Zero emissions trucks

An overview of state-of-the-art technologies and their potential

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Author(s):
Eelco den Boer (CE Delft)
Sanne Aarnink (CE Delft)
Florian Kleiner (DLR)
Johannes Pagenkopf (DLR)

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Subcontractor information

German Aerospace Center
Institute of Vehicle Concepts
Prof. Dr. Ing. H.E. Friedrich
Pfaffenwaldring 38-40
D-70569 Stuttgart, Germany

http://www.dlr.de

Preface

This report has been developed to contribute to the discussion on future road freight transport and the role on non-conventional drivetrains. The primary objective of the report is to assess zero emission drivetrain technologies for on-road heavy-duty freight vehicles. More specifically, their CO_2 reduction potential, the state of these technologies, their expected costs in case of a technology shift, the role of policies to promote these technologies, and greenhouse reduction scenarios for the European Union have been studied.

The authors would like to thank many industry experts (Annex A) for sparing some of their time to give insights and share knowledge. The authors are grateful for the critical reviews of Elaine Olivares, Rachel Muncrief, John German, Ben Sharpe, and Nic Lutsey of the International Council for Clean Transportation. Furthermore, we would like to thank our colleagues at the Oeko-Institute for their peer review of the draft report.

The content of the report is the sole responsibility of the authors.

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Summary

Heavy-duty vehicles: growing contributor to fuel use and emissions
Road freight transport is one of the fastest growing contributors to total greenhouse gas (GHG) emissions of the European transport sector. Significant emission reductions in road freight transport are needed to meet long-term climate goals therefore. However, policies targeting fuel efficiency and GHG emissions for heavy-duty vehicles are generally less developed than for passenger cars and vans. Studies looking at long-term, deep-carbon reduction scenarios for heavy-duty road transport often rely on significant amounts of biofuels to provide deep cuts to GHG emissions for this sector of vehicles. However, given the uncertainties about the sustainability of biofuels and their impact on indirect land-use change, other low-carbon vehicle technologies will likely be needed for climate stabilization scenarios.

To explore the options for zero-emission road freight transport, the International Council on Clean Transportation (ICCT) commissioned CE Delft and DLR to carry out this study, which aims to investigate the potential of battery electric and fuel cell heavy-duty vehicles.

Electric and fuel cell heavy-duty vehicles are viable options
Electric trucks are a promising alternative to conventional, primarily diesel-fuelled, trucks in the coming decades. Electricity powered vehicles, even after battery charging-discharging and transmission losses, tend to be about twice as efficient as conventional vehicles. The electricity can be provided by several electric charging methods, such as conductive charging, inductive (i.e. wireless) charging, through battery swaps or via overhead catenary wires. Alternatively, the electricity for the vehicle can be generated on-board by a hydrogen fuel cell. All of these options are investigated for both short distance (i.e. distribution trucks) and long distance applications. For both applications it is important that the consumed electricity is produced from renewable sources, to obtain near-zero emissions through the full energy pathway.

For short distance transport, the battery electric technology is a feasible option, as distribution trucks generally have lower daily driving distances, and recharging can occur at scheduled downtimes (e.g. overnight) to avoid potential vehicle operation interruptions. Currently, around 1,000 battery electric distribution trucks are operated worldwide. Significant improvements are expected within five years, especially with respect to the costs and durability of battery technologies that would increase the potential of electric distribution trucks.

For long haul applications, battery electric vehicles alone (i.e. without on-the-road charging technologies) are not a viable mainstream option. Next generation batteries with much higher energy densities, like lithium-air batteries, are currently being investigated but they are not commercially available, and several technical bottlenecks need to be resolved. Due to the significant weight of the battery pack, battery electric drivetrains are less likely to be used for long haul applications, unless applied in combination with on-the-road charging technologies like inductive charging or overhead catenary wires. With catenary wires or dynamic induction, the required-on-board battery capacity can be reduced dramatically, which could enable electric drivetrains for long haul trucks. Both overhead catenary wires and dynamic inductive charging have been successfully tested in small-scale demonstration projects.

However, massive investments would be needed to electrify strategic parts of the road network to significantly displace conventional diesel fuel demand. Battery swapping is not expected to be a viable solution in long haul applications, as the driving range is too limited, which would require more stops than is the case for conventional vehicles.

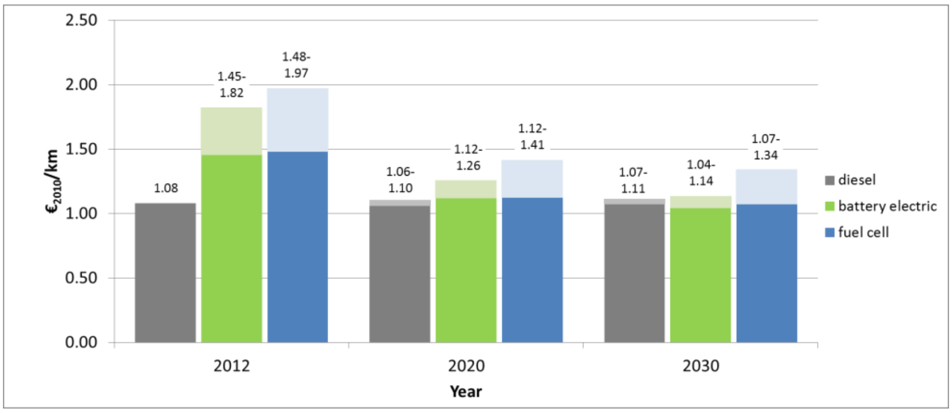
Fuel cell trucks are a viable option in the longer term, particularly for long haul applications, because of the superior driving range compared to battery electric drivetrains. Fuel cell drivetrains avoid combustion, thermal, and friction losses, and therefore are more efficient than diesel-driven powertrains. Fuel cell drivetrains are generally less efficient than full battery electric drivetrains, since hydrogen must be electrochemically transformed into electricity before it powers the electric motor. The hydrogen production pathways have challenges in simultaneously moving toward lower cost and lower carbon (i.e. more renewable) energy pathways. Furthermore, the durability of the fuel cell system, and the volume and weight of the on-vehicle hydrogen storage system are critical issues for fuel cell trucks, as is the hydrogen fuel delivery infrastructure.

Total ownership costs merge in coming decades

Currently, the total costs of ownership (TCO) for zero tailpipe emission vehicles are significantly higher than for conventional vehicles. However, for both short and long distance applications, the cost differential is expected to diminish over the coming decades, assuming increased production figures. Future costs of zero emission vehicles mainly depend on the costs of the batteries and fuel cell systems.

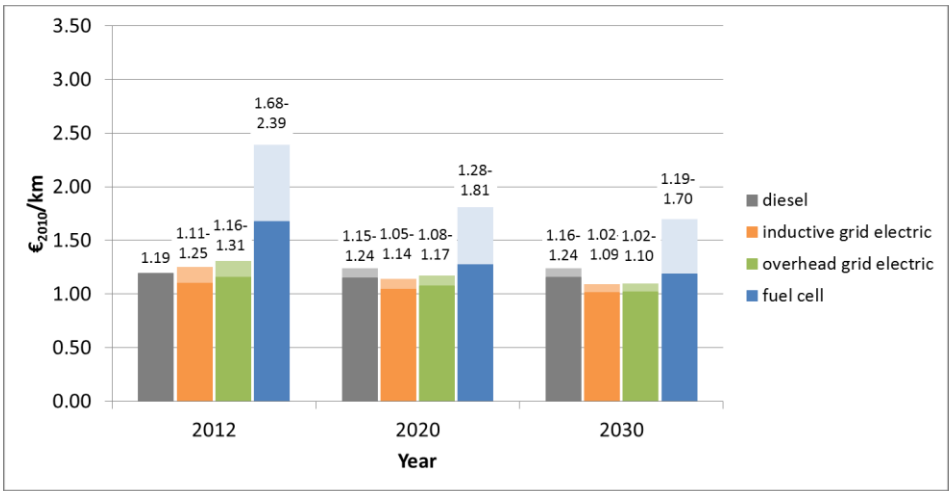
Figure 1 shows the TCO for distribution trucks with different vehicle configurations, including the upfront capital costs for technology and the vehicle energy costs (taking no other taxes than the currently applicable fuel taxes into account). Similarly, Figure 2 shows the vehicle-and-fuel costs for long haul vehicle applications. The findings indicate that electric and fuel cell vehicles may become nearly cost competitive with diesel between 2020 and 2030, both in the distribution and in the long haul segment. The dark and light colors represent a low and high scenario due to uncertainty of future costs.

Figure 1 **Total vehicle technology and fuel operation costs for distribution trucks**



Note: On-vehicle and energy costs included. Infrastructure costs are not included.

Figure 2 Total vehicle technology and fuel operation costs for long haul trucks



Note: On-vehicle and energy costs included. Infrastructure costs are not included.

The study's cost results indicate that if zero emission technologies are introduced on a large scale in the on-road freight transport sector from 2020 and beyond, the total vehicle running costs will not significantly increase (i.e. increase by more than 10%). The approximate cost parity is primarily due to the fuel savings of the more efficient advanced electric-drive technology offsetting the new incremental costs. Therefore the overall costs to shippers, and ultimate consumers of the freight goods, would be limited in the long term. The potential economic benefits from new industry growth and technology innovation in these battery and fuel cell areas were not investigated in this assessment.

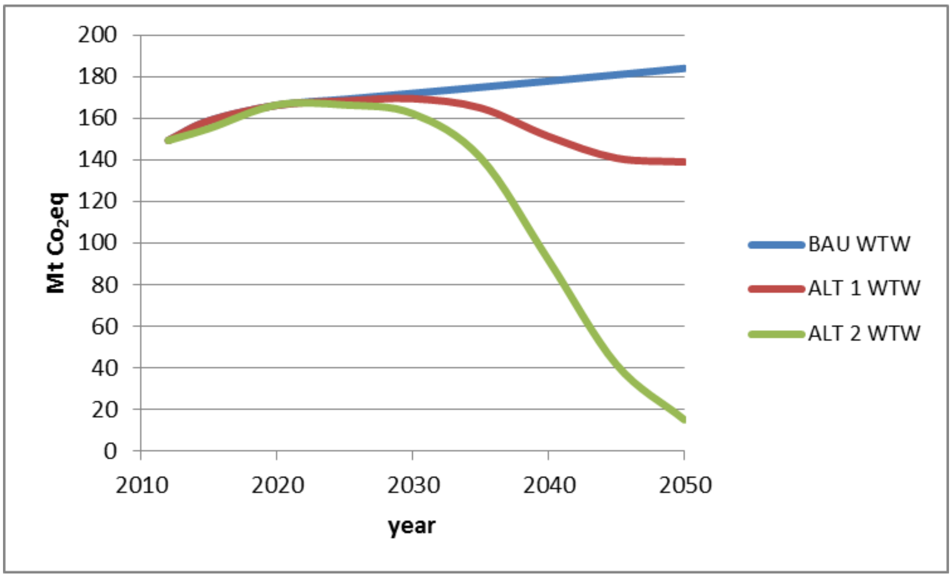
Infrastructure requires huge investments

All alternative electric-drive vehicle technologies, for long haul applications especially, require major investments in energy infrastructure. A network of either catenary wires, hydrogen refueling stations, or in-road inductive charging would be required along with the deployment of the vehicle technologies. Each of these infrastructure networks would require a huge investment. The European Commission recently published a proposal for a Directive to stimulate the development of alternative fuel infrastructure. This can be seen as a first step to develop the required infrastructure for these near-zero carbon emission electric-drive technologies.

Deep emission reductions possible

This study investigates several scenarios for advanced technology deployment to reduce the carbon footprint of the EU freight sector. With only the improvement of the fuel efficiency of conventional trucks, GHG emissions of truck transport in the EU will increase by 23% until 2050, due to increased transport volumes. In the scenario where 50% of the total EU ton kilometres are transported by alternative vehicles (including hybrid trucks and limited electric and fuel cell vehicles) by 2050, GHG emissions would decrease by 8% as compared to 2012. Increasing the share of alternative vehicles further, to 90% of the total ton kilometres, can result in an emissions reduction of 90% from EU heavy-duty vehicles, see Figure 3. These indicate that the combination of zero emissions fuels and advanced technology vehicles definitely has the potential to drastically decarbonise the freight transport sector.

Figure 3 Well-to-Wheel CO_2 eq. scenario development



Policy instruments are key to further expansion

It is not yet possible to say which of the electric-drive battery, charging, and fuel cell technologies have the highest likelihood for large-scale fleet deployment. Therefore, in the coming years, broad policy support is needed to encourage the adoption of various technology options. Examples of policy measures include vehicle or infrastructure subsidies and tax incentives for pilot projects to encourage early adopters. All government levels - EU, national, and local - can play a significant role at this stage. A broader, longer-term policy package would require a shift from a stimulating character to a more regulatory character to transform heavy-duty vehicles and fuels to the ultra low carbon options presented in this report. The sustained long-term regulation of energy carriers (e.g. through the EU's Fuel Quality Directive and Renewable Energy Directive) and of energy consumption by heavy-duty vehicles are needed to promote the deployment of these advanced technologies.

1 Introduction

1.1 Background

The European Union (EU) has set an ambitious target for reducing its greenhouse gas (GHG) emissions and aims for an 80% reduction in 2050 compared to 1990 levels. The reduction target for the transport sector is 60% over the same period, as mentioned in the Transport White Paper (EC, 2011a). Within the transport sector, road freight transport is one of the fastest growing modes of transport and has an increasing share in the total GHG emissions of transport. Over the last decade, road freight transport emissions grew by around 25% in EU 27 (EEA, 2011), without significant changes to vehicle fuel consumption.

Available projections show at least a doubling of freight transport activity between 1990 and 2050 (Rijkee and Van Essen, 2010). This implies that truck emissions will need to decrease drastically in order for the EU to reach the goals set in the Transport White Paper.

The improvement of truck energy efficiency, through the development and the uptake of new engines and cleaner fuels is stated as a key goal in the EU White Paper. In addition, the phase-out of urban distribution trucks with internal combustion engines is another goal that has been set for the road transport industry.

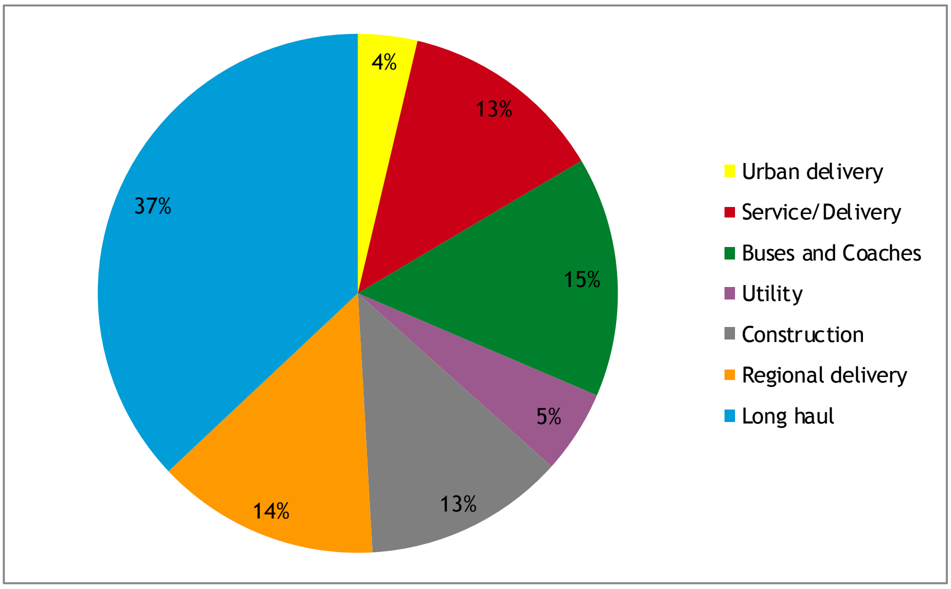
The interest in reducing GHG emissions of the road freight sector has increased over the last years. Various technical and non-technical options exist for reducing the GHG emissions of road freight transport, such as improving the efficiency of freight logistics or fuel consumption performance of vehicles. To achieve early benefits, current EC policy initiatives to reduce the fuel consumption of heavy-duty vehicles concentrate on the short term and therefore focus mainly on incremental developments. However, this is not likely to result in the emission reduction of road freight transport that is required to reach the goals set by the EC for the long term. Furthermore, given the uncertainties and difficulties with biofuels (IFPRI, 2011; PBL, 2012), it is highly uncertain if the sole use of conventional engines can result in large-scale GHG reductions from on-road freight transport over the coming decades.

However, there may be potential for zero emission vehicles that could result in the large-scale GHG reductions that are needed. Therefore, the ICCT requested CE Delft and DLR to investigate the current state of zero emission commercial vehicles and the technological improvements that will be required in order for zero emission vehicles to achieve widespread penetration in the on-road freight sector. In addition, the report examines the effects of decarbonizing the energy carriers (i.e. electricity and hydrogen).

1.2 Objectives

The goal of this scoping study is to investigate long-term options for zero tailpipe emissions technologies in the on-road transport sector. Currently, zero emission vehicles primarily operate within cities (e.g. distribution trucks and city buses), since, at present, these vehicles are typically range-limited as compared to their conventional counterparts, and refuelling infrastructure for electricity and hydrogen is nascent. However, this study also focuses on long haul trucks, since decarbonisation of this segment of commercial vehicles is vital to reducing overall GHG emissions from freight transport, as evidenced in Figure 4.

