

# FUEL CELLS FOR HEAVY DUTY TRUCKS 2030+?

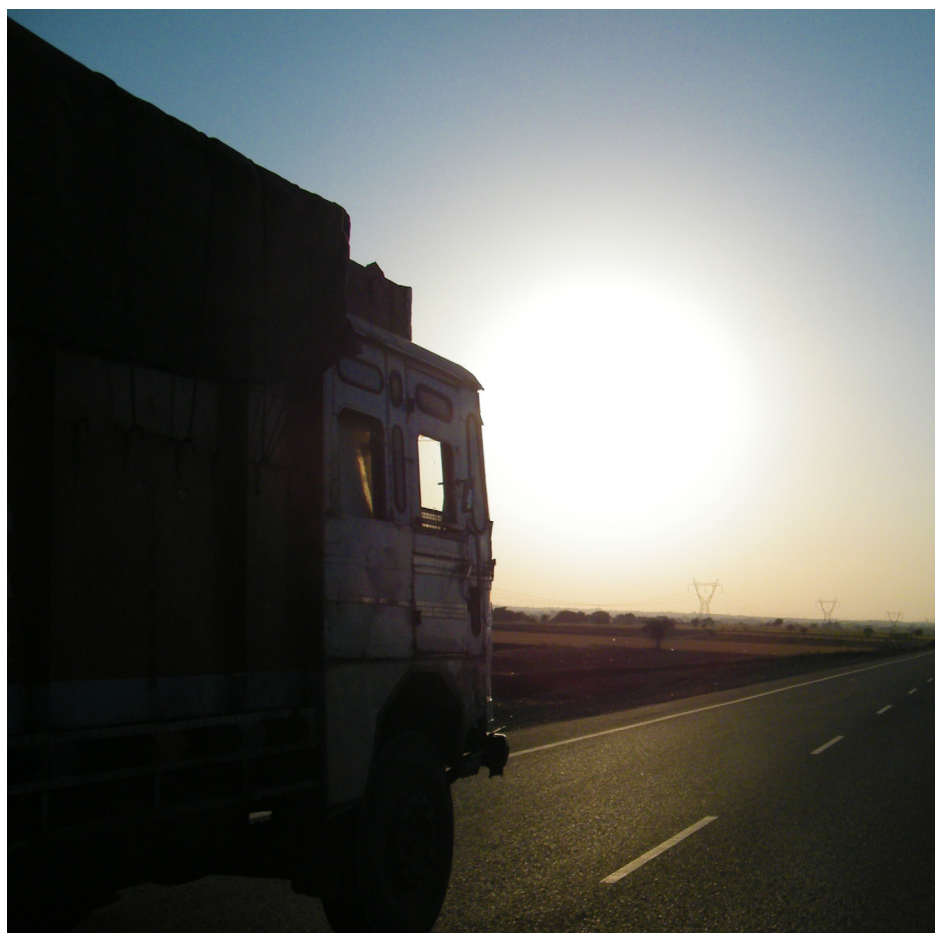
REPORT 2019:604



TEKNIKBEVAKNING  
BRÄNSLECELLER



Swedish  
Electromobility  
Centre





# **Can fuel cells become a mass-produced option globally for heavy-duty trucks 2030+?**

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ISBN 978-91-7673-604-3 | © ENERGIFORSK September 2019

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## Förord

**I syfte att koordinera teknikbevakningen, men också för att sammanställa, analysera och sprida information om utvecklingen inom bränslecellsområdet finansierar Energimyndigheten projektet Teknikbevakning av bränsleceller. Projektet och dess resultat vänder till svenska intressenter och genomförs under 2016 – 2019 som ett temaområde inom kompetenscentret Swedish Electromobility Centre med Energiforsk som koordinator och projektledare.**

I denna rapport, som tagits fram inom teknikbevakningen, har huvudsakligen ägandekostnader för fyra drivlinor (diesel, batteri, elväg och bränsleceller) för lastbilar för tre transportuppdrag, fjärrtransporter, regionaltrafik och stadsdistribution analyserats. Projektet har genomförts av Magnus Karlström (projektledare) Chalmers, Elna Holmberg och Anders Grauers från Swedish Electromobility Centre. Hans Pohl, RISE Viktoria har också medverkat.

Styrgruppen för teknikbevakningsprojektet har bestått av följande ledamöter: Pontus Svens/Annika Ahlberg-Tidblad, Scania, Mats Andersson/Staffan Lundgren/Johan Svenningstorp, AB Volvo, Stefan Bohatsch, Volvo Cars, Jörgen Westlinder, Sandvik Materials Technology, Andreas Bodén, Powercell, Bengt Ridell, Sweco Energuide, Göran Lindbergh, Swedish Electromobility Centre/KTH, Peter Smeds/Magnus Lindgren, Trafikverket, Elna Holmberg, Swedish Electromobility Centre och Bertil Wahlund, Energiforsk. Energiforsk framför ett stort tack till styrgruppen för värdefulla insatser.

Samtliga rapporter från projektet kommer att publiceras och fritt kunna laddas ner från Energiforsks webbplats under Teknikbevakning bränsleceller på [www.energiforsk.se](http://www.energiforsk.se) och på Swedish Electromobility Centres webbplats [www.emobilitycentre.se](http://www.emobilitycentre.se).

Stockholm juni 2019

Bertil Wahlund Energiforsk AB

Här redovisas resultat och slutsatser från ett projekt inom ett forskningsprogram som drivs av Energiforsk. Det är rapportförfattaren/-författarna som ansvarar för innehållet.



Swedish Electromobility Centre är ett nationellt kompetenscentrum för forskning och utveckling av el- och hybridfordon och laddinfrastruktur. Vi enar Sveriges kompetens och utgör en bas för samverkan mellan akademi, industri och samhälle.

## Sammanfattning

Projektet är huvudsakligen en kalkyl av ägandekostnader för fyra drivlinor för lastbilar för tre transportuppdrag, fjärrtransporter, regionaltrafik och stadsdistribution.

Drivlinetyperna var diesel, batteri, elväg och bränsleceller. Dessutom användes data för tre marknader; Tyskland, USA och Kina. Allt beräknades med kostnadsnivåer motsvarande läget 2030. Viktiga förutsättningar var att det är volymsproduktion av alla komponenter som t ex bränsleceller och batterier, men också att det är god utnyttjandegrad av t ex vätgasstationer, laddinfrastruktur och elvägar.

Resultaten visar att elvägar ger lägst totalkostnader, följt av batterifordon (beroende på antagen kostnadsnivå för batterierna). Bränslecellsfordon ger lägre kostnader än diesel i regional- och stadstrafik. Det finns många osäkerheter i beräkningarna, så resultaten ska inte övertolkas.

Den viktigaste delen av projektet handlade om att bedöma vilka stora osäkerhetsfaktorer som kan ha stor påverkan på framtida kostnader. Följande faktorer listades: Kostnad för drivmedel (vätgas, el och diesel), restvärden för fordon (ej diesel), fordonets förmåga att fullgöra transportuppdraget (inklusive räckviddsfrågan) och batterikostnader.

För att försöka få med kostnaden för de begränsningar som batteri- och bränslecellsfordon kan få i jämförelse med diesel, exempelvis i lastkapacitet på grund av tunga batterier, infördes en Less Function Factor (LFF). Det konstaterades att sådana begränsningar påverkar totalkostnaden för fordonet inklusive löner till förare eftersom det kan ses som att om varje fordon bara klarar cirka 90% av vad ett dieselfordon klarar så behövs det ungefär ett extra fordon för en flotta om tio fordon.

## Summary

This study is mainly a total-cost-of-ownership calculation of four different powertrains for heavy-duty trucks for three different customer mission profiles, long haul, regional and urban distributions.

The powertrain alternatives were diesel, batteries, electric road systems and fuel cells. Also, the calculations were made for three main markets for heavy-duty trucks; Germany, USA and China.

Everything was calculated for cost levels that could be relevant for the year 2030. Therefore, it was assumed cost levels of mass-market volume, for example batteries and fuel cells are assumed. Another important prerequisite was that high utilization of for example hydrogen stations and charging infrastructure is assumed.

