for heavy duty vehicles is rarely researched but an important boundary condition
- The balance of plant is identified as important components for the hydrogen truck. However, the configuration with other components (fuel-cell stack and electro motor) and the effect of temperature and pressure settings on the configuration is less known.

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