Figure 4 GHG emissions by HDV-segment in the EU 27



Source: AEA, 2011.

This study describes the potential and challenges of hydrogen and electricity as energy carriers for goods distribution and heavy-duty transport.
Which energy carrier, or mix of energy carriers, will be adopted depends on a wide variety of factors, including the efficiency of the fuel chains, the potential of different vehicle concepts and drivetrains, and the potential to store renewable energy obtained from sun and wind. The results from this study can be used to aid GHG reduction planning and regulatory development efforts as well as to contribute to the discourse on the development of future energy systems.

1.3 Methodology

Different sources have been used to investigate the potential of different zero emission vehicles. The most important sources for this study used throughout the report are a combination of extensive literature review and expert consultation. Expert responses have been anonymously processed in this report, as preferred by the interviewees. A list of consulted organisations can be found in Annex A.

1.4 Report structure

Chapter 2 includes a broad survey on the state-of-the-art and future potential of zero-emission technologies. Chapter 3 discusses the current and expected costs in future decades. In Chapter 4, an overview of the required policy instruments to bring alternative vehicles to the market is given.
Chapter 5 provides an overview of alternative drivetrain market uptake and mileage share based GHG reduction scenarios. Finally, chapter 6 summarises the main conclusions of this report.

2 State-of-the-art zero emission technologies

This section provides an overview of the alternative drivetrain technologies that may become viable options to power heavy-duty vehicles in the 2020-2050 timeframe. With a literature review, a number of technologies have been selected for in-depth research. This chapter provides an overview of these candidates that may be able to compete with the Internal Combustion Engine (ICE) in the coming decades.

In order to be attractive for transport companies, technologies should meet a list of performance criteria. The following performance criteria are used to evaluate the technologies in this study:
– usability (e.g. recharge time);
– durability;
– range (partially dependent on the weight and volume of the battery technology);
– weight and volume of technology components;
– total costs of ownership;
– reliability.

To the extent possible with available data from the industry and scientific literature, all of these factors are considered. However, it is noted that as there are not sufficient real-world data to accurately quantify the projected reliability of the advanced technologies well into the future, this aspect is not described in detail in this report.

2.1 Truck concepts and their application

For the purpose of this report, two main types of trucks have been investigated - a distribution and a long haul truck - as the typical usage profile of a truck results in different requirements for the potential zero-emission technologies. Table 1 shows the key characteristics of the two types of trucks that have been investigated.

Table 1 Definition of distribution and long haul truck

	Distribution truck	Long haul truck
Gross vehicle weight (GVW)	7.5-16 tonne	30-40 tonne
Daily range	150-400 km	800-1,500 km
Typical operation	Regional	(Inter)national
Fuel consumption	18 l/100 km	35 l/100 km

Source: TREMOVE; MAN, 2012; ACEA, 2010.

2.2 Focus on fuel cell and electric drivetrain

Several options exist for the decarbonisation of the transport sector. First and foremost, optimisation of the logistical chains can help reduce the GHG intensity of the transport sector. Secondly, technical measures to achieve the GHG reduction goals identified in the Transport White Paper (EC, 2011a).

For the longer term, advanced biofuels and alternative drivetrains, such as fuel cell electric and fully electric drivelines, will be the main options to drive deeper GHG emission reductions from trucks.

Although biofuels have the potential to reduce GHG emissions, indirect land use change (ILUC) can result in additional GHG emissions, closing the gap between the emissions from biofuels and fossil fuels. This has been shown by a broad range of recent scientific reports. Various studies have concluded that this effect is so large that the current biofuels policies in the EU will only lead to very limited GHG emission reduction in 2020 (IFPRI, 2011; EC, 2010).

The period after 2020 has not been studied in much detail, but there are no clear signs that the GHG reduction potential from biofuels will improve significantly, as the ILUC problem will remain in most cases. The amount of sustainable biofuels available is highly uncertain; several studies have tried to estimate the potentially available amount of biomass in Europe and worldwide for 2020, 2030 and beyond. Each of these studies has shown significant uncertainties (PBL, 2012).

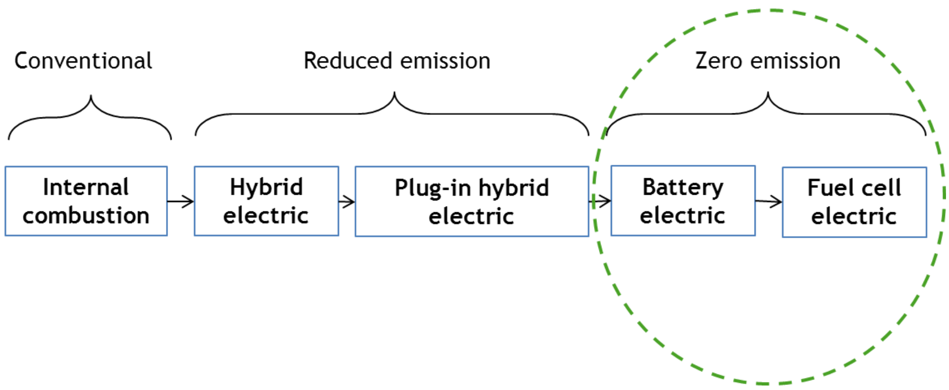
The difficulty of application of other fuels beside liquid fuels in maritime and air transport also play a role, since conventional and biofuels can be stored with a rather high energy density, in contrast to hydrogen and electricity. This implies that available future biofuels might rather be used in air and maritime transport rather than in road transport.

For the reasons mentioned above this study does not focus on fossil fuels, but concentrates on the application of fuel cell electric and full electric drivelines.

2.3 Transition to zero tailpipe emission vehicles

The general development strategy for zero emission vehicles starts with conventional vehicles that are currently on the road, as is depicted in Figure 5.

Figure 5 Development strategy for zero tailpipe emission vehicles



With the introduction of hybrid vehicles, a battery is introduced in the vehicles. Hereafter, increased battery sizes allow for plug-in charging. Hybrid drivetrains offer the potential to store energy from braking and have an improved drivetrain efficiency, resulting in lower emissions.

If batteries are increasingly used, technology improvement and reduced costs from economies of scale will pave the road for battery electric vehicles. Fuel cell electric vehicles are seen as the next step by many experts, as battery electric vehicles and fuel cell electric vehicles show many similarities with regards to the technologies used. Both concepts use an electric motor to drive the wheels and require an energy storage system, although its size may differ. However, the concepts differ in the use of energy carrier; while battery electric vehicles store electricity in a battery, fuel cell electric vehicles carry hydrogen onboard that is converted into electricity by using a fuel cell, combined with a small battery. Both energy carriers need to be produced, however, from primary energy sources.

In the next sections, the results of the assessment of the zero emission technologies for truck applications are described.

2.4 The view of truck manufacturers

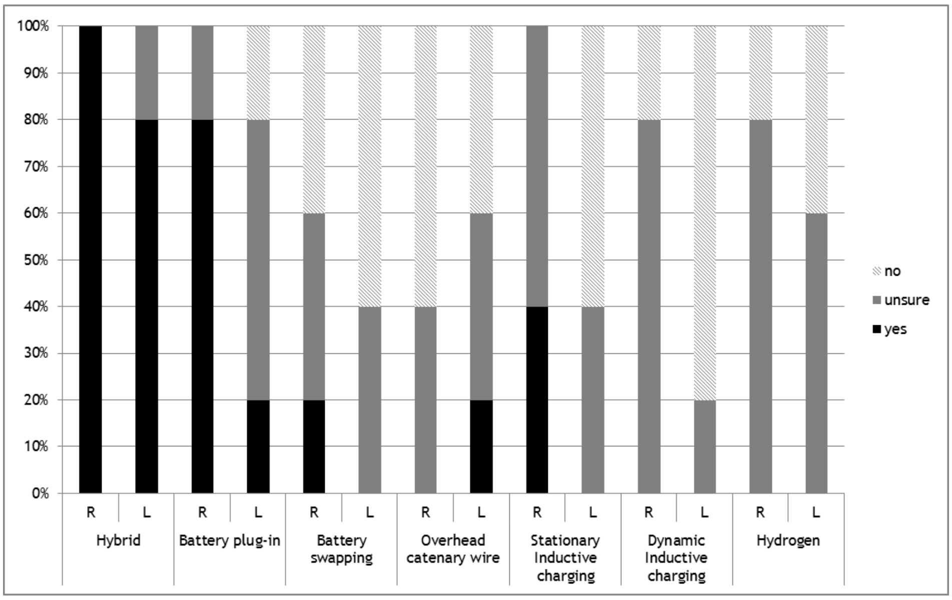
A questionnaire (see Annex B) was distributed among the main EU-market truck manufacturers in order to obtain their view on the expected developments, their activities, potential bottlenecks, and the weight criteria for the application of zero emission vehicles. Five out of the six major truck manufacturers filled out the questionnaire.

In addition to the technologies described below, vehicle manufacturers also mentioned the next generation liquid biofuels, (bio)gas, and significant efficiency improvements of conventional trucks as important future issues. Truck manufacturers have developed various market uptake scenarios. Local preferences may create a diversity of energy carriers they argue.

Expected role of zero emission technologies in the 2030-2050 timeframe

Figure 6 provides an overview of manufacturers’ point of view on the potential role of zero emissions technologies in road freight transport from 2030-2050.

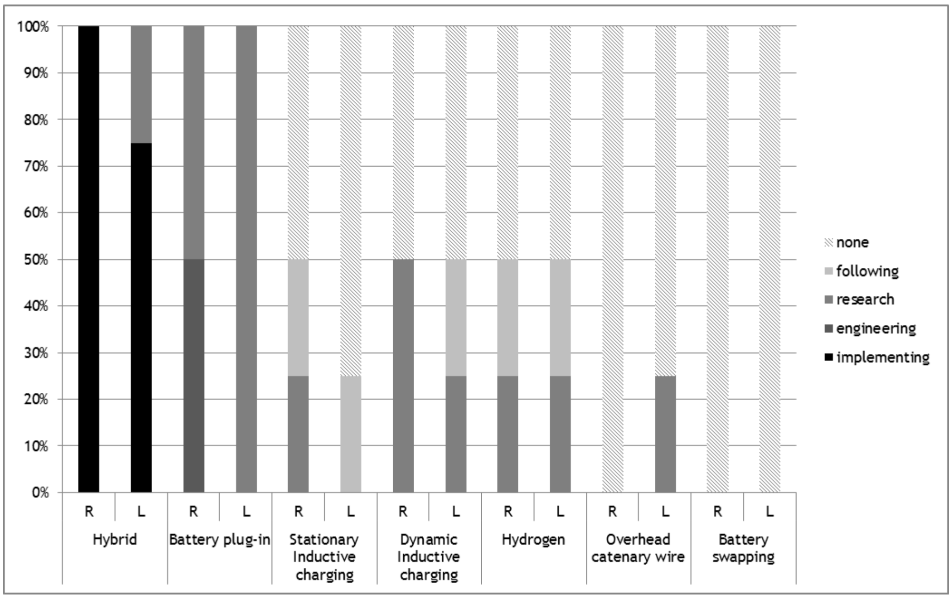
Figure 6 **Manufacturers' view on the role of zero emissions technologies in the 2030-2050 timeframe**



Note: R represents <u>R</u>egional and L represents <u>L</u>ong haul. Five manufacturers have answered the question.

In addition, Figure 7 provides an overview of the activities that are currently undertaken by the truck manufacturers and the phases of development.

Figure 7 **Manufacturers' current activities regarding zero emissions vehicles**



Note: R represents *Regional* and L represents *Long haul*. *Following* refers to actively following the developments. Four manufacturers have answered the question.

Several conclusions can be drawn from these figures:
- In general, truck manufacturers believe that a larger number of zero emissions technologies will play a role in distribution transport rather than in long haul transport. For inductive charging and hydrogen, manufacturers tend to believe that zero emission technologies will be applied in distribution vehicles rather than in long haul vehicles.
- Truck manufacturers differ in their view of the future prospects for electric drivetrains. There is uncertainty about which technologies will become reality, especially with regard to technologies that have only received limited testing.
- Battery plug-in vehicles are projected to play a role in goods distribution in the 2030-2050 timeframe, but will probably play a smaller role in long haul transport.
- Most truck manufacturers do not see a role for battery swapping or are unsure about the potential application of this technology. If applicable, battery-swapping technology would be better suited in distribution transport than in long haul transport. None of the interviewed manufacturers are employing any activities with regards to battery swapping.
- The technologies that are further away from market application receive limited attention at the moment. Apart from hybridization and battery plug-in trucks for distribution purposes, manufacturers are not engineering any other technologies yet.
- Currently, the technologies that require another type of infrastructure do not receive much attention.

Main bottlenecks

The respondents were also asked for the main bottlenecks that apply to the different zero emissions technologies. Especially for the technologies that have a larger distance to the market and have not been applied yet, respondents indicated that test fields are needed to gain experience with the technologies. Table 2 provides an overview of the bottlenecks that were most frequently mentioned by the manufacturers.

Table 2 Overview of technological and economic bottlenecks as observed by truck manufacturers

	Main bottleneck	Steps needed to overcome
Hybrid	TCO (battery)	Lower priced batteries, high volumes in passenger market
Battery plug-in	TCO (battery)	Lower priced batteries, high volumes in passenger market
Battery swapping	Business model complexity, handling	
Overhead catenary wire	Infrastructure, lack of standardization, visual pollution	Complete infrastructure network needs to be in operation
Stationary Inductive charging	Infrastructure, technology maturity, efficiency	
Dynamic Inductive charging	Infrastructure, technology maturity, efficiency	
Hydrogen	Technology maturity, costs, none fossil H_2, cost of tanks, distribution network	Distribution network, technology must be proven in less complex applications. Passenger car application

A specific concern of alternative drivetrains that was frequently mentioned is an *increase in vehicle weight*. Many of the technologies lead to additional weight, at the expense of vehicle payload. The majority of the respondents (60%) indicated that 400 kg is the maximum additional drivetrain-caused allowable weight for a distribution truck. For long haul transport, 400 kg is being seen as a maximum by 60% of the respondents, while 20% perceive that 600 kg is acceptable.

The next sections provide information on the activities of some of the manufacturers that are publicly available.

2.1 2012 International Motor Show

The September 2012 International Motor Show (IAA) in Hannover, showed a state-of-the-art overview of near market technologies in truck transport. Based on the exhibition and expert interviews, an overview of the present technologies is described below.

Distribution trucks/buses

For small trucks, innovative technologies are being developed mainly for niche applications. The following technologies were presented at IAA:
- hybrid city buses/electric city buses;
- electric trucks (light commercial and medium duty trucks);
- hybrid delivery and garbage trucks.

The difficulty with electric trucks is their short range, which is currently 150-400 km, depending on the mass of the battery. Furthermore, electric trucks are significantly more expensive that conventional trucks; these vehicles cost about three times more than conventional ones, mainly due to the high battery costs, experts indicate.

Long haul trucks

For large trucks, no alternative powertrains other than the conventional diesel engine were presented at IAA. Discussions with truck manufacturers show that they are not engineering any (near) zero-emissions technologies at the moment, but are starting to think about hybridizing heavier trucks. Truck manufacturers are involved in some research projects though. For example Volvo, Mercedes, and Scania are involved with overhead catenary wire research projects.

Another option is inductive charging of all-electric vehicles. Bombardier is developing and marketing this technology for regional fleets like trams, buses and taxis, and more recently, an inductive charging pilot has started for trucks as well.

The fuel cell technology is another option to replace the internal combustion engine. Although not exhibited at IAA, hydrogen trucks have been presented at motor shows before, and several prototype vehicles have been built that are in operation although mainly in a research and development context.

Near-commercial applications

Commercial applications are limited to urban delivery trucks and buses at the moment. Most larger bus manufacturers offer a hybrid version of a city bus or are in an advanced stage of testing. The same is true for delivery trucks.

Heavy hybrid vehicles that are used in a dynamic way can reduce CO_2 emissions by about 15-25% (TIAX, 2011a), depending on the application.

To reduce fuel consumption more significantly, the next steps include electrification and the use of fuel cell vehicles. The status of the technologies needed for electrification or the use of fuel cells are included in the following sections, including the expected developments.

2.2 Battery electric trucks

2.2.1 Technology assessment

Even more than for passenger cars, the short driving range of battery electric vehicles is problematic for trucks, since trucks have higher energy consumption and therefore need a larger battery pack. This is especially the case for larger long haul trucks due to the high per-kilometre energy consumption of heavy vehicles and their high daily operating range.

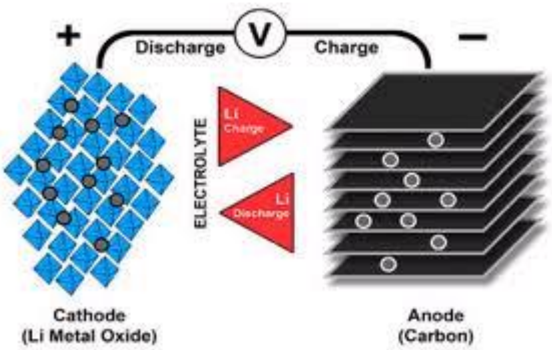
In an all-electric vehicle, the battery pack is the main electric component and makes up a large share of the total driveline cost, and as such, significantly influences the vehicle’s sale price. Other major components are more proven technologies, like the motor, inverter, and the controller. Their impact on vehicle performance, and the overall vehicle costs, are not as significant (ICF, 2011). The remainder of this section concentrates on the battery technology and its evolution over time. A battery includes electrochemical cells, the steel battery case and other components like heating/cooling devices. This report focuses on the overall battery system performance.