The results showed that Electric Road Systems has the lowest total costs, and battery trucks were the second best option (depends upon cost levels of batteries). Fuel cell trucks are cheaper than diesel trucks for urban and regional distribution. These results must be interpreted with caution because of several uncertainties in choice of, for example, the cost of electricity and hydrogen.

The most important part of the study was to assess which uncertainties have a high impact on the future costs of the alternatives. The most important factors were: cost of fuel (hydrogen, electricity and diesel), the resale value of fuel cell and battery trucks (not diesel), if the vehicle could fulfil its transport mission and battery costs.

In order to try to get the cost of the limitations that battery and fuel cell components can have in comparison to diesel, for example in load capacity due to heavy batteries, a factor called Less Function Factor was introduced. It was found that such limitations affect the total cost of the vehicle, including wages to drivers, as it can be seen that if each vehicle can handle only about 90% of what a diesel vehicle can handle, it needs approximately one extra vehicle for a fleet of ten vehicles.

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# 1 Introduction

Fuel cell trucks are a trend. For example, the American Hybrid Truck company Nikola Motors plans to build fuel cell hybrid Class 8 trucks (Hsu, 2017), Toyota will test a fuel cell Class 8 Truck soon (O'Dell, 2017), Scania together with Norwegian goods wholesaler Asko will also try-out fuel cell trucks (Scania Group, 2017), and Swedish PowerCell Sweden AB has delivered fuel cells to Switzerland's first distribution truck with fuel cell technology (PowerCell, 2016).

The increased interest is due to its zero-emission potential, but also it has features comparable to diesel vehicles, such as infrastructure build-up and refuelling patterns. Fuel cell trucks have not been used so far, because of the present drawbacks such as costs of fuel cell systems and hydrogen tanks, lack hydrogen filling stations and low durability for long-term use, such as for a long-haul truck. However, these challenges could be solved with technology improvement, mass-manufacturing and policy support.

Zero or low carbon solutions for road freight vehicles is probably needed to reach long-term targets for climate gases. Another driver for zero-emission technology is that several cities want to introduce zero emissions zones. At present road freight vehicles account for around one-fifth of global oil demand and 35% of transport-related carbon dioxide (CO<sub>2</sub>) emissions (IEA, 2017). Since the demand for freight will continue to increase the CO<sub>2</sub> emissions from road freight rapidly will be about the same as road passenger sector around 2050 with present trends (ICCT, 2016b). This is one of the reasons several countries have or will implement fuel economy standards or carbon dioxide legislation for road freight vehicles.

The road freight sector is complex to legislate because of the variety of vehicle types and their uses. Also, the freight vehicles are usually bought by a company to perform a freight task with so low total-cost-of-ownership (TCO) as possible.

Fuel cells are not the only low-emission technology for companies and policy-makers. One of the main options the next 15-20 years are more efficient internal combustion engine vehicles with biofuels, but also with electrofuels, which are drop-in replacement fuels that are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. Battery freight vehicles are an option, but also electric road systems are a promising alternative. All of these propulsion options could also be combined in different hybrid configurations.

Fuel cell trucks are used, but it is early days. Our question is if fuel cell trucks can be mass produced option in 15-20 years. One of the main decision criteria is if fuel cell trucks can be economically viable compared to other alternatives in some use cases and main markets. Several reports and articles have been studying TCO of fuel cell trucks, but they have mainly been focusing upon long haul and a specific country.

Therefore, our report will compare the total-cost-of-ownership of fuel cell trucks with other low emission options. We will also calculate for three use cases of trucks: urban distribution, regional delivery and long haul. Our assessment is

based upon the year 2030+ to include technology performance and cost improvements. The base case is the use of trucks in Germany, but we will evaluate if the context of the situation in China and USA will change the conclusions.

## 2 Total Cost of Ownership Model

### 2.1 OVERVIEW OF MODEL

In this report, Total Cost of Ownership (TCO) of a heavy duty truck is all costs associated with having a vehicle for the first owner.

As an example, the Swedish consultancy firm WSP calculated the TCO for a long haul truck in Sweden (table 1). The cost of owning and buying a truck entails different cost categories divided into fixed, running and driver expenses.

**Table 1 Average TCO of a Tractor (emission standard EURO 5 and three axles) for the year 2014 in Sweden. Purchase of trailer not included (WSP, 2014) (2)**

Category	Cost type	Cost		%
Fixed Costs	Depreciation, fixed	3 190	€ <sub>2014</sub> /year	2,1
	Finance	2 380	€ <sub>2014</sub> /year	1,6
	Fixed Taxes	2 140	€ <sub>2014</sub> /year	1,4
	Insurance	3 130	€ <sub>2014</sub> /year	2,1
	Other fixed costs	3 880	€ <sub>2014</sub> /year	2,6
Running Costs	Fuel (Diesel)	48 800	€ <sub>2014</sub> /year (1)	33
	Depreciation, running	9 570	€ <sub>2014</sub> /year (1)	6,4
	Maintenance	7 720	€ <sub>2014</sub> /year (1)	5,2
	Tires	3 910	€ <sub>2014</sub> /year (1)	2,6
Driver Costs	Salary	47 600	€ <sub>2014</sub> /year	32
	Payroll Tax	17 500	€ <sub>2014</sub> /year	12

(1) If 130 000 km/year (2) €1 to 9.6 SEK

All TCO analysis in this report start with the year 2030 and all costs are calculated based upon €2017.

Our goal in this study is that the costs should be as realistic as possible in an end-consumer context, and the individual assumptions, limitations and methods used will be explained.

## 2.2 TCO FORMULA, VARIABLES DEFINED AND EXPLAINED

The Total-Cost-of-Ownership equation used in the report is:

$$TCO_{2030} = (PP + (CECtkd + DCtt + MRCtkd + OCt) \left( \frac{1-(1+r)^{-t}}{r} \right) - RP(1/(1+r)^t)) LFF \quad (1)$$

where  $t$  is ownership period (years),  $r$  is yearly interest rate,  $tkd$  is total kilometers driven during ownership period, and  $tt$  is driver's hours during ownership period.

and where  $PP$  is the purchasing price (€) of heavy duty truck,  $CEC$  is consumer energy cost (€/km),  $RP$  is the resell price (€) in the end of the ownership period,  $DC$  is the driver cost (€/h),  $MRC$  is Maintenance and Repairs Costs (€/km),  $OC$  is Other Costs, such as insurance, and  $LFF$  is the less function index, which is a proxy for a cost penalty because of less payload, due to extra weight/volume of batteries or/and hydrogen storage tanks.

The purchasing price (€) equation of heavy duty truck is:  $PP = RPE \sum K \text{ Component cost } n \quad (2)$

where  $RPE$  is retail price equivalent = 1,48 (Reference?).

The consumer energy cost (€/km) equation is:

$$CEC = fc(EC + InfraC + TaxC) \quad (3)$$

where  $fc$  is fuel consumption (kWh/km),  $EC$  is energy cost (€/kWh),  $InfraC$  is infrastructure cost (€/kWh) and  $TaxC$  is tax cost (€/kWh).

Several of the variables will have different values depending on geographical area, powertrain, fuel and transport use case.

$LFF$  is the less-function factor, which is explained in chapter 4.9.

### 3 Goal and Scope

#### 3.1 COMPARED FUEL/POWERTRAIN ALTERNATIVES

Several alternatives exist for future trucks. This study considers several options, see table 2. However, we focus upon four combinations, see the grey areas.

The four ones are chosen, because the other options have similar TCO characteristics as at least one of the four. PHEV is outside the scope of this study as it is an intermediate solution between the two extremes BEV and diesel (ICE).

**Table 2 Compared fuel and powertrain**

Abbreviation	Fuel type	Powertrain type
Base case	Diesel	ICE
D-HEV	Diesel	HEV
Efuel-HEV	Electrofuel	HEV
D-PHEV	Diesel/Electricity	PHEV
Bio-ICE	Biofuel	ICE
Bio-HEV	Biofuel	HEV
Bio-PHEV	Biofuel/Electricity	PHEV
El-BEV	Electricity	BEV
El-ERS	Electricity	ERS/ICE
Hy-ERS	Electricity/Hydrogen	ERS
NG-ICE	Natural gas	ICE
NG-ICE	Natural gas	HEV
H2-FCV	Hydrogen	FCV
H2-FC/PHEV	Hydrogen/Electricity	FCV/PHEV
Bio-FC	Other C-fuel	FCV
Efuel-FC	Electrofuel	FCV

### 3.2 CUSTOMER TRANSPORT MISSION PROFILES

The base case for our calculation is long-haul use in Germany 2030+. However, we also investigate the duty cycle regional delivery and urban delivery.