There are five parameters that have been used to assess the appropriateness of batteries for vehicle application:
1. Energy/weight ratio.
2. Energy/volume ratio.
3. Power to weight ratio.
4. Battery lifetime.
5. Charging time.

Worldwide, approximately 10 battery manufacturers are producing traction batteries for the automotive market.[1] Batteries for passenger vehicles and truck applications are the same. However, the amount of cells in the battery is larger in the case of trucks. The preferred solution is Lithium Ion (Li-Ion) currently, but this encompasses a number of different chemistries. The anode generally features graphite, but different chemistries are under development and commercially applied (ICF, 2011). Individual manufacturers claim that their chemistry is the best combination of properties for automotive use (durability, energy density, safety under abuse and overcharge situation).
A basic overview of a Li-Ion battery is shown in Figure 8. The basic operation occurs in discharge by ionized lithium flowing from the anode (positive terminal made from lithium embedded in carbon-based materials, usually graphite) to the electrolyte (composed of lithium salts in organic solvents) through a plastic separator (a micro porous membrane) and then to the cathode (negative terminal made of lithium metal oxide or phosphate).

[1] Some of the manufacturers are: A123 systems, Johnson controls, Hitachi, LG Chem, GS Yuasa, SB Limotive, AESC, Panasonic, Sanyo and Primearth EV Energy Co.

Figure 8 Basic overview of Li-ion battery

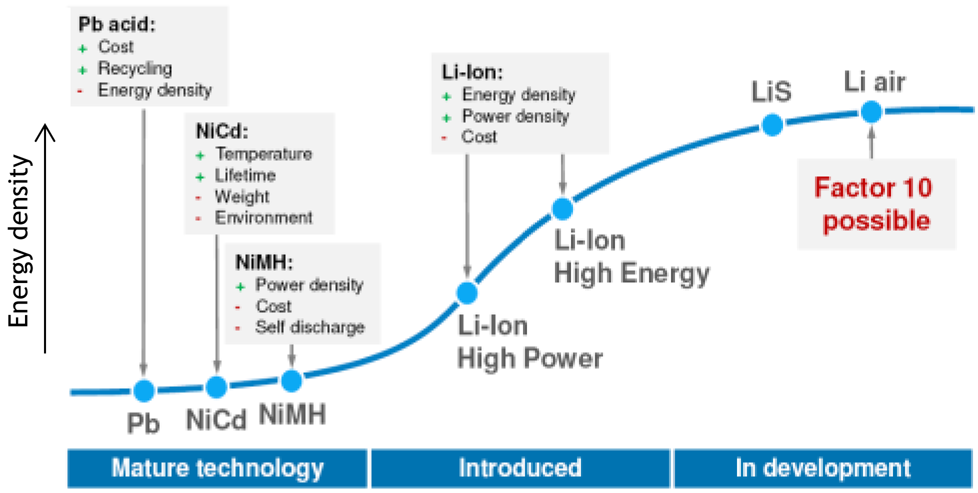


Source: ICF, 2011.

At present, the average energy density of EV batteries is around 100 Wh/kg on a battery level. However, significant developments are expected in the next decades. Energy density improvements of a factor 3-10 are cited in various literature sources (ICF, 2011; Horne, 2011), as evidenced in Figure 9. The factor 3-10 that has been cited in literature is currently in a research phase. The most promising battery chemistries appear to involve silicon, sulphur and air (oxygen). ICF (2011) estimates that in 2030, the energy density may increase to 300 Wh/kg. Several consulted experts are less optimistic about the potential to significantly improve the energy density. These experts know the figures mentioned in scientific literature, but cannot confirm that these figures are realistic.

The power density is between 500 and 1,000 W/kg on a battery level, depending on the battery chemistry that is chosen. This is within the requirements of automotive application, including trucks.

Figure 9 Expected battery developments (energy density on y-axis)



Source: ICF, 2011.

As can be seen in Figure 9, Li-S and Li-air batteries are under development and are being seen by some as the ultimate battery chemistry solution.
Most scientists agree that several bottlenecks need to be resolved before Li-air and Li-s batteries or other new battery concepts can be brought to the market.

It is not sure if the factor 10 potential in energy density can be fully realised. However, scientific literature also states that "*lithium battery technology evolves at a pace so rapid that evaluation of its progress may easily become obsolete*" (Scrosati and Garche, 2010).

In the following textboxes, the two most important battery chemistries currently being investigated are described in more detail.

Li-air batteries

Li-air batteries use oxygen as a catalytic air cathode to oxidise a metal anode such as lithium. Theoretically, with oxygen as essentially unlimited cathode reactant source, the capacity of the battery is limited only by the lithium anode. Estimates of energy density vary from *equal to ten* times the energy capacity of current lithium-ion batteries.

Also, the introduction of Li-air batteries could greatly reduce costs as lithium batteries currently use a cathode, which is the most expensive component of lithium batteries. Lithium-air has a theoretical specific energy of 13,000 Wh/kg. Li-air batteries gain weight as they discharge. This is because oxygen from the air combines with Li to form Lithium peroxide. The power density of Li-air batteries is potentially high, and in practise, is still very low at the moment due to battery chemistry problems.

There are many challenges that need to be overcome in order to increase power output and life of the battery:

– Oxygen diffuses at a very low rate in the porous air cathode. Therefore, there may be a need to pump oxygen into the battery system, which implies that an air compressor and blower need to be built into the vehicle. This may cause additional weight though.
– The reaction creates a solid, which accumulates on the cathode and hinders contact between electrolyte and air, reducing the rate capability (power) density.
– A stable electrolyte, effective membrane or air clean-up must be found since even the slightest amount of water contact with the metal anode would create hydrogen gas and create a fire hazard.

At the moment, scientists reported positive laboratory experiments. However, the current performance of such batteries is limited to a few charge–discharge cycles (10-50) with low rate capability, since the battery chemistry is not yet fully reversible. A prototype Li-air battery has been promised by IBM in 2013. Commercialization of the battery is expected around 2030, but given the large uncertainties with this technology this time frame is hard to predict correctly.

Sources: ICF, 2011; Christensen et al., 2012; Greszler, 2012.

Li-S batteries

Lithium-sulfur batteries may succeed lithium-ion cells because of their higher energy density (300-350 Wh/kg) and the low cost of sulfur. The volumetric energy density is close to that of advanced Li-ion.

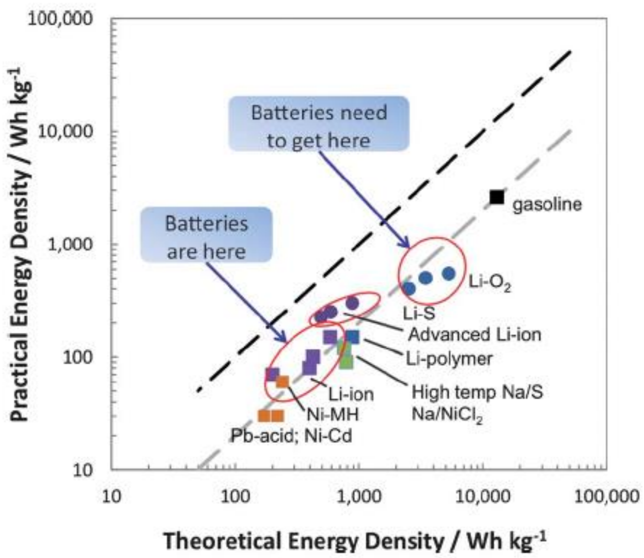
Unlike conventional insertion cathode materials, sulfur undergoes a series of compositional and structural changes during cycling, which involve soluble polysulfides and insoluble sulfides. As a result, researchers have struggled with the maintenance of a stable electrode structure, full utilization of the active material, and sufficient cycle life with good system efficiency. Although researchers have made significant progress on rechargeable Li-S batteries in the last decade, these cycle life and efficiency problems prevent their use in commercial cells.

Obstacles remain to commercializing (2020-2030) the technology, including the need to improve the number of times the batteries can be recharged and the speed with which they can be charged.

Source: Scrosati and Garche, 2010.

In terms of stored energy per unit of mass, a battery scores much lower than conventional fuels, such as gasoline or diesel. Even the Li-S and Li-O_2 batteries that are currently being investigated, will not reach the energy density equivalent to that of conventional fuels. However, since electric vehicles are more energy efficient than conventional vehicles, energy density may not be as significant. Figure 10 illustrates the energy density of current battery systems, battery systems under development, and gasoline.

Figure 10 Energy density of different battery systems versus gasoline



Note: The difference between theoretical and practical energy density relates to the weight of the steel battery case, other inactive components (heating/cooling devices) and inefficiencies.

Source: Thackeray, 2012.

The figure illustrates the enormous challenge of increasing the practical energy density of today's batteries toward the energy stored and delivered by gasoline.

The energy density of diesel is around 40 times higher than that of batteries, when taking the projected battery improvement of factor 3 in the next 15-20 years into account. With a factor of 10, improvement in energy density, batteries would still perform at a factor 12 lower in terms of energy density. However, energy density is not the only parameter to look at, since electric drivelines are more fuel-efficient than conventional drivelines. Therefore, batteries would not need the same energy density as diesel, but can be around a factor 3 lower for achieving the same range as diesel powered vehicles.

In Table 3, the driving range of a conventional distribution truck and a battery electric distribution truck are depicted, based on vehicles that are currently commercially available on the market. A problem related to energy density and driving range is battery weight and volume, mainly caused by the large amount of metals used to produce a battery. Most of the weight of the vehicle comes from the battery. Table 3 shows battery/fuel weight and volume and driving range for both a conventional and battery electric truck. Twenty percent of the battery capacity is generally left unused, due to cycle life. This implies that part of the battery weight is not useful.

Table 3 **Driving range of electric and conventional vehicles with current battery technology**

	Battery electric truck (10 tonne GVW)[2]		Conventional distribution truck (10 tonne GVW)	
Energy consumption (kWh/100 km)	100	Electricity	180	Diesel
Useful energy storage capacity	120	kWh	200	l (~2,000 kWh)
Energy carrier weight	1,500	kg	160	kg
Energy carrier volume	850	l	190	l
Range	120	km	1,100	km

Note: The battery pack weight is based on the typical value of 100 Wh/kg and 140 Wh/l (ICF, 2011; Thackeray, 2012). Calculation of battery mass has been based upon 80% depth of discharge (DOD). This implies that only 80% of the battery capacity can be used for driving.

Source: Man, 2012; expert interviews; own analysis.

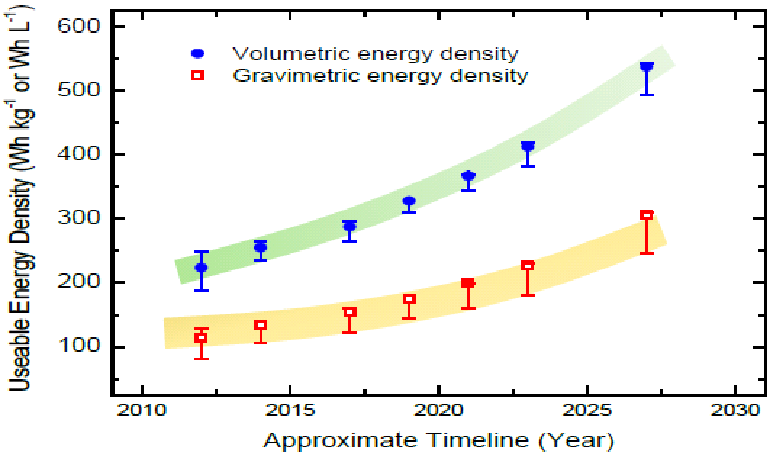
The data show that massive battery packs are needed to ensure an acceptable driving range, which lowers the payload of an electric truck. However, the absence of the gearbox and lower weight of the engine partially compensates for this and results in a net additional weight of around 600 kg, experts indicate. In case of volume transport, this may not be a problem. Furthermore, limited range is only a problem if a vehicle does not return to a central depot to charge overnight.

Although less critical than the weight (some volume may be available under the chassis), the volume of a battery may also be a barrier. The additional volume required to store a battery is relatively lower than the required additional mass for Li-ion batteries. The current specific energy density of Li-ion batteries as compared to the required volume is 40% higher than the energy density per unit of mass (100 Wh/kg of battery corresponds to 140 Wh/l on a battery level).

2 The values in this table are typical values for the currently available Smith Newton distribution truck.

The energy density of advanced Li-Ion batteries may be at a level of 220 Wh/kg and 300 Wh/l (Greszler, 2012). In Figure 11, the expected development of battery energy density according to Howell (2012) is shown.

Figure 11 Expected volume and mass energy density development

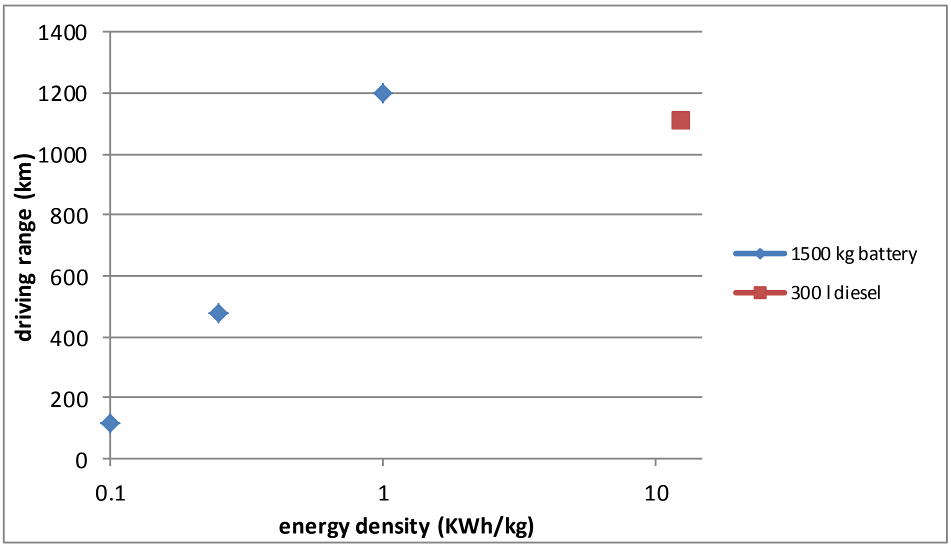


Source: Howell, 2012.

Due to the need for a flowfield volume in the porous cathode, the Li-air battery requires a relatively large volume for the cathode compared to its advanced Li-ion counterpart. Additionally, if Li-air based cells will have a need for a compressor and air clean-up equipment, the battery volume may equal or be larger than that of advanced Li-ion cells. Thus the expected volumetric energy density after 2025 is unsure (Howell, 2012; Greszler, 2012).

Using the fuel consumption figures from Table 1, the impact of improved battery energy density on the driving range can be illustrated. Figure 12 shows the driving range of current and future battery technologies, including the compromise of the increase of the vehicle energy carrier on board.

Figure 12 Driving range of delivery vehicles at different battery energy densities

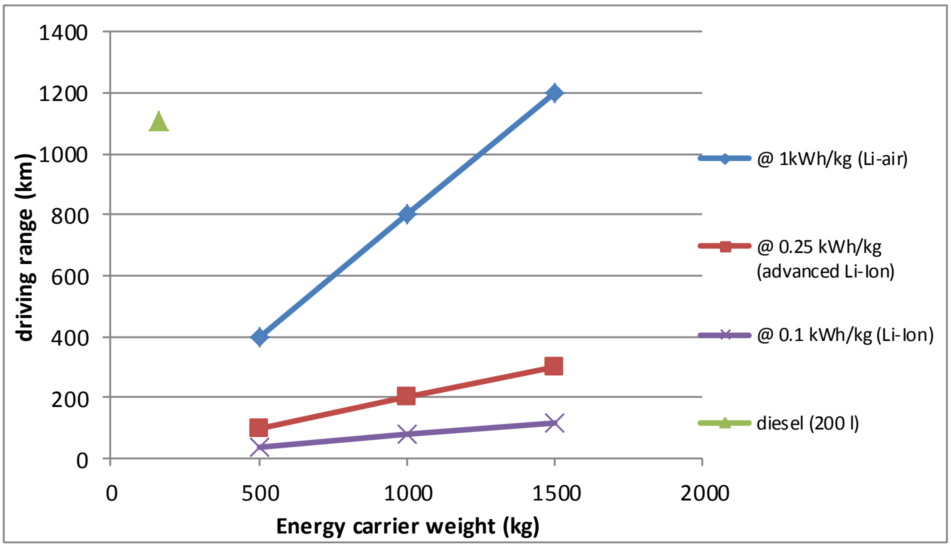


Note: The scale on the x-axis is logarithmic. The driving range has been based on 80% DOD.
Source: MAN, 2012; expert interviews; own analysis.

The figure shows that with energy density improvements to the potential future value of 1,000 Wh/kg, battery electric trucks may provide a wider driving range compared to conventional trucks.

In the figure below, the battery weight and the driving range are plotted for different energy densities. The figure shows that even when taking a factor of 10 for energy density improvement into account, the driving range can only be comparable when adding significant energy carrier weight.

Figure 13 Driving range as function of battery weight for 100, 250 and 1,000 Wh/kg for delivery vehicle



Note: The corresponding energy carrier volume (in litres) is 50-70% of the energy carrier mass for (advanced) li-ion batteries. While the energy density in terms of mass is estimated to be significantly higher for Li-air, the battery volume is not estimated to reduce in comparison with Li-ion batteries. Additional weight due to battery charging is not included in this figure, but is approximately 125 kg (500 kg battery), 375 (1,500 kg battery) (Greszler, 2012). The driving range is based on 80% DOD.

Source: MAN, 2012; expert interviews; own analysis.

With respect to long haul trucks, taking a driving range of 800 km into account, the application of electric drivelines is not possible at the moment, because the battery weight would be too high; currently this is approximately 50% of the gross vehicle weight and the largest part of the 27 tonne payload capacity of such a truck. Table 4 shows the impacts of a reduction in battery weight over time. The battery weight of 2,000 kg shown in the third column will not become reality in the next decade, but possibly after 2030 (ICF, 2011). While mass is most critical in the short term, volume is most critical for Li-air batteries. A 40 tonne truck with an 800 km range would require 6.5 m^3 of li-air batteries, which would weigh approximately 2 tonnes. In addition, the battery gains weight during battery charging, since oxygen is chemically bound to one of the electrodes.

Table 4 **Long haul vehicle battery weight as function of energy density**

		Long haul truck (40 tonne GVW)		
		Current Li-ion	Advanced Li-ion	Li-air
Energy consumption (kWh/100km)		200	200	200
Battery energy density (kWh/kg)		0.1	0.25	1
Battery energy density (kWh/l)		0.14	0.3	0.3
Battery capacity	kwh	2,500	2,500	2,500
Driving range	km	1,000	1,000	1,000
Battery weight	kg	25,000	5,000	2,500
Battery volume	l	18,000	8,333	8,333

Note: The Li-air battery weight reflects the discharged condition. Charging will increase the weight of the battery due to chemical reaction of Li with oxygen. The weight increase due to charging is approximately 500 kg. Energy consumption is related to the battery weight to some extent. This has not been taken into account. Driving range is based on 80% DOD.

Source: MAN, 2012; Greszler, 2012; Howell, 2012; expert interviews; own analysis.

High charge/discharge rates

Scientists reported approaches that could yield in a dramatic cut in charge times by increasing the surface area of the anode or cathode (Mukherjee, 2012; Sanghan, 2012). The approaches in realizing high-rate capability have included incorporation of nanostructured anodes and cathodes that provide a large specific surface area and shorter Li+ diffusion distances. The volumetric energy density of the electrode will, however, be reduced due to its expanded structure. This is a negative development for automotive applications.

The technology provides the opportunity to achieve charge rates of above 10C[3] (Mukherjee, 2012). Instead of 1-2 km per minute, scientists believe that there is a reasonable goal of obtaining a driving range between 15 and 75 km of per minute of charging for passenger cars. At that pace, even a large battery with a 450 km range could fully charge in less than 10 minutes (ibid.).

Battery life

The battery performance can substantially degrade over time, which may reduce peak power capability, energy density, and safety.
There are four key measures of battery durability, which are (ICF, 2011):
– calendar life, which is a measure of degradation with time;
– deep cycle life, which is the number of cycles of charging and discharging to low state-of-charge (SOC) levels;
– shallow cycle life, which measures the number of cycles of small SOC variation of a few percent that a battery can withstand;
– survival temperature range, which is the range of temperature that a battery can be subjected to when not in operation.

Li-ion battery manufacturers have set goals or targets for all of these measures, but it is not clear if current batteries can meet them. For calendar life, the goals are typically set at fifteen years at a temperature of 35°C. Lifetimes degrade in case of hotter temperatures. For deep cycle life, where the charge cycles vary from 90% to 10% of SOC, the goal is typically 5,000 cycles, while the shallow cycle life expectation is 200,000 to 300,000 cycles.

[3] 1C refers to a charging time of one hour.

The goal for the temperature range is -40°C to +66°C, but this has not been addressed by battery manufacturers yet.

It is difficult to conclude whether current batteries already meet or exceed specific targets in any area because of the highly interactive effects of these variables. Currently, several battery manufacturers have met the 5,000 cycle deep discharge goals and the 200,000 cycle shallow discharge goals (ICF 2011). Electric truck manufacturers interviewed in the context of this report refer to 1,000-2,000 deep cycles at the moment, with an expected cycle life up to 4,000-5,000 deep cycles within five years.

According to ICF (2011), it appears that current battery life should exceed seven years and may be around ten years. However, there is still much uncertainty regarding battery calendar life at more severe ambient temperatures such as those encountered in North Africa, South Spain or Arizona. ICF (2011) anticipates continued improvement to 2020 by which time, expectations are that average life may be in the thirteen to fifteen year range.

As indicated before, the durability of more advanced battery concepts like Li-air has not been proven, since the battery is still under development in laboratories.

2.2.2 Current Vehicles

Smith Vehicles is the largest electric truck manufacturer in the world, with around 1,000 trucks on the road worldwide. Most of these vehicles operate in the United States. Smith offers three basic types of its Newton trucks, ranging from 7,5 tonnes to 12 tonnes GVW. Operating on urban delivery routes, a single overnight charge provides sufficient range (approximately 65-190 kilometres). Smith can deliver different configurations, with different payloads and battery capacities.

Figure 14 Smith Newton truck

Renault is the first OEM to develop a full electric vehicle. The Midlum concept truck, which is used in trials with Carrefour in France, carries two tonnes of batteries, has a 5.5 tonne payload and a range of 135 km. A second identical vehicle will be joining the Nestlé Switzerland fleet. The vehicle was developed in conjunction with its technical partner PVI.

Technical characteristics of the All-electric Renault Midlum 16 t:

- Operating range: 100 km
- Recharging time: standard 8 hours
- Electric motor power: 103 kW
- Total battery capacity of 150 kWh
- Payload: 5.5 tonnes
- GVW: 16,000 tonnes
- Bodywork: refrigerating unit

In addition to the Midlum, a dozen of Renault Maxity (GVW up to 4.5 tonnes) electric trucks operate in Europe. These vehicles are used for in-town deliveries, urban cleaning, and refuse collection services.

In the US, battery electric trucks for niche applications are under development. The Balqon Corp. produced a full electric heavy-duty short-haul truck for drayage operations at the Port of Los Angeles in 2007. This demonstration project resulted in an order of 25 heavy-duty, battery electric trucks in 2009 (Port of Los Angeles, 2012). The Nautilus XE20 (Figure 15), has a 140 kWh Lithium Ion battery pack which supports a 150 kW electric motor. A four-speed fully automatic transmission is installed to provide the required torque. This configuration provides a range of 150 km (unloaded) to 80 km (loaded) for a maximum gross combination weight rating of 40 tons and a maximum speed of 40 km/h (Nautilus XE20, 2012).

Figure 15 Balqon's Nautilus XE20

Source: Port of Los Angeles, 2012.

The larger XE 30 has a 250 kWh battery pack, a top speed of 72 km/h, and a GVW rating of 55 tons.

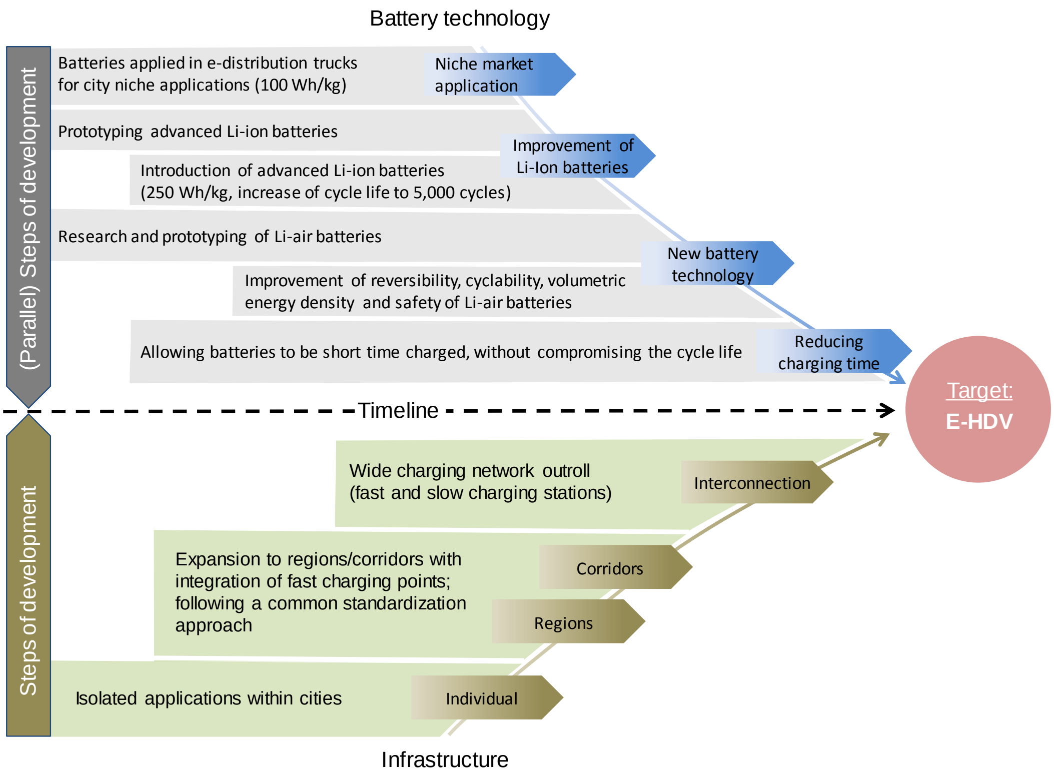
2.2.3 Conclusion and discussion

Currently, electric trucks are mainly seen as an alternative for conventional vehicles city goods distribution, since vehicles can be charged overnight. When taking the potential battery energy density of advanced Li-ion batteries into account, the technological bottlenecks for this application are limited, with around 1,000 vehicles currently operated around the world. With a reduction of battery costs due to increased production, battery electric distribution vehicles may become more attractive for this niche application.

The battery energy density (Wh/kg) is, and will remain, a bottleneck for long haul applications since significant weight and volume increases are unacceptable. If the projected factor of 5-10 in energy density improvement is realised, the weight increase of a 40 tonne GVW truck would be around 2,000-4,000 kg. Industry representatives argue that this increase in weight is far too much. Electric drivetrains will not be used before 2030 to drive long haul trucks and most likely will be of limited use in the following decades, due to unacceptable weight increases. Industry experts confirm this view. However, electric long haul trucks may still be an option when combined with an innovative charging infrastructure, such as with overhead catenary wires or dynamic inductive charging (see Section 2.3). In this case, battery development will determine whether such an infrastructure is necessary for the main roads/corridors only, or an even wider coverage will be required.

Further expansion of the use of electric distribution trucks depends on two factors: further development of the battery technology and costs, and the development of the energy infrastructure for vehicle charging, especially a fast charging network, as is shown in Figure 16. The figure illustrates the steps needed.

Figure 16 Battery technology and infrastructure roadmap to 2050



The role of battery electric vehicles may become larger with the introduction of next generation batteries that have a higher energy density and allow for fast charging. At the moment, the development of Li-S and Li-air as well as fast charging is the subject of scientific academic research and prototypes have not been applied in vehicles yet. Several challenges need to be overcome. Li-air batteries require improvements in durability, in the volume of the cathode and in the power density for example. Issues like these are related to the specific battery technology and should be resolved by developers of that particular technology.

When the advanced batteries would be ready for the market and series applications would take place as a result, cannot be foreseen at the moment, but is expected after the year 2030.

Infrastructure availability has to be realized step by step, as shown in Figure 16. This starts with the development from currently available individual overnight charging stations to public stations and corridors that can result in a nationwide interconnection.

2.3 Charging technologies/Energy infrastructure for electric trucks

2.3.1 Plug-in charging

The easiest concept for charging is plug-in electric charging. A slow charge system is enough to regenerate a battery over night (typically 8 hours), which is typically sufficient for urban applications. For example, a 120 kWh battery can be regenerated in about 8 hours by using a charging unit of 15 kW. The cost of a power station is relatively low in comparison to the cost of batteries. The cost per plug-in point is estimated at 5,000 euros, but the exact figure depends on a number of factors like the availability of power sources and size of the vehicle. Additional costs may result from retrofitting existing, or building new structures, to accommodate charging stations.

Fast battery charging

The charging time is an important criterion for the uptake of electric vehicles, especially for longer distance applications. 'Fast charging' can potentially reduce the time needed for charging. However, there are some difficulties with fast charging at the moment, mainly related to the internal resistance of a battery to ion flow. These issues can result in heat gain, efficiency losses, and a phenomenon known as 'plating', which can drastically shorten a battery's lifespan.

Currently, fast charging stations typically have a power of 50 kW, which charges a passenger vehicle within 30 minutes. Experts indicate that in the next years, charging stations will be scaled up to power ranges of 200 kW. In the next decades, the power that is used may increase even further.

If these numbers are translated into a 200-500 kWh battery for distribution trucks that is charged in 15-30 minutes, it would require 400-2,000 kW of power. The way of charging such a battery is basically not very different from charging a passenger vehicle battery. However, the power needed for charging is much higher, typically a 10 kV connection. If this infrastructure is not available, significant investment may be needed depending on how many transformation stations/connections need to be upgraded and a connection to the 10 kV network may be necessary. The cost of such a cable is approximately 108,000 euro per km (CE Delft, 2010).

Discussion
Overnight plug-in charging can be easily applied to urban distribution. For the large-scale application of electric distribution trucks, a fast charging network may be necessary. This requires both batteries that allow for high power charging and a network of charging stations. The first requires significant improvements of the current batteries, and the latter may require a significant investment.

2.3.2 Inductive charging

The concept
In contrast to plug-in charging systems, inductive charging moves power between two or more systems without the use of a wire (i.e. it is a form of wireless charging) (Chawla and Tosunoglu, 2012). With an inductive power charging system, a changing electromagnetic field is created between two power systems (the sending and the receiving system) and power is transferred from one system to the other. The sender - or primary coil - is connected to the power grid and therefore is constantly powered in order to send power to the receiver - or secondary coil - when needed (ibid.). The energy that is picked up by the receiving coil is then converted to charge the battery (in the case of stationary charging) or to directly drive the electric motor (in the case of dynamic charging).

Inductive charging does have several useful applications to electric vehicle charging. As the sending device can be installed underground, the system can be installed beneath bus stops, garages or other parking lots (Delphi, 2012). More recently, the possibilities of placing electromagnetic strips in city roads or highways are being explored as well (i.e. road electrification) (Chawla and Tosunoglu, 2012). While the former mentioned application can be considered *stationary* inductive charging, the latter application has been called *dynamic* or *in-road* inductive charging.

PRIMOVE is often mentioned as a leading developer of both stationary and dynamic inductive charging; their state-of-the-art system has been able to transfer 200 kW during e-bus pilot projects (both stationary and dynamic) in Augsburg and Mannheim, Germany, and 200 kW in a stationary and dynamic light rail project in Augsburg, Germany (PRIMOVE, 2012). These applications of inductive charging to electric vehicles are described in the next sub-sections. This is based on available literature on the one hand, and on the results from interviews on the other. Two interviews were held, one with a leading technical consulting company on inductive charging, and one with a well-known developer of both stationary and dynamic inductive charging systems and pilot projects for different vehicle types.

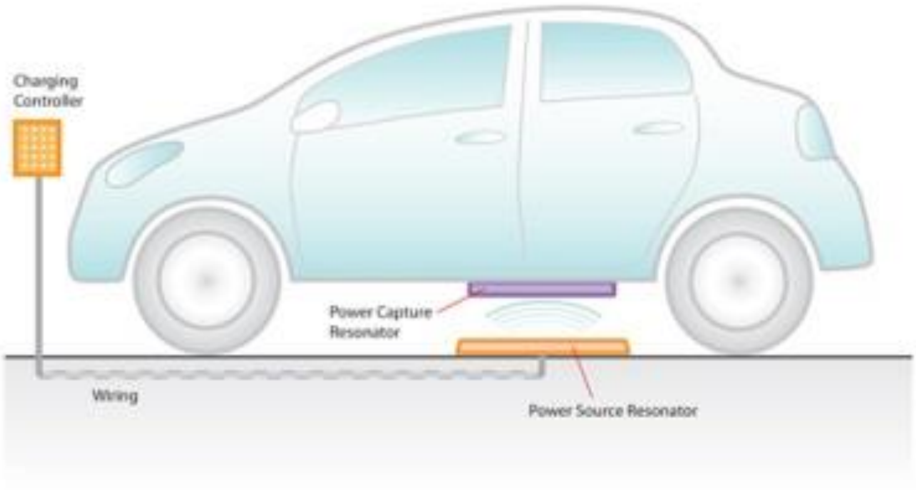
Stationary inductive charging

The motivation
As aforementioned, stationary inductive charging finds its application in charging vehicles while they are parked or stopped. When inductive charging devices are embedded in garage floors, parking spots or bus stops, drivers can simply position their electric vehicles over these energy sources to charge them without any further actions required (Delphi, 2012), which significantly enhances convenience and safety (Kluth and Ziegner, 2012). Both interviewees on this topic argued that convenience and time savings is the main added value of inductive charging over plug-in systems, and is an important condition

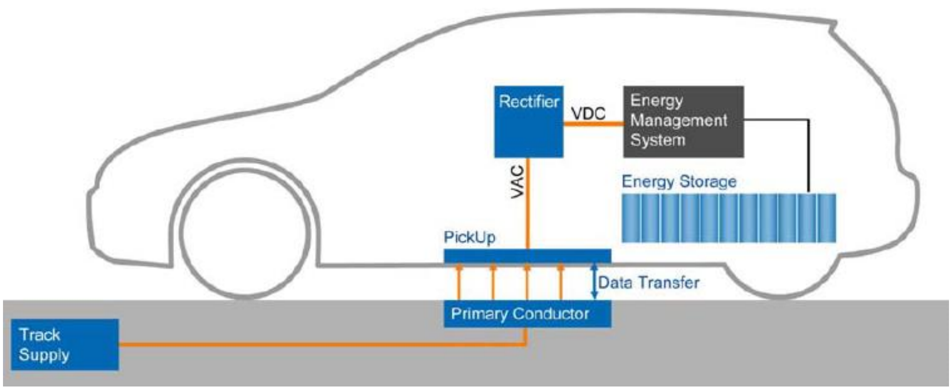
for the wide-scale adoption of electric vehicles in consumer segments they believe.