The main difference between the different use cases is the distance between refuelling, the yearly mileage and duty cycle. They also have different component sizing as a consequence of the duty cycle and mission profile.

For example, our base case long haul in Germany has a distance between refuelling of 500 km and average yearly mileage of 130 000 km/year.

**Table 3** List of Customer mission profiles

Abbreviation	Geography	Vehicle use
Base-Long	Germany	Long Haul
Base-Reg	Germany	Regional distribution
Base-City	Germany	City distribution

The long-haul vehicle is a tractor with a trailer (up to 40 tons permissible maximum laden mass), daily distance in the German base case is designed to 500 km between refuelling/recharging and a yearly distance of about 130 000 km/year.

The regional vehicle has a rigid body and no trailer (up to 40 tons permissible maximum laden mass), daily distance in the German base case is designed to 300 km between refuelling/recharging and a yearly distance of about 60 000 km/year. The mission profile has lower average speed and more start-and-stop compared to the long-haul vehicle.

The urban distribution has a rigid body (up to 16 tons permissible maximum laden mass), daily distance in the German base case is designed to 200 km between refuelling/recharging and a yearly distance of about 40 000 km/year. The average speed is lower compared to the regional delivery mission profile.

## 4 General data for all use cases

### 4.1 FUEL CONSUMPTION (TANK-TO-WHEEL) FOR POWERTRAIN/FUEL COMBINATIONS

Fuel consumption is Tank-Wheel, therefore the energy losses from recharging are not included in the energy uses from an electric truck but included in cost for recharging.

Energy use for different duty cycle, powertrains and geographical areas are available in Table 4.

**Table 4 Fuel consumption (tank-to-wheel) different fuel/powertrain and mission profiles**

Fuel/ Powertrain	Geography	Vehicle use	kWh/km	Reference
D-ICE	Germany	Long Haul	3,3	(1)
El-BEV	Germany	Long Haul	1.6	(1)
El-ERS	Germany	Long Haul	1.6	(1)
H2-FCV	Germany	Long Haul	2.8	(1)
D-ICE	Germany	Regional distribution	2.9	(1)
El-BEV	Germany	Regional distribution	1.1	(1)
El-ERS	Germany	Regional distribution	1.1	(1)
H2-FCV	Germany	Regional distribution	2	(1)
D-ICE	Germany	Urban distribution	2,4	(1)
El-BEV	Germany	Urban distribution	0.67	(1)
El-ERS	Germany	Urban distribution	0.67	(1)
H2-FCV	Germany	Urban distribution	1,2	(1)

(1) Own assumptions based upon stakeholder discussions and Burke (2018), Kleiner (2017), Lee *et al* (2018), AFLEET Tool. (2017).



## 4.2 HYDROGEN COST

Hydrogen can be produced from many primary energies. The hydrogen cost depends on several factors, among them:

- Cost of primary energy (electricity, coal, methane...)
- Cost of production equipment (electrolyser, reformer, CCS...)
- Cost of transport to the refuelling stations (truck, pipeline, on-site production...)
- Cost of refuelling station (capacity, 350 or 700 bar, utilisation rate...)

This incomprehensive list indicates that the number of possible combinations is very large. Some technologies and solutions are developing rapidly, which contributes to the difficulty to assess the hydrogen cost.

Analogously to electricity, it is likely that hydrogen will be produced and distributed differently in various regions of the world. This implies that the hydrogen cost probably will differ as well. But unlike electricity, hydrogen will potentially be shipped between countries in large scale. If this happens and the cost of transport is limited, it will lead to an internationally rather similar cost of hydrogen.

If hydrogen is produced using electricity, it could be argued that the hydrogen cost must be higher than the electricity cost, due to losses in the conversion as well as cost of equipment. However, this can to some extent be compensated by the lower costs of hydrogen storage, compared to the storage of electricity. Given an increasing global share of renewable electricity from intermittent sources such as sun or wind, the energy storage needs will increase.

Among all studies of hydrogen, few try to span several continents, several production and distribution methods and several time perspectives. However, at least one does, the Technology Roadmap – Hydrogen and Fuel Cells (IEA, 2015). This report states a cost of hydrogen today between less than 1 USD/kg (natural gas reforming in the United States) and 6 USD/kg (electrolysis in Japan), excluding transport and distribution. The costs will develop until 2050, making the production alternatives and regions in the world slightly less different. Hydrogen cost at the refuelling station is also indicated, but only for cars and only in the US. The cost per gasoline litre equivalent is expected to stabilise on 1.6 USD (+/- 30%) when the refuelling network has been established. This corresponds to 6 USD/kg hydrogen. The production mix is not indicated but the scenario is based on a maximum climate change of 2 degrees Celsius.

A more recent study focusing on hydrogen from electricity (Greensight, 2017), indicates a cost of hydrogen from electrolyzers for trucks between 45 – 55 NOK/kg. This corresponds to 5.7 – 7 USD/kg hydrogen.

Therefore, we use 0.18 €/kWh or approximately 6 USD/kg for the hydrogen fuel cost including infrastructure cost.

### 4.3 INFRASTRUCTURE COST ELECTRIC ROAD SYSTEMS

This section describes how the cost for electricity from electric road systems have been estimated. The cost is estimated to be 0.23 €/kWh which includes cost for producing and distributing the electricity, as well as the cost for the electric road system itself. It is based on electricity prices for industry in Germany and estimated cost for building the electric road systems. The cost model group the costs into categories.

- Cost for buying the electric energy
- Annual cost for grid connection (not depending on energy use)
- Cost for the electric road system
- Cost for the grid connection

The cost model calculates an cost contribution from these costs, per kWh of energy the ERS system delivers. A key factor for the cost is how much the ERS is used. This can be defined as a utilization factor which is the annual energy delivered by the ERS divided by the theoretical maximum energy it can deliver. Since a year has 8760 hours, 1 kW of installed power can theoretically deliver 8760 kWh per year. Due to the ERS being used much less some times of the year, like for example nights and part of the weekends, and since the ERS system has to be sized for the peak load the worst hour of the year, the average utilization of the ERS system has been assumed to be 20%. This is a fairly high value, given the few hours per day that a road operates at its highest traffic density.

#### 4.3.1 Cost for buying electric energy

The cost for electricity has been based on German electricity prices for 2016, from Eurostat. The total price excl. VAT was 0.149 €/kWh, of which 0.044 €/kWh was cost for the electricity, 0.036 €/kWh was cost for the grid and 0.07€/kWh was non-recoverable taxes. Since the grid cost is not directly related to how much energy is used it is excluded from the cost for the actual energy used.

After subtracting the grid cost from the statistics, the remaining direct cost for electric energy is

$$C_{Energy} = 0.044 \text{ €/kWh} + 0.070 \text{ €/kWh} = 0.114 \text{ €/kWh.}$$

#### 4.3.2 Annual cost for grid connection

In the Eurostat data the grid fee has been expressed as an average cost of 0.036 €/kWh, but in most grids it is payed as an annual cost which is determined by the installed power and not by the used energy. Therefore, the grid cost has been translated into an annual cost of 63 €/kW/yr, which corresponds to the average grid cost 0.036 €/kWh given in the Eurostat statistics if the utilization factor of the grid connection is 20%

$$C_{Grid} = 63 \text{ €/(kW*yr)}$$

Since we also assumed that the ERS system has a utilization factor of 20% the annual grid fee contributes to a cost of

$$\frac{63 \text{ €/(kW*yr)}}{20\%*8760 \text{ h/yr}} = 0.036 \text{ €/kWh}$$

#### 4.3.3 Cost for the electric road system

The cost for building the ERS system is assumed to be 2'000'000 €/km, and the average installed power to be 2000 kW/km, which leads to a specific cost of

$$C_{ERSInvest} = 1000 \text{ €/kW.}$$

The economic life of the ERS has been set to 10 years. When also including the effect of interest and maintenance cost it has been assumed that the total annual cost for the ERS is the initial investment divided by 8 years.