The concept
There are two forms that can be used for stationary inductive charging applications: magnetic induction coupling and magnetic resonance coupling (see Figure 16) (Thrush, 2012). The former is comparable to the technology that has been used in electric toothbrushes. When applied to electric vehicles, it requires precise parking alignment in order to start the recharging. It has been proven to be efficient though and is relatively inexpensive (ibid.). Magnetic resonance coupling is more state-of-the-art though, as it can move power over larger distances and it can adapt to natural misalignment (Delphi, 2012), which further increases user convenience (Thrush, 2012). However, it is also more complex and expensive (ibid.).

Figure 17 Examples of stationary inductive charging systems



Stationary inductive charging system of Delphi (2012) with a charging plate above the ground.



Stationary inductive charging system with charging plate positioned underground (IAV, 2012).

It is believed that stationary magnetic resonance coupling can obtain efficiency levels of over 90%, which is quite high, but slightly lower than induction coupling (close to a 100%) (Thrush, 2012). Both interviews confirmed that it is possible to obtain such efficiency levels.

Some researchers are sceptical about the safety of the electromagnetic field radiation that results from the inductive charging system. Different international standards for such exposures have been developed, and is summarised in Table 5.

Table 5 **Examples of international standards for electromagnetic field radiation limits**

Threshold in milli Gauss (mG)	Country
2,000	USA (IEEE)
200	Europe (ICNIRP)
62.5	S. Korea (KRISS)

There have been a few successful tests and pilot projects, such as the OLEV system (Lee, 2012) and a test project of Siemens and BMW (Kluth and Ziegner, 2012), that have shown that it is possible for inductive charging to stay below these thresholds. Also, Bombardier's PRIMOVE system has been proven to be compliant with all applicable codes and standards for electromagnetic compatibility (EMC) and electromagnetic field emission (EMF). Their PRIMOVE 200 e-bus system in Mannheim, Germany, has been homologated by TÜV SÜD for passenger operation on public roads in November 2012; confirming that it does not present any health or safety hazard to passengers, drivers, operating staff or pedestrians, and that it does not interfere with other systems or electrical appliances like mobile phones or heart pacemakers. Both interviewees are confident that safety is less of an issue as long as the radiations are lower than the above-mentioned thresholds, which can be done in stationary situations.

Future developments and pilot projects
Both interviewees argued that stationary inductive charging will first be applied in public transport niche markets, such as the city bus and tram. Considering that these vehicles drive on fixed routes and make stops frequently, inductive charging systems could be installed on several stops during those routes they argued. By strategically positioning the charging points, the adaptations needed to the infrastructure, and hence the costs, are minimised. Thereby, one interviewee argued that it may be easier to get funding within the public transportation segment, as municipalities that aim to reduce the emissions of their city might be willing to invest in the necessary infrastructure.

Several pilot projects are in operation in the public transportation segment. Conductix-Wampfler has operated 30 electric busses in Genoa and Turin with its Inductive Power Transfer (IPT) technology, which has used the state-of-the-art magnetic resonance coupling for 10 years now (Wampfler, 2012). The batteries of the busses are fully charged at night, and then topped-off when stopping at designated bus stops. According to the company, this results in a 200 km driving range a day without the necessity of making any additional stops for recharging (ibid.). In this project, 95% of the energy that is taken from the grid is actually stored in the batteries of the busses. Also, the buses have not experienced any problems with the safety and it has been confirmed by independent institutions that the magnetic fields stay below the recommended thresholds (ibid.). There are several similar pilot projects with inductively charged electric busses in operation or planned in Switzerland, Germany, Japan, New Zealand, the Netherlands (Utrecht), and the USA.

Several other players are active in the bus industry. WAVE is developing Wireless Power Transfers (WPT) for the electric vehicle market and has several pilot projects for shuttle busses on the campuses of universities in the USA (WAVE, 2012). PRIMOVE static and dynamic charging systems has been tested in several pilot projects with trams, e-buses, e-vans and e-cars in Europe (PRIMOVE, 2012). In addition, the cities of Brunswick and Mannheim in Germany as well as Bruges in Belgium will introduce the wireless PRIMOVE charging system on selected inner-city bus lines as of 2013. Several 12 m and 18 m electric buses from three different OEMs will then be operated in daily passenger service.

There are also several companies that are active in developing technologies and pilot projects of magnetic resonance coupling for passenger cars, such as the Delphi Wireless Charging System that is being developed by Delphi and WiTricity Corporation (Delphi, 2012), Plugless Power solutions, which is manufactured by Evatran (Plugless Power, 2012), and the Wireless Electric Vehicle Charging (WEVC) system of Qualcomm (2012) that is now being tested in the East of London, both for stationary and dynamic charging situations.

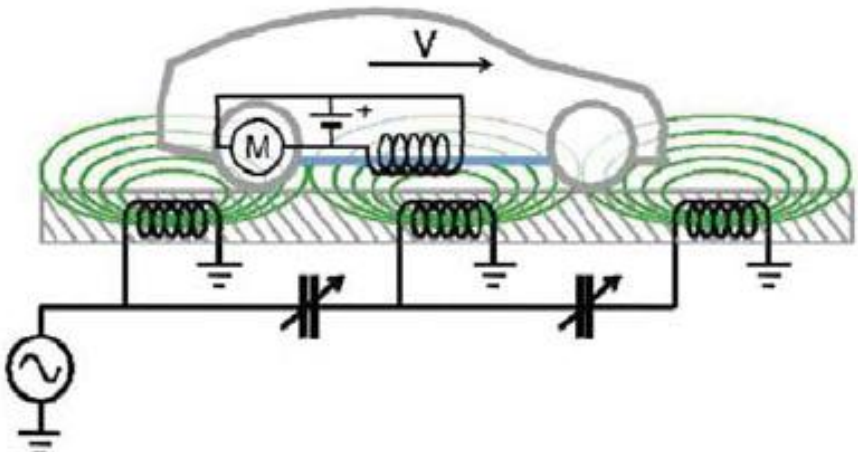
Although stationary inductive charging will have several advantages over plug-in charging systems in terms of safety and user-friendliness, in particular when magnetic resonance coupling is used, it is unlikely to lead to the wide-scale implementation of electric trucks. Stationary inductive charging does not solve the limited driving range before the vehicle needs to be recharged. However, it seems likely that if combined with inroad inductive charging (explained below), stationary inductive charging could be applied, at the parking lots on company grounds for example, in order to fully recharge trucks that are temporarily stationed.

Dynamic/in-road charging

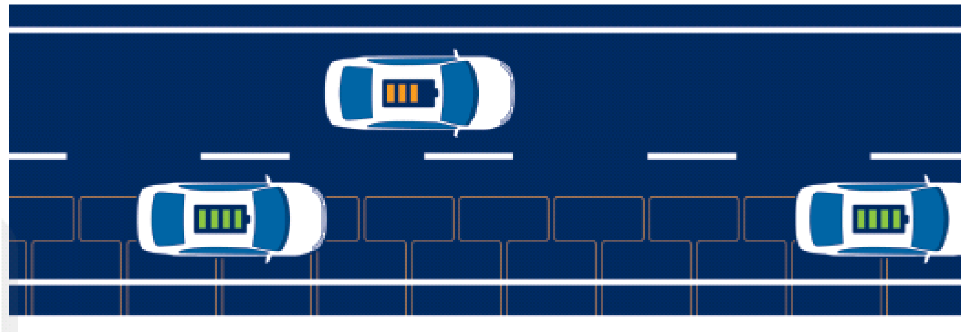
The concept

As mentioned previously, dynamic charging involves an electromagnetic field placed in city roads and in highways (AEA, 2011). Dynamic charging allows the battery of the electric vehicle to be charged while driving over these electrified sections of the road (ibid.). This technology would eliminate the limitations to the driving range of electric vehicles mentioned earlier (Chawla and Tosunoglu, 2012), and may therefore be well suited for electric trucks as well. There are some additional benefits of reduced battery weight - and hence reduced battery costs - and for aesthetics in contrast to battery development and overhead catenary wires, respectively (Lee, 2012).

Figure 18 Example of dynamic/in-motion charging



Dynamic charging technology (Thrush, 2012).



Application of inductive charging for in-road dynamic charging (IAV, 2012).

There are two main hurdles that need to be overcome for dynamic inductive charging to be widely adopted. First, the retrofit costs of the road infrastructure will be very high (Chawla and Tosunoglu, 2012; AEA, 2011), although it is argued by some that building charging stations in the larger cities will be equally expensive when considering the high real estate prices (AEA, 2011). According to Lee (2012) only parts of the route need to be electrified in case of a commercial truck fleet driving on fixed or semi-fixed routes. A similar argument was made by one of the interviewees, who stated that only specific parts charging points would be needed, such as on uphill roads and on some parts of flat roads. This interviewee argued that the main cost driver is getting the energy along the road, as such an infrastructure is not in place yet. The sending coils itself only need to be installed 25 cm under the surface, which ensures minimal interference. On the positive side, it is possible to simultaneously use this infrastructure for electric cars, busses, and trucks – which is not the case for some other technologies, such as the overhead catenary wire. Consequently, the retrofit costs can be shared between different vehicle types. However, the investments that are needed to create the infrastructure for dynamic charging will be significant.

Second, there are concerns over the energy losses that may occur when power is transferred within the electromagnetic field (Thrush, 2012). According to Thrush (2012) it will be very difficult to achieve an efficiency of over 90%. Some of the interviewees confirm this. Chawla and Tosunoglu (2012) argue that energy losses can be kept low if the electromagnetic field only transfers power at the point at which the electric vehicle drives over it. According to one of the interviewees, there is only a minor difference in efficiency between stationary and dynamic situations, and in both applications the possibility of obtaining an efficiency of over 90% has been shown. Independent monitoring results is needed to confirm the statements made.

Safety will be less of an issue with dynamic inductive charging than with stationary charging the interviewees argued. With dynamic inductive charging, people within the vehicle are not exposed. People outside the vehicle would have to stand within a metre of the vehicle or so, which is unlikely to happen on highways.

Irrespective of energy losses, the impact of a wide-scale application of dynamic charging on the (renewable) electricity system (e.g. on supply/demand imbalances) has yet to be determined as well.

(Future) Developments and pilot projects
There are a few pilot projects demonstrating dynamic charging, mostly focussed on busses, as was the case for stationary inductive charging. The PRIMOVE bus was mentioned in the previous sub-section, and has tested both stationary and dynamic charging in its pilot projects (PRIMOVE, 2012). This is similar to Qualcomm (2012), although the pilot focusses on cars rather than on busses.

The Korea Advanced Institute of Science and Technology (KAIST) is running a pilot project in an amusement park in Seoul. In this project 400 metres of recharging strips have been embedded in the road. The Online Electric Vehicle (OLEV) drives on a fixed route in the park while recharging as it drives over the recharging strips (The Independent, 2012). KAIST has obtained an energy efficiency of 80% with a one-centimetre gap between the magnetic strip and the vehicle receiver. In Berkeley, California, the Defence Advanced Research Projects Agency (DARPA) operates a pilot project called the PATH program, which moves busses over set routes using in-road charging (AEA, 2011). Finally, the Ingenieurgesellschaft Auto and Verkehr (IAV) is working on dynamic charging pilot projects on motorways and argues that an energy efficiency of over 90% can be obtained with dynamic charging, which results from the fact that the magnetic field is only activated when a sensor detects that the electric vehicle is driving over the induction field (IAV, 2012).

As mentioned before, electrified highways can tackle the main problem of the current limited driving range of electric vehicles. Therefore, it may well be a technology that can be applied to long haul trucks in the future. Scania, Volvo and Bombardier are involved in the first pilot for electric trucks (Scania, 2012). In this pilot, two types of charging – conductive overhead wires and inductive charging – will be investigated on a road between Stockholm and Gothenburg in Sweden (Vattenfall, 2011). One of the involved parties argued that this is the first step that is needed - to show that dynamic inductive charging can work for electric trucks. The PRIMOVE bus project in Lommel mentioned earlier transferred 40-80 kW (PRIMOVE, 2012). For this project, larger amounts will be needed; for a flat road 140 kW is required (Vattenfall, 2011). The PRIMOVE e-bus and tram projects mentioned earlier have shown that the system can handle 200 kW (PRIMOVE, 2012), which approaches the ranges that are required for electric trucks. This project will show whether such amounts are also workable for road vehicles, and further research is needed to see whether there are ways to reduce this amount. If this pilot is proven successful, the development of a standard will become relevant and a cost optimum needs to be found.

Figure 19 Hybrid truck with electric drivetrain of Scania that is used in the inductive charging demonstration project

Discussion
Several pilot projects are available that show that at least some applications of stationary and dynamic inductive charging can work. Stationary inductive charging will be especially useful in public transportation, as these modes make frequent stops on fixed routes. In the passenger car segment it may provide a valuable alternative to plug-in systems through enhancing convenience and safety. However, for trucks, stationary inductive charging will not be enough to lead to a breakthrough of electric trucks, as it does not enable the driving range that is needed for long haul trucks. Rather, it may find its application on parking lots on company grounds, to fully recharge trucks that are temporarily stationed.

Dynamic charging does have the potential to provide enough driving range for electric long haul trucks. However, the application of this technology to heavy vehicles needs to be first proven in pilot projects. Hereafter, a standard needs to be developed in order to create an in-road charging infrastructure that can be used by all vehicles and is consistent within different countries. These infrastructure costs will be very high though, which complicates dynamic inductive charging. However, dynamic inductive charging has the potential to lead to zero emission trucks, assuming that there will be enough renewable energy available.

2.3.3 Battery switching

The motivation
In an earlier section it was pointed out that the limited driving range combined with the time it takes to recharge an electric vehicle is a major limitation to the widespread adoption of electric vehicles (Mak et al., 2012). While this will also be a problem to passenger cars, it is an even more significant barrier to the HDV segment, as distribution, and especially long haul trucks, have relatively long driving cycles. In addition, the costs of electric vehicles is also a barrier to their uptake; the battery costs are the most significant influence on these relatively high upfront costs (AEA, 2009). The innovative concept of ‘battery swapping’ has the potential to tackle both these hurdles simultaneously and is further described in this section.

The information in this section is based on literature, as no interviewees could be arranged on this topic.

The concept

The concept of battery swapping is relatively simple; the electric vehicle can drive to a battery swapping station where its depleted battery is exchanged for a fully charged one (Mak et al., 2012). The depleted batteries are recharged at the station and hereafter used for other electric vehicles with depleted batteries (ibid.). This concept is argued to reduce the time it takes to recharge an electric vehicle from a couple of hours to a few minutes (ibid.). An additional advantage of this concept is the fact that the electric vehicle owners will only own the vehicle, not the battery. Rather, the batteries are leased from the recharging service providers. In this concept, users get access to the charging infrastructure network and are charged for the batteries in accordance with their usage (i.e. the miles that are driven). Basically this concept shows a lot of similarities with cell phone contracts, and has several advantages to the electric vehicle owners:

- Battery swapping significantly reduces the charging time and therefore extends the driving cycle (Mak et al., 2012).
- From the user's position, it will reduce the upfront capital costs of electric vehicles significantly, as the costs of purchasing the battery (around $ 10.000) are eliminated (ibid.) Meanwhile, the battery swapping stations would need enough stock of batteries to ensure that batteries are always available when a user drives to the swapping station to replace its batteries. The net costs will be higher therefore, as more batteries would need to be manufactured than would otherwise be the case.
- It will be easier to take advantage of technical improvements in the battery by regular swaps in contrast to when the batteries are owned over their whole lifetime (Mak et al., 2012).

Figure 20 Example of a battery swapping station from Better Place

Source: Better Place, 2012.

There are several obstacles that need to be overcome for battery swapping to enable the widespread uptake of electric vehicles in general, such as:

- In addition to charging spots at homes and offices, an infrastructure of swapping stations needs to be developed in a cost-effective way (Mak et al., 2012). The scale of the investment that is required will be very high; approximately 3 million dollar per station (NY Times, 2011). Thereby, companies may be reluctant to make such large investments up to the point at which there is a significant demand for electric vehicles. Potential buyers of the electric vehicles on the other hand, may be reluctant to do so until the charging infrastructure is sufficient (Mak et al., 2012). In addition, the costs of ensuring a stock of batteries that is sufficient to cover demand and to ensure that fully charged batteries are always available, will be very high.
- Batteries need to be standardised across manufacturers and swapping stations (AEA, 2009). Additionally, the vehicle and station designs should be standardised to make sure that each vehicle can make use of each station. This seems a very difficult point to realise as it implies that the battery needs to be placed in the same way (at the same location in the vehicle for instance) by all manufacturers and for all types of HDVs. It may be very difficult to accomplish this for both a small urban delivery truck and for a large truck-trailer combination for example. Furthermore, the battery has to be complementary with the computer and software of the vehicle. This implies that with advancing technology, the number of batteries to be stored at swapping stations will be even higher.
- Swapping stations would need enough stock of charged batteries to facilitate fast service (AEA, 2009). If a large stock of depleted batteries is recharged at the same time, this may put a heavy load on the electricity grid (Mak et al., 2012).

If the battery swap concept would be applied to electric trucks, it would make the recharging time competitive with the time it takes to refuel a conventional diesel vehicle, eliminating an important barrier to the uptake of electric trucks. However, with the existing battery technology it would still require relatively more stops than would be the case for a truck with an internal combustion engine. Future improvements in the battery technology can increase this range though (Nu, 2012). Either way, it seems reasonable that especially for trucks that are used in urban distribution with low daily driving cycles, battery swapping could be well applied (from a user perspective). On the one hand, this would improve the business case of electric distribution trucks by reducing the upfront capital costs, while these trucks would only need one or two stops a day at a swapping station to create a sufficient driving cycle. However, the investments in swapping stations and battery stocks would be very high. Thereby it will be difficult to standardise the battery and vehicle design for different types of vehicles and different manufacturers.

For long haul trucks the situation is even more complex, as these vehicles have a longer daily driving range that this would require a lot of stops during the day with the current battery technologies, which transport companies do not find acceptable. Also, it would be more difficult to create a sufficient infrastructure of battery swapping stations over the whole route.

Developments and pilot projects

The main player developing this concept of battery swapping was Better Place, headquartered in California. The company went bankrupt early in 2013[4]. The company's aim was to build a charging network of both charging spots at homes, offices and malls and of strategically located battery swapping stations (AEA, 2009). Better place had partnerships with several governments to accomplish this goal; in Israel, Denmark and the Netherlands (Schiphol), the first fully automated swapping stations were built. It cost between 225 euro and 330 euro a month to lease the batteries and gain access to the swap stations and charge spots (Better Place, 2012). An article in the NY Times (2011) has quoted costs of 2.3 million euro per station. Better Place focussed on the lighter weight vehicles, such as passenger cars and taxis.

Not all manufacturers of electric cars were compatible with the infrastructure of Better Place though. Better Place only had a partnership with Renault; they have designed their electric vehicles in such a way to facilitate a rapid battery swap at Better Places' stations (AEA, 2009).

There have not been any pilot projects with heavier electric vehicles, such as busses or trucks yet in Europe. In China (Qingdao), battery swapping is, amongst others, applied for busses.

Discussion

Battery swapping can be considered a state-of-the-art technology with the potential to significantly reduce charging times and the costs of electric vehicles. However, in order for battery swapping to become an important element of electric driving, standards would be needed both in terms of the design of the swapping stations and design of the electric vehicles so that all electric vehicles could make use of each swapping station. Creating an infrastructure of swapping stations would require significant investments, although this will also be the case for the other electric charging technologies described in this chapter.

Whether it is feasible to apply the concept of battery swapping to heavier vehicles is unclear, but seems likely. The concept of battery swapping could be useful for electric trucks in theory, especially in urban applications, as these vehicles would only need one or two stops a day. For long haul trucks, significant improvements in battery range would be needed first to reduce the number of stops on the route. An infrastructure with significant coverage would be needed as well.

2.3.4 Overhead catenary

Motivation

Zero tailpipe emission transport is possible with electric powertrains. Electric power trains can be realized using fuel cell heavy-duty vehicles (FCHDV) and battery electric heavy-duty vehicles (BEHDV). However, both have the disadvantage of limiting the payload as the energy needs to be stored onboard, with batteries having a comparably low energy density (even lower than hydrogen) resulting in either a reduced range or a (unacceptable) payload reduction.

[4] www.treehugger.com/cars/better-place-files-bankruptcy.html

In contrast, trucks operating under an overhead catenary entail a couple of advantages compared to hydrogen and pure battery-electric trucks. These originate in the fact that the required traction energy is not stored on-board.

First, overhead catenary technology frees up payload capacity (given that the pantograph equipment is less in weight in volume than an alternative energy storage). Second, this implies that the need for on-board energy storage capacity is drastically reduced. Third, range is no longer a limitation. More advantages are later briefly discussed. First, the catenary concept itself is outlined. A catenary is an overhead electric wire that transports electric current to mobile loads (i.e. trains, trolley busses and trams). The energy is transmitted constantly to the vehicle via a roof-mounted pantograph.

Concept

The catenary operated HDV as it is tested today should allow the HDV to operate fully electric under a catenary at long-haul distances and when not under a catenary, operation fuelled by an internal combustion engine. Therefore, the concepts which are developed and tested today are serial hybrid trucks. Possible application fields could be highways and niche applications like highly frequented special freight corridors, especially in densely urbanized areas.

Infrastructure equipment

The wayside equipment is similar to that of direct current operated bus trolley lines, which are in operation in many parts of the world for decades. The traction power supply is made up of the substations consisting of switching systems and a transformer that converts the alternate high voltage current of the grid to low direct current (typically 600–1,500 V) which flows into the catenary. Direct current is primarily used instead of alternating current as the vehicle using DC will not need a heavy transformer on-board, which would reduce payload substantially.

The catenary that is connected to the substation provides the contact to the vehicle’s pantograph and assures the electricity to be transferred from the catenary to the vehicle. The catenary is composed of support masts, booms, isolators and two overhead wires (one for the energy going to the vehicle and a return wire for the way back to the substation) that span over the lane. The return wire is necessary as the current cannot flow back to the substation via the lane for the vehicles are rubber-wheel-based and must therefore be guided through a wire. Figure 21 shows a possible solution to a wayside infrastructure equipment. This is a testing track for catenary trucks in Germany operated by Siemens.

Figure 21 Catenary for hybrid-electric trucks

Source: Gerstenberg, Lehmann et al., 2012.

Vehicle equipment

As only major highway sections are expected to be equipped with overhead wires, vehicles must be able to be fuelled by another fuel. Therefore, trucks will have some sort of hybrid power train.

The Siemens truck of the eHighway research project has a serial hybrid powertrain, which means it has an internal combustion diesel engine (ICE) with 300 kW connected to an electric motor. The electric motor has a power of 200 kW. The truck can operate fully autonomous when powered by the ICE. Partial electric operation when not under the catenary is possible when the powertrain is also equipped with an energy storage (the eHighway concept vehicle has electric double-layer capacitors to allow electric passing of another vehicle).

By employing a battery with larger energy density, emission free operation to logistics hubs or inside cities that fall under tight emission legislation would also be possible.

The truck equipment of the Siemens truck is made up of (Gerstenberg, Lehmann et al., 2012):

- diesel powerpack (300 kW);
- permanent magnet synchronous generator and motor (200 kW);
- power electronics;
- active Pantograph, that can be steered and lifted during driving;
- electric double-layer capacitors for energy storage.

Due to very high infrastructure costs, only one of several highway lanes in real world projects will be electrified. As a consequence, if a truck under a catenary is to pass another, the vehicle has to switch from electric to ICE mode, i.e., the pantograph is to be released and the truck runs on the diesel motor or the energy storage.

Figure 22 shows a catenary operated truck as tested by Siemens in a pilot project to demonstrate technical feasibility.

Figure 22 Hybrid Truck under a catenary

Source: Siemens.

As outlined above, the catenary operation offers a couple of advantages compared to other drive train concepts. First and foremost, it allows fully zero tailpipe emission operation when under a catenary. This is in particular relevant in regions where emission legislations are put in place. These legislations are expected to further increase in the EU in the up-coming years. In addition, the electric traction means locally emission-free operating, which is an asset for examples in municipalities with tight air quality and noise regulations. When energy is produced 100% based on renewables, driving results in zero emissions on a well-to-wheel basis. The energy is supplied to the vehicle from an external source (overhead wire) and therefore does not need to be stored onboard, freeing up payload and transport capacity (volume).

High power demands can be satisfied by the highly efficient electric drivetrain, which is especially useful in mining sites with steep slopes and heavy loads. In general, it is possible to utilize already existing infrastructure (as motorways), i.e. by equipping a highway lane with an overhead catenary and additional traction power supply installation instead of building entirely new infrastructure (for example a railroad line). An additional asset is that the infrastructure can also be shared with conventional trucks and cars, eliminating the need for a catenary dedicated lane. This also implies a possible piecemeal implementation process. However, equipping a highway lane with electric power supply means high investment burdens, both in the wayside equipment and in the vehicle equipment (this is discussed in more detail below). In addition, as was the case for a dynamic charging system, the impact of a wide-scale application of overhead catenary wires on the (renewable) electricity system may be significant and should be further investigated.

Hybrid electric trucks with the electric equipment as pantograph, electric motors and inverters on-board will likely be significantly more expensive than conventional diesel trucks. Therefore, transport companies will be hesitant to employ such trucks unless legislation forces them to do so or lower operating costs, i.e., reduced energy costs can compensate for the higher initial investment costs. Table 6 gives a comparison of energy consumption and costs. This is outlined in more detail in the cost chapter.

Table 6 Efficiency and energy consumption

	Diesel Truck	Catenary Truck
Drivetrain efficiency diesel Tank to wheel Pantograph to wheel	 Approx. 35% 	 Approx. 66%
Energy consumption per km In ICE mode Under catenary	 0.34 l/km 	 2.21 kWh/km (estimate)
Energy cost rate	1.19 €/litre	0.12 €/kWh (estimate)
Energy costs per km	0.4 €/km	0.27 €/km

Note: The catenary operated truck in the calculation is assumed to run 100% electric for simplicity.

Developments and pilot projects

There are a couple of pilot projects under way worldwide. Siemens is testing an overhead-wire heavy-duty truck in a research project financed by the German federal ministry for the Environment. In collaboration with research bodies, Siemens developed and tested the feasibility of a serial-hybrid heavy-duty truck, powered by electricity when under a catenary and on an integrated internal combustion engine when not under an electrified wire.

The Ports of Los Angeles and Long Beach in the USA are planning to electrify the highway connecting both ports and the hinterland highway with an overhead wire to transport shipped goods to logistic sites (GNA, 2012). This is driven by tightening emission legislations to meet air quality and emission limits in the Los Angeles area. This is especially relevant in the emission-rich harbor environment and in view of anticipated increasing harbor related traffic that goes through densely populated areas. Plans to implement the Siemens eHighway system described above are concrete, which is why the highway electrification in Los Angeles may be the first real-world project becoming operational. The trucks are planning to have a serial hybrid drive train.

In Sweden, OEMs Scania, Volvo and again Siemens are developing a serial hybrid truck for operations under a catenary as well. Figure 23 shows the prototype of a Scania truck. Plans to equip major parts of the Swedish highway network are currently being discussed (Elektriska vägar, 2012).

Figure 23 **Overhead catenary prototype truck by Scania and Siemens**

Source: Elektriska vägar, 2012.

In addition, a study has demonstrated feasibility of electrifying roads in the north of Sweden to connect an iron ore mine (Trafikverket, 2012). The 160 km route was investigated for trucks loading up to 90 tons. Concrete talks with industry and state stakeholders are under way to start building this route.

In mining applications, serial-hybrid trucks have long been used where a very high traction power is required (in the range of 2,000–6,500 kW) due to high slopes and heavy loads (Figure 22). Electric drivetrains are advantageous to internal combustion engines in terms of maintenance effort and costs in this MW-power level. In addition, substantial potential energy cost savings have been reported. The trucks typically operate at 1,500–2,600 V DC. An example is Zambia, where mining truck manufacturer Hitachi is currently replacing older trolley mining trucks with new ones (IM Mining, 2012). Companies currently manufacturing trolley mining trucks include Hitachi, Liebherr and Siemens.

Figure 24 Mining trucks under a catenary

Sources: Left: Aggregates Business Europe, 2012; right: Siemens.

Table 7 Catenary operated trucks

	Application
Under operation	
Hitachi and Siemens (Zambia, Chile, South Africa)	Mining Truck 2-6 MW traction power
Demonstration	
Siemens (Germany)	Test vehicles - 200 kW electric motor
Scania, Volvo and Siemens (Sweden)	Test vehicles: - mining site electrification planned - motorway electrification in South Sweden
Siemens (Los Angeles, LA)	Study: - no test vehicle so far, electrification of LA and Long Beach harbours connecting roads - logistics site planned

Discussion

Implementing overhead wire trucks requires massive investments. Without government spending on the catenary infrastructure and subsidies of the vehicle equipment, a business case for operators may not be given. Wayside electric equipment alone is estimated to cost in the range of 2-3 million euro per highway-km (SRU, 2012). This figure does not include the cost for electric trucks. Whether operational savings due to lower energy requirements can outweigh higher upfront costs needs to be examined. The economic side is further investigated in Chapter 3.

Besides the economic viability, further issues that need clarification include payload and capacity restrictions due to the electric drive train components, the wayside integration of the infrastructure (e.g. under bridges) market penetration into logistic fleets and homologation issues.

The general feasibility for heavy-duty trucks has been demonstrated by Siemens; however as there are currently not yet any series applications, conclusions in terms of the market maturity cannot yet be made. The future will show how overhead catenary systems in road applications may become introduced through a pilot project or widespread parallel introduction.

2.4 Fuel cell hydrogen trucks

2.4.1 Technology assessment

While fuel cell powered demonstration trucks are still relatively rare, development and demonstration activities on portable (i.e. APU, mobile phone power devices), stationary, and passenger car fuel cell technology are increasing worldwide. This section covers a technology assessment with regard to storage, energy, and power issues focussing on fuel cell truck applications. Current demonstration vehicles and those already on offer are outlined.

Two main concepts for using hydrogen as an energy carrier providing traction power exist. One option is to operate an internal combustion heat engine using hydrogen instead of diesel. Some demonstration projects from BMW proved its feasibility (BMW, 2006). The main disadvantage of this concept is the limited efficiency being constrained by the thermodynamic process (Roussel, 2012). The other option is to use a fuel cell. This is more efficient thanks to the electro-chemical process (REXEL, 2012).

When using fuel cell powered trucks, the question arises as to whether a fuel cell powertrain can meet the transport requirements. Therefore, existing bottlenecks will be identified by looking at essential requirements such as performance, durability, refueling time, hydrogen storage capacity and weight, derived from real world logistic requirements.

Performance

The efficiency of a fuel cell system in comparison to a diesel internal combustion engine system is higher as the fuel cell system is based on an electro-chemical process and, therefore, not limited by the thermodynamic efficiency of heat engines. Current fuel cell systems reach efficiencies of 50 to 60% (Eichlseder, 2008) whereas the efficiency of diesel engines for heavy-duty trucks is limited to about 37% (NANUPOT, 2010).

The required traction power is about 100-200 kW for a distribution truck (7.5 t-16 t GVW) and 250-500 kW for long haul trucks (16-40 tonnes GVW) (NANUPOT, 2010). In comparison to a fuel cell hybrid electric powertrain, fuel cell power output depends on the power of the additional battery needed. A fuel cell system without any battery will hardly meet the vehicle requirements in terms of fast acceleration or recovery of brake energy and storage facility due to the fuel cells inherent characteristics. Hence, a battery is necessary (Ming et al., 2006). Experts say when battery power is high enough, which may be achieved with high power batteries, fuel cell power might not be at the same level as diesel engine power.

The widely-used fuel cell system for automotive applications today is the low temperature (60°C–120°C) polymer electrolyte membrane fuel cell (LTPEMFC). This fuel cell has the advantage of a low operating temperature, which means that the warm up time of fuel is very short for generating electricity. In addition, the system specific power density[5] is currently at the same level as diesel engines in truck applications; present systems reach 300-400 W/kg,

[5] The fuel cell system specific power is the system peak power divided by the system mass.

covering the fuel cell stack and balance of plant[6] but excluding the hydrogen storage, power electronics, battery and electric motor. This type of fuel cell can be used for power requirements of up to 500 kW (Eichlseder, 2008).

To reach the U.S. Department of Energy's (DOE) specific system power density target of 650 W/kg in 2017 (DOE, 2011a), further development is necessary. One main step includes raising the operational temperature. The focus of current research is not only on the fuel cell system but also on the cell level. Emphasis is on development of waterless and high temperature membranes, reduction and development of new catalysts, usage of thin metallic bipolar plates, etc. (REXEL, 2012). In general, low temperature electrolyte membrane fuel cell's operating temperature is between 60°C-120°C and high temperature polymer electrolyte membrane fuel cell's operating temperature is between 120°C-200°C. Recent and on-going technological improvements on the stack and system level led to a specific stack power density goal from the DOE of 2,000 W/kg and to a specific system power density goal from the DOE of 650 W/kg in 2017 (DOE, 2011a).