$$T_{ERS} = 8 \text{ yr}$$

The annual cost for the ERS, per kW of installed power, is

$$\frac{C_{ERSInvest}}{T_{ERS}} = \frac{1000 \text{ €/kW}}{8 \text{ yr}} = 125 \text{ €/(kW * yr)}$$

With the 20% utilization factor this means that the cost for the ERS contributes to a cost of

$$\frac{125 \text{ €/(kW*yr)}}{20\%*8760 \text{ h/yr}} = 0.071 \text{ €/kWh}$$

#### 4.3.4 Cost for the grid connection

The cost for building the new grid to supply the ERS has one fixed cost per place the ERS is connected to the grid. This cost is assumed to be 2000 € and one such connection is made for each km of electric road system.

$$C_{GridInvestFixed} = 2000 \text{ €/connection}$$

Each km has a peak power of 2000 kW.

$$P_{Grid} = 2000 \text{ kW}$$

Added to the fixed cost is a grid connection cost per kW of installed peak power, which has been estimated to 250 €/kW.

$$C_{GridInvest} = 250 \text{ €/kW}$$

The investment in the grid supplying the electric road has been assumed to have an economic life of 20 years, which is adjusted to 16 years when calculating the annual cost, to include the effect of interest and maintenance.

$$T_{Grid} = 16 \text{ yr}$$

The cost for the grid investments, per year and kW of peak power, can be calculated as

$$\frac{C_{GridInvestFixed}/P_{ERS} + C_{GridInvest}}{T_{Grid}} = \frac{2000 \text{ €}/2000 \text{ kW} + 250 \text{ €/kW}}{16 \text{ yr}} = 15.7 \text{ €}/(\text{kW} * \text{yr})$$

With the 20% utilization factor this means that the cost for the grid investment contributes to a cost of

$$\frac{15.7 \text{ €}/(\text{kW} * \text{yr})}{20\% * 8760 \text{ h/yr}} = 0.009 \text{ €/kWh}$$

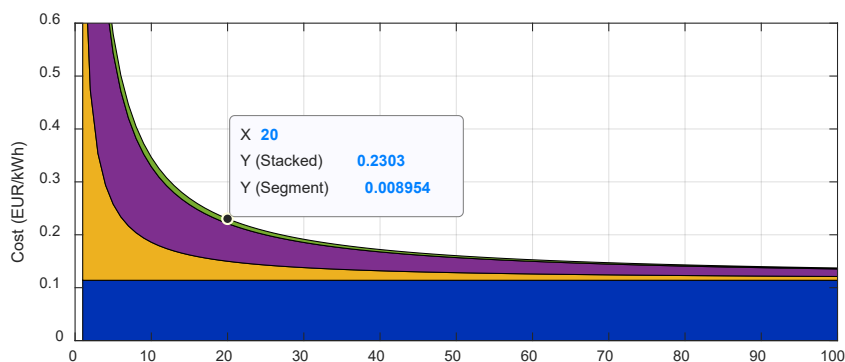
#### 4.3.5 Total cost for the electric energy from the ERS

The total cost is simply the sum of the above cost components:

- Energy related costs 0.114 €/kWh
- Annual cost for grid connection 0.036 €/kWh
- Cost for the electric road system 0.071 €/kWh
- Cost for the grid connection 0.009 €/kWh

This results in a total cost of 0.23 €/kWh.

This cost of course change depending on the assumed parameter values. The most important factor is most likely the influence of the utilization factor. In the below diagram it is shown how the cost components vary with the utilization factor.



**Figure 1** Total cost for energy from an ERS as function of its utilization factor in %.  
(blue = energy cost, orange = annual fees, purple = cost for ERS investment, green = cost for grid investment)

It can be noticed that the cost can only be reduced rather little, to about 0.17 €/kWh if the utilization factor is doubled to the very high value 40%. Instead, it can increase much more, up to 0.58 €/kWh if the utilization factor drops to only 5%. So, it is very important for the cost of ERS that the utilization factor is high.

#### 4.4 INFRASTRUCTURE COST BEV (NOT ERS) RECHARGING

The costs for stationary charging can be calculated with a cost model which is very similar to the cost model for the ERS. The total cost is 0.20 €/kWh, which is a little lower than for ERS, due to a lower investment cost for stationary chargers than for the ERS. This cost includes

- Cost for buying the electric energy
- Annual cost for grid connection (not depending on energy use)
- Annual cost for land rent
- Cost for the chargers
- Cost for the grid connection

Just like for the ERS, the utilization factor for the chargers is a key factor for the cost. We have assumed that the utilization factor for stationary chargers is 20%, just like for the ERS.

##### 4.4.1 Cost for buying electric energy

The cost for electricity is the same as for the ERS

$$C_{Energy} = 0.114 \text{ €/kWh.}$$

##### 4.4.2 Annual cost for grid connection

The grid cost is the same as for the ERS, and we assume one grid connection per charging station.

$$C_{Grid} = 63 \text{ €/(kW*yr)}$$

Since we also assumed that the chargers have a utilization factor of 20% the annual grid fee contributes to a cost of

$$\frac{63 \text{ €/(kW*yr)}}{20\% * 8760 \text{ h/yr}} = 0.036 \text{ €/kWh}$$

##### 4.4.3 Annual cost for land rent

Unlike the ERS, chargers need extra space, apart from the road they serve. Therefore, there is a land rent added to the annual cost of the chargers. This cost can most likely vary very much, depending on how far from a city the charger is. In this case we have assumed the land rent, per charger and year, to be

$$C_{LandRent} = 1000 \text{ €/(charger*yr)}$$

Since each charger is 500 kW this cost is

$$\frac{C_{LandRent}}{500 \text{ kW}} = 2 \text{ €/(kW * yr)}$$

With the 20% utilization factor this means that the land rent contributes to a cost of

$$\frac{2 \text{ €/(kW*yr)}}{20\% * 8760 \text{ h/yr}} = 0.001 \text{ €/kWh}$$

#### 4.4.4 Cost for the chargers

The cost for building the chargers is modelled as one fixed cost per charger unit and one cost scaling with the charger power

$$C_{ChgFixedCost} = 400 \text{ €/unit}$$

$$C_{ChgPowerCost} = 500 \text{ €/kW}$$

We assume that each charging station has 4 chargers of 500 kW each. Note that variations in charger power only has very small effect on the cost for charging, if the utilization factor is constant. This is shown in a diagram in section 4.4.6. The economic life of the chargers is assumed to be the same as for the ERS

$$T_{Chg} = 8 \text{ yr}$$

The annual cost for the four 500-kW chargers, per kW of installed power, is

$$\frac{4 * (C_{ChgPowerCost} * 500 \text{ kW} + C_{ChgFixedCost})}{4 * 500 \text{ kW} * T_{Chg}} = 62.6 \text{ €/(kW * yr)}$$

With the 20% utilization factor this means that the cost for the chargers contributes to a cost of

$$\frac{62.6 \text{ €/(kW*yr)}}{20\% * 8760 \text{ h/yr}} = 0.036 \text{ €/kWh}$$

#### 4.4.5 Cost for the grid connection

The cost for building the new grid to supply the charging station has a fixed part. This cost is assumed to be 2000 €, like for the ERS, and one such connection is made for each charging station.

$$C_{GridInvestFixed} = 2000 \text{ €/connection}$$

Each charging station has a peak power of 2000 kW (4\*500 kW).

$$P_{Grid} = 2000 \text{ kW}$$

Added to the fixed cost is a grid connection cost per kW of peak power, which is the same as for the ERS

$$C_{GridInvest} = 250 \text{ €/kW}$$

The investment in the grid supplying the chargers has been assumed to have an economic life of 20 years, which is adjusted to 16 years when calculating the annual cost, to include the effect of interest rates and maintenance.

$$T_{Grid} = 16 \text{ yr}$$

The cost for the grid investments, per year and kW of peak power, can be calculated as

$$\frac{C_{GridInvestFixed} / P_{Chg} + C_{GridInvest}}{T_{Grid}} = \frac{2000 \text{ €} / 2000 \text{ kW} + 250 \text{ €/kW}}{16 \text{ yr}} = 15.7 \text{ €/(kW * yr)}$$

With the 20% utilization factor this means that the cost for the grid investment contributes to a cost of

$$\frac{15.7 \text{ €/(kW*yr)}}{20\%*8760 \text{ h/yr}} = 0.009 \text{ €/kWh}$$

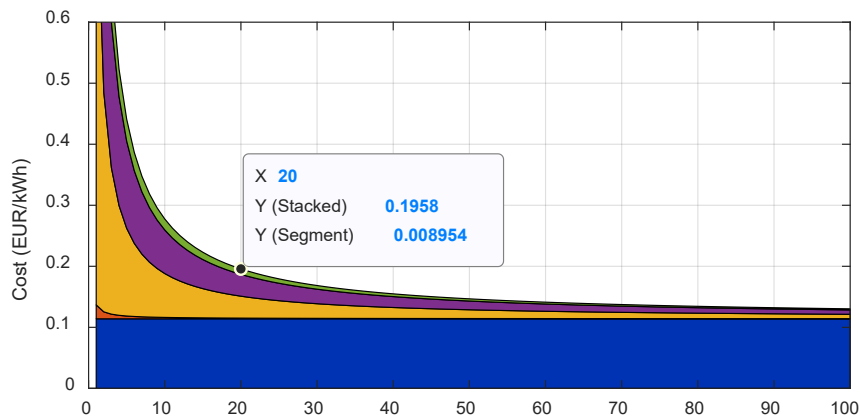
#### 4.4.6 Total cost for the electric energy from the chargers

The total cost is simply the sum of the above cost components.

- Energy related costs 0.114 €/kWh
- Annual cost for grid connection 0.036 €/kWh
- Annual cost for land rent 0.001 €/kWh
- Cost for the electric road system 0.036 €/kWh
- Cost for the grid connection 0.009 €/kWh

This results in a total cost of 0.20 €/kWh.

Just like for the ERS the most important factor for the cost is most likely the utilization factor. In the below diagram it is shown how the cost components vary with the utilization factor.



**Figure 2** Total cost for energy from stationary chargers as function of its utilization factor in %. (blue = energy cost, red = land rent, orange = annual fees, purple = cost for charger investment, green = cost for grid investment)

The cost variation, if the power of the chargers is changed, is plotted in the below diagram. Note that the number of chargers change such that the total power of all chargers in the charging station is always 2000 kW, and the utilization factor is not varied. This means that a higher charger power requires less chargers to service the same vehicles. This is the reason why the cost for the electricity is almost the same, irrespective of charger power.

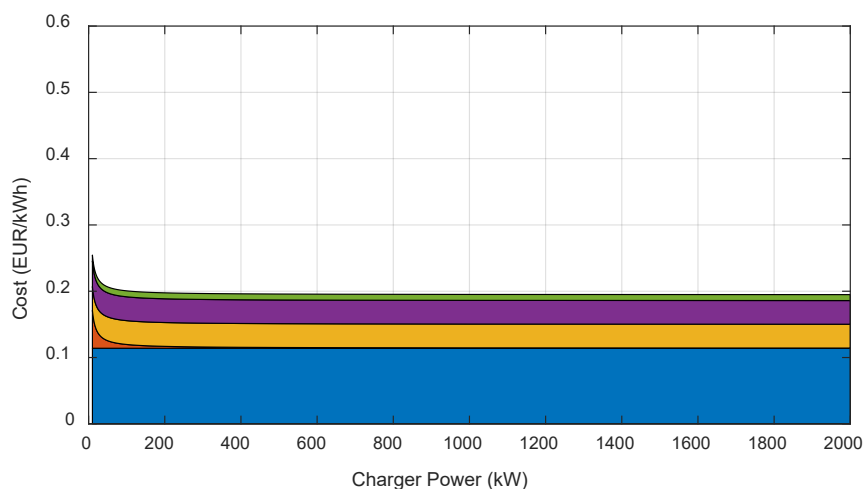


Figure 3 Total cost for energy from stationary chargers as function of the power of the chargers. (blue = energy cost, red = land rent, orange = annual fees, purple = cost for charger investment, green = cost for grid investment)

#### 4.5 COMPONENT COSTS

Table 5 provides the component costs used in the TCO calculation. The values are assumed to represent the costs for the truck manufacturer.

Table 5 Component costs for the OEM (for year 2030)

Component	€/unit	Unit	Reference
Pantograph/Current Collector for ERS	18 000	#	(1)
Glider (Long haul)	56 000	#	(1)
Trailer (Long Haul)	21 000	#	(1)
Glider (Regional)	38 000	#	(1)
Glider (Urban)	28 000	#	(1)
ICE-engine	60	kW	(1)
Treatment system	30	kW ICE	(1)
Gearbox	20	Kg gearbox	(1)
Dieseltank	2	Litre	(1)
Fuel Cell (PEM)	50	kW	(1)
Hydrogen storage	10	kWh	(1)
Electric machine	10	kW	(1)
Power electronics	6	kWh	(1)
Energy Battery	150	kWh	(1)

(1) Own assumptions but based upon stakeholder input and Kleiner (2017).



#### 4.6 COMPONENT SIZING AND PURCHASE PRICE FOR VEHICLE TYPES

Table 6, Table 7 and Table 8 present the purchase price of different vehicle types. The purchase price is assumed to be the same in all countries 2030.

**Table 6 Purchase price long-haul tractor with trailer (2030), battery size and hydrogen storage size are calculated based upon fuel economy(table 4), distance between refueling 500 km and 80% depth-of-discharge for the batteries (2).**

	Diesel		Battery Electric		ERS		Fuel Cell	
	Size	Cost	Size	Cost	Size	Cost	Size	Cost
Current Collector for ERS					1	18 000		
Glider (long haul)	1	56 000	1	56 000	1	56 000	1	56 000
Trailer	1	21 000	1	21 000	1	21 000	1	21 000
ICE	335	20 100						
Treatment system	335	10 050						
Gearbox	300	6 000	100	2 000	100	2 000	100	2 000
Dieseltank	400	800						
Fuel Cell (PEM)							335	16 750
Hydrogen Storage							1375	13 750
Electric Machine			335	3 350	335	3 350	335	3 350
Power Electronics			335	2 010	335	2 010	335	2 010
Energy Battery			1000	150 000	100	15 000	50	7 500
<b>Sum (OEM Costs)</b>		<b>113 950</b>		<b>234 360</b>		<b>117 360</b>		<b>122 360</b>
Retail price equivalent (RPE)		1.48		1.48		1.48		1.48
<b>Purchase Price</b>		<b>167 000</b>		<b>347 000</b>		<b>174 000</b>		<b>181 000</b>

(1) Based upon Kleiner (2017), but also own assumptions and stakeholder input.

(2) 80% is often used for electric buses with larger batteries. Furthermore, we assume that the battery is dimensioned for 80% utilization, that does not mean that you always use it.

**Table 7 Purchase price regional truck (2030), battery size and hydrogen storage are calculated based upon fuel economy (see table 4), distance between refueling 300 km and 80% depth-of-discharge.**

	Diesel		Battery Electric		ERS		Fuel Cell	
	Size	Cost	Size	Cost	Size	Cost	Size	Cost
Current Collector for ERS					1	18 000		
Glider (long haul)	1	38 000	1	38 000	1	38 000	1	38 000
ICE	335	20 100						
Treatment system	335	10 050						
Gearbox	300	6 000	100	2 000	100	2 000	100	2 000
Dieseltank	400	800						
Fuel Cell (PEM)							335	16 750
Hydrogen Storage							473	4 728
Electric Machine			335	3 350	335	3 350	335	3 350
Power Electronics			335	2 010	335	2 010	335	2 010
Energy Battery			412,5	49 253	100	15 000	50	7 500
<b>Sum (OEM Costs)</b>		<b>74 950</b>		<b>107 613</b>		<b>78 360</b>		<b>75 610</b>
Retail price equivalent (RPE)		1.48		1.48		1.48		1.48
<b>Purchase Price</b>		<b>111 000</b>		<b>159 000</b>		<b>116 000</b>		<b>110 000</b>

(1) Based upon Kleiner (2017), but also own assumptions and stakeholder input.