Looking at the volumetric power density of the fuel cell stack, Nissan announced that their new fuel cell stack has reached 2,500 W/l (Nissan, 2011). This already meets the official target value of 2,500 W/l by DOE for 2020 (DOE, 2011a).

To implement a fuel cell system in space-constrained vehicles, its system volume is essential. Comparing volumetric power densities may be misleading since definitions of the system borders vary. Taking the currently available heavy duty *HyPM^{TM} HD 180* hydrogenics module for bus applications as a reference, the module volumetric power density is approximately 197 W/l (Hydrogenics, 2012) which would result in a total required volume of 1.52 m^3 for a 300 kW fuel cell stack. As mentioned before, when using a fuel cell system and a battery, which both provide electrical power, varying the power ratio between the fuel cell system and the battery becomes feasible.

Thus, the fuel cell system power must not necessarily equal the conventional diesel engine power level, but the total power (fuel cell system power and battery power) must.

It is vital to maintain state-of-the-art driving dynamics like acceleration rates, etc. in all driving situations. Interviewees[7] have confirmed that a 300 kW fuel cell system in combination with an applicable battery in a long haul vehicle should suffice. In contrast to the fuel cell system volume of 1.52 m^3, the volume of a 350 kW diesel engine is approximately 1.43 m^3 (MAN Engines). For distribution trucks, fuel cell volume of a 150 kW system results in the same dimension as the diesel engine. See Table 8.

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6 Balance of plant means the fuel cell stack and all the equipment necessary to operate the stack in an accurate manner. This includes coolant pump, air filter, cathode Blower, H_2 recirculation pump, control unit, etc.

7 The consulted experts were NyCellSys and Hydrogenics.

Table 8 **Fuel cell system volumes in comparison with diesel engine volumes**

Energy converter	Distribution truck (150 kW)	Long haul truck (ICE: 350 kW; FC: 300 kW)
Fuel Cell (LTPEM)	0.76 m^3	1.52 m^3
Diesel engine	0.77 m^3	1.43 m^3

Durability

In order to be competitive in terms of durability, fuel cells must reach a lifetime of at least 10,400 hours[8] in distribution truck and at least 14,560 hours[9] in long-haul truck applications. Current fuel cells under real testing environments have reached 2,500 operating hours in 2011 (DOE, 2011a). The target of the DOE is set to 5,000 hours for 2017 (DOE, 2011a). Until today, the longest life span under cyclic conditions reached so far in a test was 7,300 hours. This was just reached on the cell level by a Membrane Electrolyte Assembly (MEA) and not by a whole system (DOE, 2008).

In 2011, a fuel-cell bus demonstration has reached 10,000 hours during real-world-service operation with the original stack and no cell replacement (UTC, 2011).

To sum up, the durability of fuel cells is a critical barrier for commercialization and, therefore, needs substantial improvement before widespread implementation in long hauling trucks can become a real option. Thus, field tests are necessary to identify further research and development needs.

Refueling time

Current refueling time is 7-10 minutes in bus applications (storage of approximately 35 kg H_2) according to NEXTHYLIGHTS (2011). The target for the next bus generation is to reach refueling times of less than 7 minutes (compared to diesel refill times of approximately 3 minutes) (NEXTHYLIGHTS, 2011).

Hydrogen Storage

Storage of hydrogen is a crucial issue. Currently, many vessels for storing hydrogen are on the market, reflecting a multitude of available storage options. Storage options are liquid, compressed, physical and chemical adsorption. Tanks used for liquid hydrogen storage today are highly insulated stainless steel tanks. The volumetric storage density is about 40 kg/m^3 on the overall storage volume (Eichlseder, 2008; DOE, 2009). Theoretical energy density of liquefied hydrogen is 70.8 kg/m^3 at 1 bar and -253°C (Eichlseder, 2008). The gravimetric storage density is about 6 mass%[10] (DOE, 2009; Eichlseder, 2008). However, the energy input required for liquification of the compressed gas is extremely high: about 30-40% of the energy content of the hydrogen itself (REXEL, 2012). The ‘boil off effect’ is another disadvantage with liquefied hydrogen storage technology. Evaporation of the liquid hydrogen through heat introduction cannot be avoided. This leads to an increase of the pressure within the vessel. Due to security reasons pressure must be decreased

[8] Assumptions: 260 yearly working days; 4 hours of operation; life time of 10 years.

[9] Assumptions: 260 yearly working days; 7 hours of operation; life time of 8 years.

[10] 6 mass% means 6 kg H_2/100 kg vessel.

by blowing off hydrogen. According to REXEL (2012) the storage will be empty in 4 to 9 days at present for a system that is not running.

Based on the information above, compressed gaseous hydrogen storage has been developed. Unfortunately, the volumetric storage density of the 350 bar technology is only at approximately 16 kg/m^3 on the overall storage volume level (Eichlseder, 2008; DOE, 2009). The theoretical energy density of the 350 bar technology is 23.3 kg/m^3 at 350 bar and 25°C (Eichlseder, 2008). The gravimetric storage density amounts to only 3.5 mass% (DOE, 2009). In comparison to the liquefied storage, storage of compressed hydrogen is within a closed system for automotive application possible without any losses (Eichlseder, 2008). The energy consumption due to compression accounts to approximately 15% of the energy content of hydrogen (REXEL, 2012).

To enhance storage densities, the 700 bar technology has been developed achieving 23 kg/m^3 on an overall storage volume (Eichlseder, 2008; DOE, 2009). The theoretical energy density of 700 bar technology is 39.3 kg/m^3 at 700 bar and 25°C (Eichlseder, 2008). The gravimetric storage density is about 5.4 mass% when using composite materials (Eichlseder, 2008; STORHY, 2008). The 700 bar technology is currently state of the art and widely used within a lot of prototypes. To reduce the weight of the tanks, carbon reinforced steel, aluminum or plastic vessels have been developed. Vehicle implementations of these options are currently being tested.

Another option of hydrogen storage is physical or chemical adsorption. Whereas physical (molecular) adsorption denotes an attachment through surface interaction, chemical (atomic) adsorption is an intercalation in the atomic lattice. The gravimetric storage density of physical adsorption is currently at a maximum of 3 mass%; 8 mass% would be possible by using special synthetic materials like polyaniline or polypyrrole (Eichlseder, 2008). The volumetric storage density is approximately 42 kg/m^3 on the overall storage volume (Eichlseder, 2008). In contrast, chemical adsorption in particular complex metallic hydrides are currently at the same level of gravimetric and volumetric storage density as physical ones when taking the storage vessels into account (Eichlseder, 2008). In contrast, the theoretical volumetric and gravimetric storage densities are enormous but vary widely depending on the used chemical combination (Eichlseder, 2008). The expected future potential of complex hydrides is 10 mass% (REXEL, 2012). Unfortunately, the great potential of the complex metal hydrides at present cannot be exploited due to the complexity of reversible loading and unloading cycles. Furthermore, it is a relatively new research area; test results on energy losses or safety aspects are not publicly available.

For this reason, research and development of gaseous and liquid storage options have to be further continued if acceptable storage densities are to be pursued. The suitability of other storage options like complex metal hydrides is still uncertain but should become a core focus of research activities.

The tank size of trucks varies widely and depends on the required operational range. Therefore, it is assumed that one refill per day is acceptable. For distribution applications, the daily operational range is set to 200 km, whereas a range of 1,000 km for long haul trucks is assumed; see Table 1.

The energy consumption of fuel cell vehicles is higher due to the lower tank-to-wheel efficiency in comparison to the battery electric vehicle. MAN illustrated the energy consumption of delivery trucks and long haul trucks as approximately 1 kWh/km and 2 kWh/km (see also Section 2.2.1) (MAN, 2012).

Based on a literature overview created by Helmers and Marx (2012), tank-to-wheel efficiencies for battery electric cars and fuel cell cars are 73% and 50%[11] respectively. Applying these numbers to the truck applications, a minimum storage of 8.8 kg H_2 for the distribution truck and 87.6 kg H_2 for the long haul truck is essential to achieve the examined ranges. See Table 9.

Table 9 Weight of hydrogen needed for the daily operational range

FCHEV	Distribution truck (<16 t)	Long haul truck (40 t)
Energy consumption (kWh/100 km)	146	292
Energy demand for a daily range of operation (kWh)*	293	2,920
Weight of hydrogen needed (kg H_2)**	8.8	88

* Distribution truck range: 200 km; long haul truck range: 1,000 km.

** Lower heating value H_2: 120 MJ/kg; 33.33 kWh/kg.

Table 10 shows the volume of hydrogen needed for different storage options when taking the theoretical gravimetric storage density into account.

Table 10 Volume H_2 required for the daily operational range

	Theoretical gravimetric storage densities	Distribution truck (range 200 km; 8.8 kg H_2)	Long haul truck (range 1,000 km; 87.6 kg H_2)
Storage options[1]	(kg H_2/m^3)	(m^3 H_2)	(m^3 H_2)
700 bar	39.3	0.22	2.2
350 bar	23.3	0.38	3.8
Liquid	70.8	0.12	1.2
Physical combination	Unknown[2]	-	-
Chemical combination	Unkonwn[3]	-	-

1 Different theoretical volumetric storage densities in reference to the text below.

2 Depends on the used chemical combination of the physisorbed material.

3 Depends on the chemical combination.

Note that these are not the total required storage volumes. Total required storage volume depends on the vessel used and its specific dimensions. The overall required storage volume is calculated in Table 11 (Eichlseder, 2008; DOE, 2009). Publicly available information on vessels is limited. Thus, data available for typical storage vessels for automotive applications with a maximum of 2 kg H_2 (350 bar technology), 5 kg H_2 (700 bar technology) and 9 kg H_2 (liquid) storage capacity from Eichlseder (2008) are used. In general, storage vessels are mainly custom-built and not available as mass products on the market. For distribution trucks, vessels with a maximum of 5 kg H_2 storage capacity may be applicable but not for long haul trucks. Specific vessel data used can be found in Annex A.

11 The tank-to-wheel efficiency is the overall powertrain efficiency taking all specific component efficiencies such as fuel cell system, battery, power electronics, etc. into account.

Table 11 Total required storage volume of storage vessels including hydrogen

	Practical gravimetric storage densities	Distribution truck (range 200 km; 8.8 kg H_2)	Long haul truck (range 1,000 km; 87.6 kg H_2)
Storage options[1]	(kg H_2/m^3)	(m^3 H_2 storage)	(m^3 H_2 storage)
700 bar	23	0.38	3.8
350 bar	16	0.55	5.5
Liquid	40	0.22	2.2
Physical combination	42	0.21	2.1
Chemical combination	42	0.21	2.1

1 Different practical volumetric storage densities in reference to the text below.

The illustrated volumes in Table 10 and Table 11 demonstrate existing differences between theoretical and practical hydrogen storage volume. Practical storage volume is nearly twice the theoretical storage volume depending on the vessel specific dimensions.

The DOE specific target for the fuel cell storage system[12] are 40 kg/m³ storage and 5.5 mass% up to 2017 (DOE, 2011). Note that the gravimetric storage densities shown above may not be comparable due to the uncertainty of the storage system definition in Eichlseder (2008).

Physical and chemical adsorption leads to the lowest required volume and meets the DOE specific target. Liquid hydrogen storage meets the DOE specific target as well and therefore is in terms of storage volume a good solution, followed by the 700 bar state of the art technology and the 350 bar technology.

The 700 bar state of the art hydrogen storage volumes are larger than diesel tanks by a factor of 1.9 (for distribution trucks) and 8.46 (for long-haul trucks) respectively when 0.2 m³ for a 100 liter diesel tank and 0.45 m³ for a 400 liter diesel tank are taken as a reference (Autoteileplus, 2012). The liquid hydrogen storage volume, as well as the volume for physical and chemical adsorption methods are, nearly the same as for the distribution truck. Therefore, for distribution trucks, this volume may be acceptable, but not for long haul trucks. Note, that the vessels taken into account are not optimized for long haul vehicle applications. Thus, the figures in Table 11 may be an overestimate.

The storage volume depends largely on the driving concept required for different applications. When the fuel cell is used as a range extender less fuel cell power as well as hydrogen storage would be necessary but a bigger battery would be required. A plug-in function could make sense for applications with a high demand of stop and go phases as well high recuperation rates, such as port applications. Additional advantages in terms of packaging are that the requirements at the port on speed (maximum speed is approximately 40 km/h) and on the operation radius (approximately 4 km) are not that high as they are for distribution or long haul trucks on public roads.

12 The storage system definition by the DOE includes all components necessary for balancing the storage plant like tank, material, valves, regulators, piping, mounting, brackets, insulation, added cooling capacity, etc.

Weight

With a LTPEM fuel cell system power of 300 kW at the current power-to-weight ratio of 350 W/kg (Eichlseder, 2008), the mass of the fuel cell system would be 857 kg. This is lower than a current heavy-duty truck with 350 kW diesel engine weight of approximately 1,000 kg (MAN Engines). Whereas additional weights could come from components such as the battery, power electronics, and electric motors depending mainly on the vehicle configuration, the hydrogen as well as the storage vessels will definitely lead to additional rear weight. Table 12 and Table 13 illustrate different weights of storage including fuel in comparison to conventional ICE vehicles. Assuming a standard 100 liter tank for a diesel distribution vehicle with a maximum range of 556 km, an additional storage mass of 69 kg compared to a diesel tank would result, when looking at the 700 bar current state of the art technology. In terms of weight, liquid storage would be at present the best option due to the highest mass percentage, resulting in an additional 53 kg weight.

Table 12 Tank weights including fuel for distribution truck

Distribution truck (100 l Diesel; range: 556 km; consumption: 18 l/100 km)					
Diesel storage	**(Density: 0.83 kg/l; tank weight: 200g/l)**				
	Tanksize in liter		kg storage tank	kg diesel	kg in total
	100		20	83	103
Hydrogen storage distribution truck	**(8.8 kg H_2; range 200 km; consumption 4.4 kg H_2/100 km)**				
	Storage options	kg H_2/100 kg storage*	kg storage tank	kg H_2	kg in total
	700 bar	5.4	163	8.8	172
	350 bar	3.5	251	8.8	260
	Liquid	6	147	8.8	156
	Physical combination	3	293	8.8	302
	Chemical combination	3	293	8.8	302

* Gravimetric storage densities are in reference to the text below.

Taking the 700 bar current state of the art technology and a 400 liter long haul truck diesel tank into account, storage mass results in additional 1,298 kg compared to a diesel tank, as shown in Table 13. The liquefied storage alternative results in an excess mass of 927 kg compared to the diesel tank. For this reason, fuel cell application for distribution trucks should be possible from a technical point of view, whereas further storage technology development for long haul trucks is necessary.

Table 13 **Tank weights including fuel for long haul trucks**

Long haul truck (400 l Diesel; range: 1,143 km; consumption: 35 l/100 km)					
Diesel storage	**(Density: 0.83 kg/l; tank weight: 200 g/l)**				
	Tanksize in liter		kg storage tank	kg diesel	kg in total
	400		80	332	412
Hydrogen storage distribution truck	**(87.6 kg H_2; range 1,000 km; consumption 8.76 kg H_2/100 km)**				
	Storage options	kg H_2/100 kg storage*	kg storage tank	kg H_2	kg in total
	700 bar	5.4	1,622	87.6	1,710
	350 bar	3.5	2,503	87.6	2,590
	liquid	6	1,460	87.6	1,550
	Physical combination	3	2,920	87.6	3,010
	Chemical combination	3	2,920	87.6	3,010

* Gravimetric storage densities are in reference to the text below.

The storage weight depends largely on the vehicle concept. Using a fuel cell system as a range extender, less storage would be necessary due to the fact that the battery is the main power unit. The total drivetrain weight depends also on the battery specific gravimetric power density.

Despite fuel cell technology related bottlenecks (durability, heavy storage weight and volume) fuel cell drivetrains for special niche applications already exist (see Section 2.4.2). Those applications could fuel a widespread introduction by generating real-world application results and raising awareness of the manufacturing companies.
In addition, further research and development is necessary to overcome the named bottlenecks. It is, however, difficult to predict if and when these improvements and a subsequent phasing in of the fuel cell technology into the truck market can be achieved.

Besides the technical and operational issues of replacing a conventional combustion engine by a fuel cell, the main challenges of today and for the next years are cost reductions on the system and component level and the arrangement of an adequate hydrogen fuelling infrastructure. The infrastructure and the cost issues are addressed in Section 2.5 Chapter 3, respectively.