**Table 8 Purchase price urban truck (2030), battery size and hydrogen storage are calculated based upon fuel economy (see table 4), distance between refueling 200 km and 80% depth-of- discharge**

	Diesel		Battery Electric		Fuel Cell	
	Size	Cost	Size	Cost	Size	Cost
Glider (Urban)	1	28 000	1	28 000	1	28 000
ICE	150	9 000				
Treatment system	150	4 500				
Gearbox	100	2 000	100	2 000	100	2 000
Dieseltank	400	800				
Fuel Cell (PEM)					150	5 000
Hydrogen Storage					240	2 400
Electric Machine			150	1 500	150	1 500
Power Electronics			150	900	150	900
Energy Battery			167	25 000	10	1 500
<b>Sum (OEM Costs)</b>		<b>44 300</b>		<b>57 400</b>		<b>41 300</b>
Retail price equivalent (RPE)		1.48		1.48		1.48
<b>Purchase Price</b>		<b>66 000</b>		<b>85 000</b>		<b>61 000</b>

(1) Based upon Kleiner (2017), but also own assumptions and stakeholder input.

#### 4.7 MAINTENANCE COSTS, SALARY COSTS AND OTHER COSTS

The maintenance costs are calculated based on km/year. The values used are presented in Table 9. Tires are included in maintenance costs.

The maintenance costs in Table 9 are used for all vehicle types even though it could be argued that different costs apply for different types.

**Table 9 Maintenance cost for long-haul, regional and urban truck**

Vehicle	\$/vehicle km	
ICE_Diesel	0.147	Kleiner et al (2017c)
BEV	0.098	Kleiner et al (2017c)
ERS	0.098	Kleiner et al (2017c)
FCV	0.103	Kleiner et al (2017c), but also own assumption

Other costs, for example insurance, are 10 000 €/year for all vehicle types.

The hourly salary is different between different countries. However, we assume 2000 hours/year as work load.

#### 4.8 OWNERSHIP PERIOD, RESALE VALUE AND INTEREST RATE

For all use case the ownership period is seven years. The resale value after seven years is assumed to be 22%. Based upon discussion with stakeholders.

Interest rate for truck operations is 8% (Steinbach *et al*, 2015).

#### 4.9 LESS FUNCTION FACTORS

Sometimes, a change of fuel or powertrain has an impact for the vehicle owner and user. In some cases, the change only implies a more restricted number of refuelling stations. In other cases, it leads to reduced cargo capacity and other consequences having a direct impact on the total cost of ownership. Electrification with hydrogen and fuel cells as well as with batteries has the following potential consequences:

- Reduced cargo capacity (volume and/or weight) – depending on range requirements
- Reduced availability of refuelling or recharging stations during an introduction period
- Longer time needed for refuelling or recharging – in particular for battery electric vehicles.

The most demanding application in relation to these potential restrictions is long haul. Obviously, there are also potential positive consequences, among them improved acceleration and access to areas and time periods where or when diesel trucks are not permitted.

Given the limited scope of this study, we do not manage to analyse all potential factors influencing the function of electrified vehicles. However, we attempt to address the probably most important negative one; reduced cargo capacity.

Most studies of electrified vehicles neglect the less function factor. If they include it, they typically check if the vehicle meets the specification in terms of range. If so, it is considered fully functional, otherwise it is not considered at all. Our approach is to calculate the approximate additional weight and volume that the change to hydrogen or batteries implies. The calculation includes weight and volume savings thanks to the removal of the diesel powertrain including the diesel tank, as well as the additional weight and volume caused by the electric powertrain with batteries and, for fuel cell vehicles, also hydrogen storage.

It is preferred that the truck carries the complete powertrain including the energy storage. The truck design in Europe has limited space (compared to the US design). The additional volume and weight caused by the electric powertrain including energy storage is assumed to reduce the cargo capacity to an equal extent. There might be a design constraint caused by the allowed maximum weight per wheel axle. This constraint is not considered in our calculations.

Finally, the reduced cargo capacity is assumed to increase the total cost correspondingly, even though vehicles obviously not always will be used with 100% cargo. As the 'less function factor' is calculated on the total cost of ownership, including wages, it has a large influence on the total cost.

Below is a table illustrating the calculation of the LFF for hydrogen storage at 700 bars. To incorporate the LFF, the total cost has been multiplied by the factor in the columns to the right in the table. For example, for a range of 700 km, the increased weight leads to an increased cost of 4%.

**Table 10 Less Function Factor for Hydrogen Storage (700 bar)**

Range (km)	Hydrogen storage		Net increase (%)		TCO LFF	
	Weight (kg)	Volume (m3)	Weight	Volume	Weight	Volume
100	283	0,4	-0,6%	-0,1%	0,99	1,00
200	566	0,8	0,2%	0,3%	1,00	1,00
300	849	1,2	1,0%	0,8%	1,01	1,01
400	1 132	1,6	1,8%	1,2%	1,02	1,01
500	1 415	2,0	2,5%	1,7%	1,03	1,02
600	1 698	2,3	3,3%	2,2%	1,03	1,02
700	1 981	2,7	4,1%	2,6%	1,04	1,03
800	2 264	3,1	4,9%	3,1%	1,05	1,03
900	2 547	3,5	5,7%	3,5%	1,06	1,04
1000	2 830	3,9	6,5%	4,0%	1,07	1,04

Similarly, the table below for battery electric propulsion shows that the weight increase is dominating for the LFF penalty.

**Table 11 Less Function Factor Battery storage**

Range (km)	Battery system		Net increase (%)		TCO LFF	
	Weight (kg)	Volume (m3)	Weight	Volume	Weight	Volume
100	800	0,4	-0,6%	-0,7%	0,99	0,99
200	1 600	0,8	1,7%	-0,2%	1,02	1,00
300	2 400	1,2	3,9%	0,2%	1,04	1,00
400	3 200	1,6	6,1%	0,7%	1,07	1,01
500	4 000	2,0	8,3%	1,2%	1,09	1,01
600	4 800	2,4	10,6%	1,6%	1,12	1,02
700	5 600	2,8	12,8%	2,1%	1,15	1,02
800	6 400	3,2	15,0%	2,6%	1,18	1,03
900	7 200	3,6	17,2%	3,0%	1,21	1,03
1000	8 000	4,0	19,4%	3,5%	1,24	1,04

The less function factor presented is an important factor for the total cost of the different compared powertrains. However, it is only when the cargo is on the weight or volume limit which this factor has its full effect. In some situations, the cargo is not so heavy or does not need so much volume and for such transports the factor will be lower. Therefore, the LFF cost shall not be interpreted as a cost which always burdens the TCO of a certain type of powertrain.

A powertrain type with a high LFF, but apart from that a low TCO, may find niches in which it can have a lower cost than the alternatives, as long as it only transport light cargo.

## 5 Yearly driving distance, driver salary and energy prices in China, Germany and USA

### 5.1 YEARLY DISTANCE FOR DIFFERENT MISSION PROFILES AND COUNTRIES

Table 12 shows the yearly distance for different mission profiles in different countries.

**Table 12** Yearly distance different mission profile and country (km/year) – Own assumptions, but based upon GFEI (2017), ICCT (2015b).

	Germany	USA	China
<b>Long Haul</b>	130 000	160 000	70 000
<b>Regional</b>	60 000	75 000	30 000
<b>Urban</b>	40 000	50 000	20 000

### 5.2 ENERGY PRICES IN GERMANY, USA AND CHINA

Table 13 provides the numbers used for energy prices 2030. The tax used for diesel, hydrogen and electricity is based upon the assumption of use a road tax, but also some taxation for the carbon-content of the fuel.

**Table 13** Energy Prices in Germany, USA and China year 2030+, Own Assumptions, but based upon IEA (2017)

	Germany	USA	China
Electricity energy cost	0.15	0.12	0.10
Electricity infrastructure cost (BEV)	0.03	0.03	0.03
Electricity infrastructure cost (ERS)	0.06	0.06	0.06
Electricity tax (road)	0.02	0.01	0.01
Diesel energy cost (incl. infrastructure)	0.11	0.11	0.11
Diesel tax cost	0.05	0.01	0.01
Hydrogen energy cost	0.16	0.16	0.16
Hydrogen infrastructure cost	0.02	0.02	0.02
Hydrogen tax cost	0.02	0.01	0.01

### 5.3 SALARY DRIVER GERMANY, USA AND CHINA

Table 12 presents an estimation of salaries for truck drivers in Germany, USA and China for the year 2030.

**Table 14 Salary drive Germany, USA and China (2030) \$/hour. Own Assumptions**

	<b>Germany</b>	<b>USA</b>	<b>China</b>
Salary (€/hour)	33	27	14



## 6 TCO Results

### 6.1 LONG HAUL GERMANY, USA AND CHINA

Figure 1 compares the total-cost-of-ownership results obtained for different geographical areas, powertrains and fuel for the mission profile long haul.

What stands out in Figure 1 is that Electric Road Systems are the most cost-efficient options in all regions, even if battery packs are as cheap as 50 €/kWh. A possible explanation for this might be that the cost of the infrastructure for the electric road systems is not significant if well utilized and the ERS truck is cheap compared with a battery electric long haul truck. Not considered here, but potentially important for the ERS solution, is the need for a certain coverage of charging networks.

The present study was designed to assess the competitiveness of fuel cell trucks. In all regions, fuel cell trucks and hydrogen are more expensive than diesel trucks and diesel. The difference is not massive. However, the cost of fuel cell truck and diesel trucks is similar. The primary variable explaining the cost difference is the cost of hydrogen and diesel. One significant result of our study is if hydrogen is relatively cheap, it will be able to compete with diesel long term.

Fuel cell trucks compared with battery electric trucks are more cost-efficient in Europe and China, but not in the USA. This result is valid if the battery costs 150€/kWh. If the battery cost is as low as 50€/kWh, the battery electric truck will be cheaper in all regions. Our use of the Less Function Factor (LFF) also affects the comparative result.

The ranking of the propulsion systems is similar in all three geographical areas, but the costs are not. The main explanation why the costs differ is that the yearly mileage differs substantially but the vehicle depreciation and the 'Other' post are the same in absolute values and thus much higher per kilometer in China, where the total mileage is low.

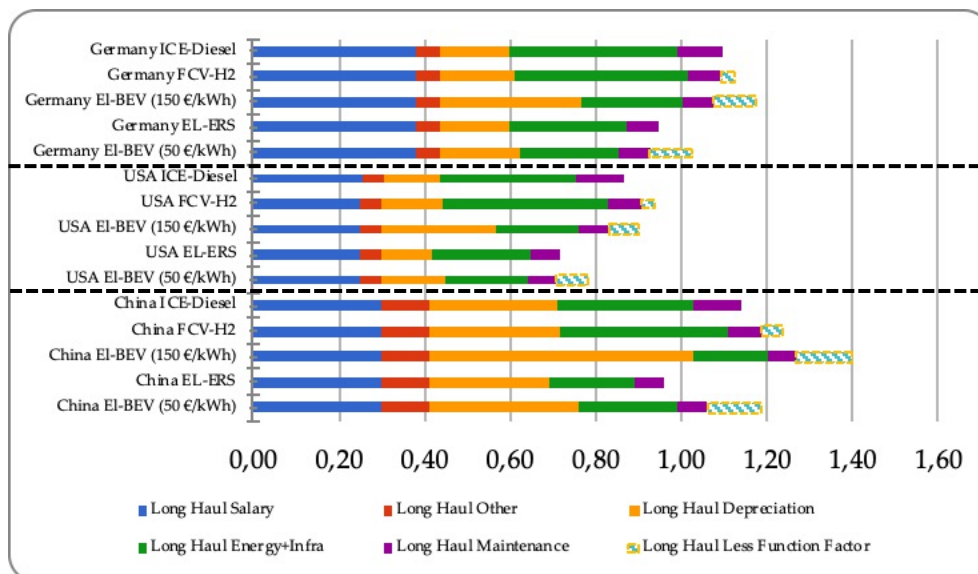


Figure 4 TCO (€/vehicle,km) 2030 Long Haul Germany, USA and China. Sensitivity analysis included if battery pack costs 50 €/kWh or 150 €/kWh.

## 6.2 REGIONAL TRUCKS GERMANY, USA AND CHINA

As shown in Figure 2, Fuel Cell trucks for regional use are more cost-efficient than diesel trucks in all regions. The difference between the transport mission long haul and regional are more start-stop and more urban traffic in the regional case. Therefore, the energy-efficiency difference tank-to-wheel between an electric powertrain, with braking energy recuperation, and diesel powertrain are changed. One option to reduce the energy use of a diesel powertrain is to use a hybrid. However, this is outside the scope of this study. Generally, the battery electric trucks and Electric Road systems are more competitive than fuel cell trucks, except in China where the short annual driving distance make the BEV slightly more expensive than the fuel cell truck. If battery packs cost is as low as 50 €/kWh, the battery electric truck is the low-cost option compared to electric road systems.

Another main conclusion for the regional truck case is that the relative importance of the cost of the truck and the salary increase compared to the long haul case. For example, in China the yearly distance of the regional truck is low compared to the USA. Therefore, the cost of deprecation dominates in China besides the value of the salary.

The analysis assumes that all types of vehicles can operate without any restrictions and the LFF is thus zero. This is assumed since the vehicle needs less energy stored onboard due to the shorter driving range, and regional distribution trucks are less often than long haul trucks operating on the limit for weight or size. A closer look at specific applications might reveal cases when it is not possible to replace a diesel truck with an electrified truck without consequences. It could also be discussed if ERS is possible in cities.

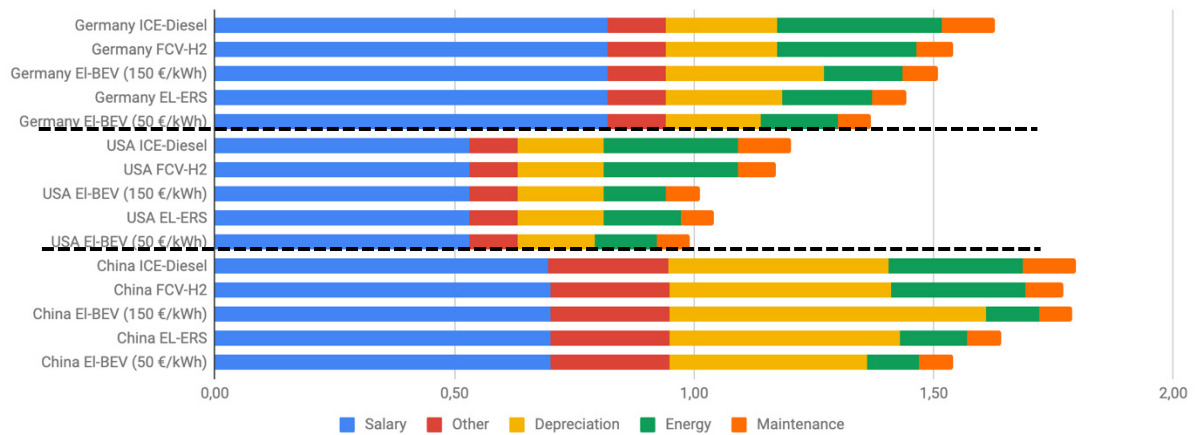


Figure 5 TCO (€/vehicle,km) 2030 Regional Germany, USA and China. Sensitivity analysis included if battery pack costs 50 €/kWh or 150 €/kWh.

### 6.3 URBAN TRUCKS GERMANY, USA AND CHINA

From figure 3, we can see that for urban trucks, the fuel cell truck is competitive compared to the diesel trucks. As for the regional distribution trucks there is no less function cost for urban distribution trucks.

In Germany the battery electric truck has about the same cost as a fuel cell truck if the battery cost is about 150€/kWh. If the cost of the battery pack is as low as 50 €/kWh than the battery electric truck is cheapest.

Since the yearly distance driven is low for an urban truck compared to long haul, the relative importance of the cost of energy and infrastructure is reduced. Salary costs become the dominating cost, which implies that the vehicle must allow for an efficient use.

When the TCO is compared the different powertrains rank in the same order for urban distribution trucks as for regional distribution trucks, even in the relative difference may be a different. So, a type of power train which is cost effective for an urban distribution truck typically is it also for regional distribution, and vice versa.

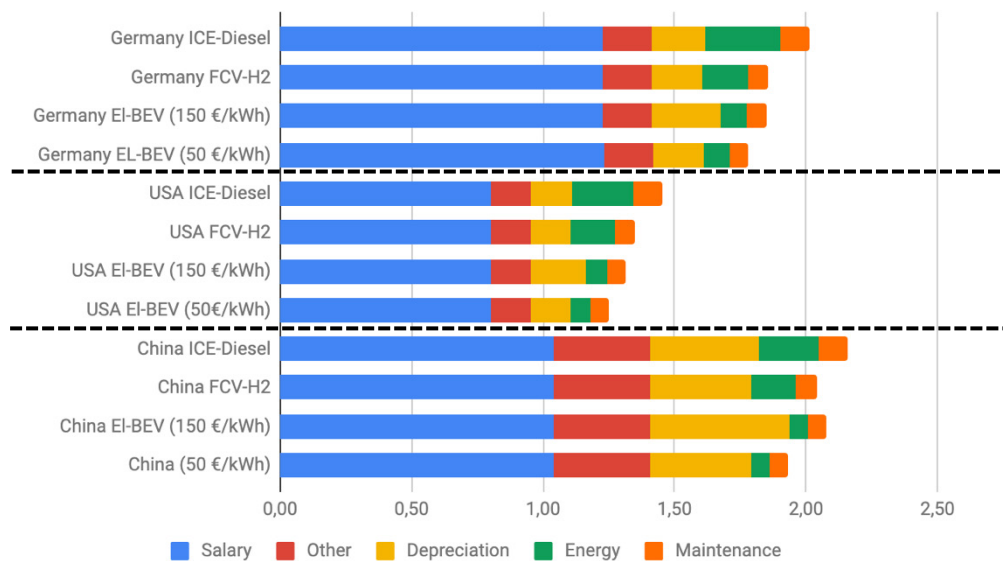


Figure 6 TCO (€/vehicle,km) 2030 Urban trucks Germany, USA and China. Sensitivity analysis included if battery pack costs 50 €/kWh or 150 €/kWh.

#### 6.4 FACTORS WITH A HIGH TOTAL COST IMPACT

Several of the data used in this study is uncertain. In table 15 shows an attempt to categorise the factors how much they influence the final result and how uncertain they are.

Table 15 Factors influencing the final TCO results

	Low total cost impact	High total cost impact
High uncertainty	Cost of fuel cell system Cost of hydrogen storage Cost of electric machine	<b>Cost of hydrogen, electricity, diesel</b> <b>Residual value of BEV, FCV</b> <b>Less transport efficiency</b> <b>Km between refuelling</b> <b>Battery life length</b> <b>Cost of battery</b>
Low uncertainty	Not listed	Total mileage Powertrain efficiencies Maintenance costs

## 7 Discussions

This study set out with the aim of assessing the competitiveness of fuel cell trucks. Our focus is the TCO for the first owner. Several assumptions about energy use, cost of components and energy are uncertain. Our results, therefore, need to be interpreted with caution.

The main goal of this study is not to calculate the absolute numbers but to try to assess the most critical factors influencing the results.

As shown, the cost of fuel or electricity has a large impact on the TCO, especially in the long-haul case. The cost of hydrogen will probably vary between different geographical areas. The same is valid for electricity. For example, we have assumed the same price of electricity everywhere in the USA. In reality, the price varies substantially between different cities. The price could also vary between night and day, for example.

Another aspect relating to electricity is that energy and power cost must be handled separately. High power charging directly from the grid might lead to high costs as the grid needs to be reinforced.

In our study, we have tried to assess the consequences of reduced cargo capacity because of the weight or volume of extra battery or hydrogen storage. Our approach could be discussed, but the potential effects of limit cargo capacity should be assessed.

One limitation of our study is not to include plug-in hybrids. Plug-in hybrids are generally a solution for vehicles which most days drive a certain distance, for which the battery is sized, but sometimes they need to drive longer, which the engine or fuel cell can enable. Their main advantage is that the battery can be made smaller, but still provide a very large fraction of the energy, while the much cheaper fuel or hydrogen tank can provide a few long trips. Such a vehicle can combine the possibility to mainly use cheap electricity, and only use the more expensive fuel for a low number of long trips. They are generally interesting mainly for trucks that have irregular daily driving ranges, and we have not included that type of driving in our analysis.

However, other factors than cost could influence the willingness to buy a fuel cell truck. Compared to a diesel truck, the hydrogen truck could have advantages, such as accessibility to low-emission zones. Compared to battery electric truck, the limits of available power could be a problem for a high-power charging infrastructure for at battery electric trucks. The fuel cell truck could have more flexibility in accepting transport missions than a battery electric truck because the battery capacity could set limits. The electric road system could be limited because there is a need for high utilization to make the system cost-effective. Fuel cell trucks and hydrogen infrastructure could be more manageable to stepwise build up.

The report has compared TCO, but for a fairer comparison, more detailed studies of charging time or battery load will affect the transport efficiency are needed. For

example, long charger times could have consequences for the complete the supply chain. The study has included the Less Function Factor to asses some of the effects, but it is a rough assessment.

## 8 Conclusions

PEM fuel cell heavy-duty trucks could be a techno- economically reasonable solution. However, its potential success on the market depends on several factors, among them: availability and cost of hydrogen, regulations, incentives and taxation schemes (for all types of trucks), and techno-economic maturity of fuel cells and hydrogen storages.

The TCO ((Total-Cost-of-Ownership) calculation assumes that the relative cost per vehicle-kilometre is an important factor when selecting the type of vehicle.

Energy cost per vehicle-kilometre depends on energy efficiency and cost of fuel/electricity. For example, the cost of hydrogen is not only production costs, but also infrastructure cost, such as a refilling station, and taxes.

The relative energy efficiency advantages of electric powertrains compared to diesel powertrains is less prominent in long haul applications compared to city distribution. Therefore, the relative competitiveness for diesel is better for long haul than for city distribution.

Fuel cell trucks are therefore more competitive in regional and urban distribution. However, that is also the case for battery electric and electric roads systems.

Another reason why battery and fuel cell trucks are more competitive in urban and regional distribution is the reduced need of batteries and hydrogen storage, which is expensive components.

Probably the cost of powertrain for a battery electric long-haul truck is more expensive than for a fuel cell truck. Despite the difference in component costs, the main explaining variable is the relative cost difference between electricity and hydrogen per kilometre. Battery electric trucks and ERS trucks have more energy efficient powertrains compared to fuel cells. Therefore, hydrogen starts with a disadvantage.

The relationship between hydrogen and electricity costs differs between countries, regions, and even cities. The cost of hydrogen and electricity is influenced by the need for long-term storage of energy from sources such as photovoltaics and wind power. Hydrogen is typically much cheaper to store than electricity. The cost relationship must be determined through a system analysis modelling several industrial sectors in the region. An important issue is whether there are good conditions for storing hydrogen cost-effectively on a large scale.

One challenge in such systems is that surplus of electricity is only periodically available. The cost of hydrogen from such electricity becomes too high if there is a low utilisation rate of (maybe about 10-20%) of the electrolyser.

Without clear incentives, most countries will not produce hydrogen from electricity. The main alternatives are natural gas and coal (with or without CCS).

One part of the cost of fuel for the owner is cost of the infrastructure. The cost of charging infrastructure, e-highway, heavy duty hydrogen infrastructure depends

on how the design of the systems looks like, for example, location. To calculate, scenario descriptions of likely situations for the different uses and countries are necessary. A high utilisation of the infrastructure is required to have a low cost.



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# FUEL CELLS FOR HEAVY DUTY TRUCKS 2030+?

This study is mainly a total-cost-of-ownership calculation of four different powertrains for heavy-duty trucks for three different customer mission profiles, long haul, regional and urban distributions. The powertrain alternatives were diesel, batteries, electric road systems and fuel cells. Also, the calculations were made for three main markets for heavy-duty trucks; Germany, USA and China. The results showed that Electric Road Systems has the lowest total costs, and battery trucks were the second best option (depends upon cost levels of batteries). Fuel cell trucks are cheaper than diesel trucks for urban and regional distribution. These results must be interpreted with caution because of several uncertainties in choice of, for example, the cost of electricity and hydrogen.

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