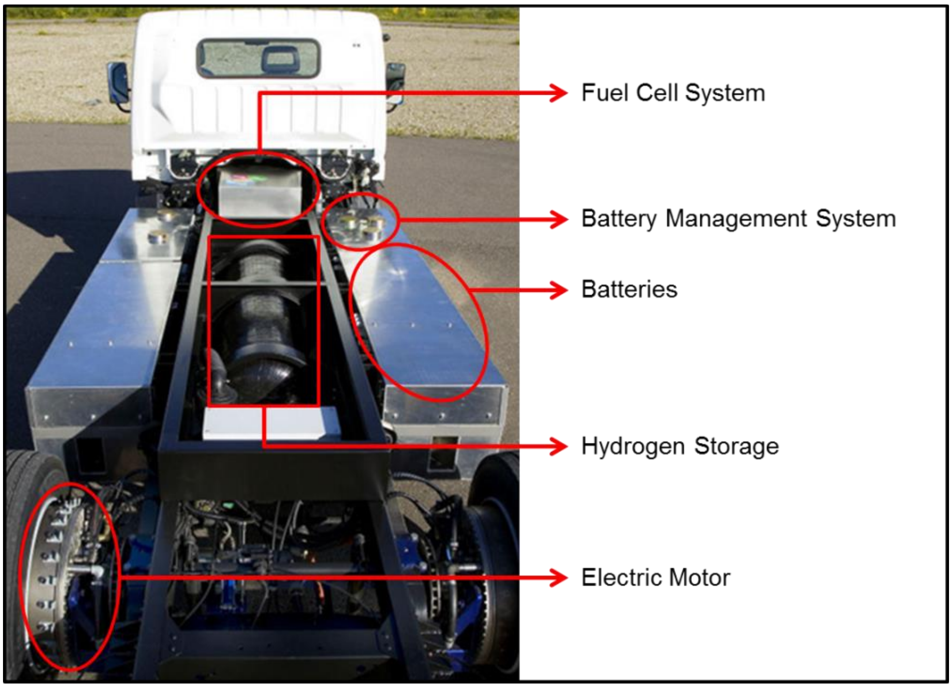
One pilot application of fuel cells in transport is observed in Contestabile (2009). Long haul trucks require auxiliary power for a number of appliances such as microwaves, refrigerators, TV, etc. when parked. At present, this auxiliary power is provided when the diesel engine idles, resulting in very inefficient fuel consumption (efficiency of 10%) and the emission of noise, CO_2 and toxic matters. In 2008, California banned idling of more than 5 min for all trucks weighing above 10,000 pounds. Dedicated auxiliary fuel cells may be applied in the near future.

Furthermore, during operation, auxiliary power is increasingly required to power electronic systems as well as to provide additional comfort to the driver. Fuel cell auxiliary power will not have significant potential in the European market as it has in the U.S., as truck drivers in Europe usually do not idle the engines while stopped overnight (Contestabile, 2009). This is due to higher fuel prices and the absence of the need for air conditioning overnight in Europe than in the U.S. Furthermore, the living space within the drivers cabin is limited in Europe due to a restriction in maximum length of a trailer truck (EG, 1996). In the U.S. there is no overall length limitation for the trailer trucks. Minimum length specifications exist only for semi-trailers (DOT, 2004). Thus, the drivers cabin in the U.S. is more spacious and might be better equipped with electronic devices such as microwave ovens, refrigerator, television, etc. which leads to a higher auxiliary power requirement. Contestabile (2009) estimates the market potential today to be about 100,000 units in total for Europe. Auxiliary power could be provided by a 5 kW diesel LTPEMFC APU system, which is expected to cost no more than 3,000 euro.

2.4.2 Current Vehicles

The type C8HE of the Dutch company Hytruck as shown in Figure 25 uses a conventional chassis of the Mitsubishi Canter 7.5 ton urban and inner city distribution vehicle. By removing the diesel motor, gearbox, differential and fuel tanks, and integrating the Hytruck H2E (hydrogen to electricity) driveline, fuel cell conversion is accomplished. The H2E driveline is made up of a 15 kW LTPEM fuel cell operating system with a 350 bar pressure tank containing 5.8 kg of hydrogen. The energy provided from this technology is transferred to the main power-unit, the lithium-ion phosphate batteries with a total capacity of 25 kWh, which supplies the electric in-line motors (30 kW per wheel) fitted at the rear wheels. The vehicle is developed to meet future requirements of inner cities and regional door-to-door distribution in terms of noise and emission limits. The daily operational range is 400 km (Hytruck, 2012).

Figure 25 Drivetrain Hytruck

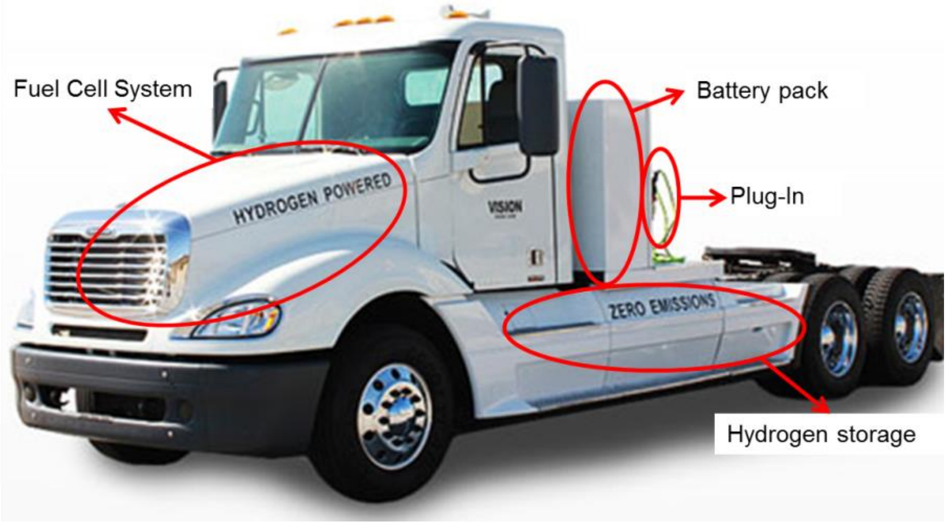


Source: Hytruck, 2012.

To strengthen the commitment of the Port of Los Angeles to zero emission solutions and in view of tightening emission reduction schemes, a hybrid fuel cell truck project in collaboration with Vision Industries started in 2010. The aim of this project is to test the performance of Vision's class 8 zero emission hydrogen plug-in hybrid fuel cell electric truck Tyrano in drayage operation (see Figure 26). Furthermore, it should demonstrate the feasibility of the technology for short and medium range hauling in heavy-duty trucks applications within and beyond the port of Los Angeles. Key parameters of the Tyrano are (Vision Motor Corp., 2012):

– 400 kW electric motor;
– lithium-ion battery (unknown capacity);
– LTPEM fuel cell output of 65 kW;
– driving range of 322 km with a standard 350 bar hydrogen fuel tank (644 km range is possible with an extended configuration).

Figure 26 Vision's Tyrano



Source: Vision Motor Corp., 2012.

A joint development agreement was announced by Vision Industries Corp. and the Balqon Corporation to build a zero emission fuel cell electric hybrid terminal tractor, the Zero-TT (see Figure 27), for applications at distribution centers, rail yards and marine terminals. The performance data are as follows: 160 kW electric motor, lithium-ion battery (unknown capacity) a LTPEM fuel cell output of 16.5 kW (Vision Motor Corp., 2012). The driving range is unknown.

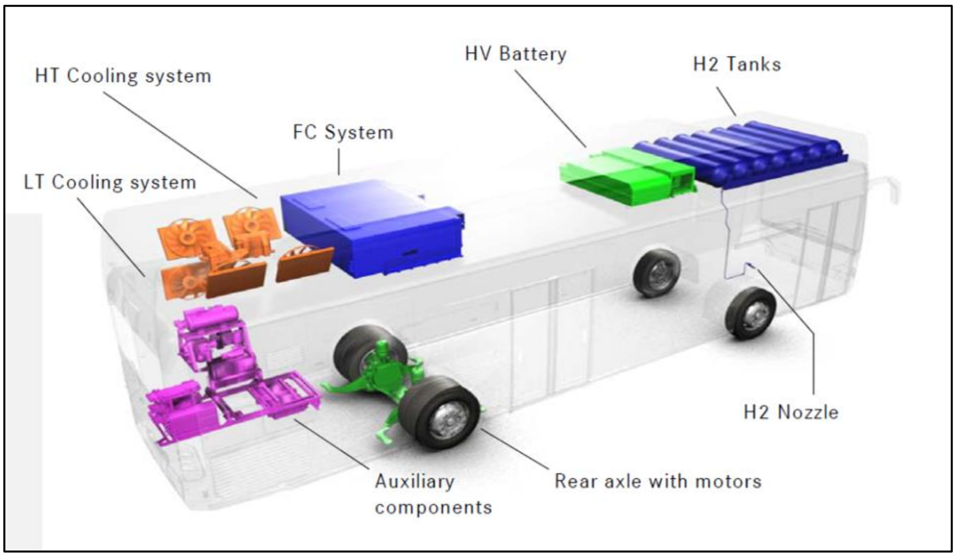
Figure 27 **Vision's Zero-TT**

Source: Vision Motor Corp., 2012.

The RMIT University in Australia is also researching hydrogen technology for heavy-duty long-haul trucks to demonstrate how vehicle design and new sustainable technologies can make freight transport more efficient. A small-scale model, which is an exact replica of the Scania Highline series, was built to test the truck against pre-defined dynamic loads with the result being scaled up using mathematical models to predict the performance of a full-scale truck (RMIT, 2011). Technical details of the small-scale model are discussed in more detail in Misiopecki (2011).

The Citaro FuelCell hybrid (see Figure 28) is the latest version (3rd generation) of a fuel cell driven bus built by Daimler buses. The complete fuel cell system is mounted on the top of the bus. Its key characteristics are: 120 kW electric motor, lithium-ion battery with a capacity of 27 kWh and a fuel cell output of maximum 160 kW. The driving range of approximately 250 km is secured by a 350 bar hydrogen storage amount of 35 kg H_2 among seven tanks (Hybrid Portal, 2012).

Figure 28 Citatro FuelCell Hybrid



Source: LBST, 2010.

Currently, four Citaro FuelCell hybrids are tested by the Hamburg transit agency Hamburger Hochbahn AG under the German NaBuz demo scheme, which aims to promote sustainable bus systems for the future. NaBuz is a demonstration project within the Clean Energy Partnership (CEP) closely linked to the European CHIC fuel cell bus project (HYER, 2011). During previous participations in different demonstration projects, overall 36 Mercedes Benz Citaro FuelCell buses (2^{nd} generation) in twelve worldwide public transportation services performed 2.2 million kilometers and 140,000 hours of operation (Daimler, 2011). Further information and results of the HyFLEET:CUTE project, which took place in the timeframe from 2006 until 2009 (HyFLEET, 2009). The HyFLEET:CUTE project involved 47 hydrogen powered buses in regular public transport service in ten cities on three continents.

The ROTOPRESS Fuel Cell (see Figure 29) is the first garbage truck operating in Berlin with a diesel engine and fuel cell with battery for auxiliary power (Hydrogenics, 2011). The 210 kW Mercedes 6 cylinder in-line diesel engine is accompanied by a 32 kW net power Hydrogenics PEM fuel cell as an auxiliary power unit (APU). Auxiliary power is used for the garbage press as well as the lift. 10 kg of hydrogen is stored at 350 bar inside two vessels (TÜV SÜD, 2012).

Figure 29 ROTOPRESS Fuel Cell

Source: TÜV SÜD, 2012.

To sum up, implementation efforts of fuel cell technology are relatively rare in the European Union. As shown above, the present fields of activity of companies and institutions worldwide are implementing the fuel cell technology in medium and light trucks, busses and class 8 heavy-duty trucks for niche applications. Therefore, the usage of hydrogen as energy carrier might be one path towards zero tailpipe emission operation within the truck segment.

2.4.3 Conclusion and discussion

A comparison of the volume between a conventional diesel engine and a fuel cell system showed that the volume of the fuel cell itself is not a bottleneck and is acceptable for distribution as well as for long haul applications. The comparison based on an upscale of the the *HyPM™ HD 180* hydrogenics module specific data since no single fuel cell system with a power output of greater than 200 kW is currently available on the market. The high power output required for truck applications is at present achieved by connecting two single fuel cell systems in parallel.

One of the most important challenges is to reach an adequate durability. This is strongly related to impurities in fuel and air, starting and stopping, freezing and humidity, that results in stress for the fuel cell system components (DOE, 2011a). The same applies to the overall fuel cell storage system in general. Storage media, materials of construction, balance-of-plant components and simple charging or discharging conditions are needed that allow hydrogen storage on an accurate as well as high safety level (DOE, 2011).

Due to the bottlenecks identified above, current durability is at a maximum of 10,000 real operating hours with the original stack and no cell replacement. The minimum requirements of the distribution truck are 10,400 hours and thus not acceptable. For long haul trucks the achieved operation hours are not acceptable, as they should at least have 14,560 hours.

Hence, the durability is a critical barrier and therefore needs substantial improvements on fuel cell system and storage level.

The refueling time of hydrogen fuelled vehicles is more than double that of conventional diesel fuelled ones. The future target is to mitigate this constraint by reaching refueling times lower than 7 minutes (for bus applications).

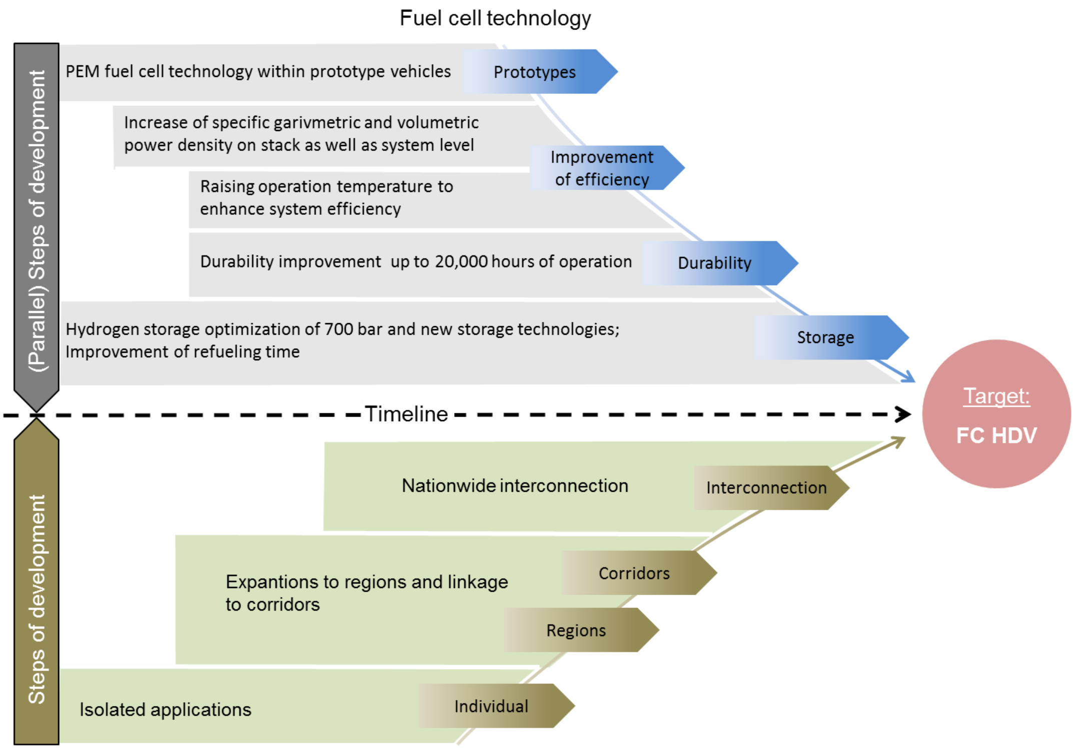
In terms of the hydrogen storage, the 700 bar technology is state of the art as it avoids the 'boil-off effect' and it needs less energy for compression compared to liquefaction. However, in terms of overall volume and weight, liquid hydrogen storage should be the favorable option as illustrated in Table 11, Table 12 and Table 13. The main advantage of the 700 bar technology in comparison to the 350 bar technology is the higher volumetric and gravimetric storage capacity. A promising alternative storage option with high potential in terms of volumetric and gravimetric storage density is the hydrogen storage within complex metal hydrides by chemical adsorption. This is a relatively new research area, and further research in terms of safety, loading and unloading complexity is necessary.

Volumes and weights illustrated in Table 11, Table 12 and Table 13 indicate that both the 700 bar and the liquid hydrogen storage technology is acceptable for distribution trucks but not for long haul trucks.

Additional weight by the fuel cell system is not an issue. Calculations show that the fuel cell system in comparison to an internal combustion engine would have less weight. But this weight advantage of the fuel cell system might be compensated by additional powertrain components like the electric motor and the required battery for example.

Fuel cell market uptake within the distribution truck segment might be possible, but depends on the availability of a fuel infrastructure and competitive costs. Implementation in long haul trucks seems to be feasible in the long run but requires further research in all aspects shown in Figure 28.

Figure 30 Fuel cell technology and infrastructure roadmap



Note: Not all of the steps identified for fuel cell technology are subsequent and may start at different points in time. The hydrogen storage optimization for example could be resolved in parallel to the PEM fuel cell technology. The timeline does not reflect a specific timeframe.

In general, aside from the cost aspects (which are described in Chapter 3), the status of technology and the infrastructure availability are crucial issues regarding the introduction of alternative technologies. Different bottlenecks exist for the implementation of fuel cell technology in heavy-duty trucks for both delivery and long haul applications. Figure 30 illustrates the main steps of development, which should be the focus of further research and development. Fuel cell technology integration in delivery trucks has recently been realized with prototypes and may achieve series application much earlier than in long haul trucks (if ever). This is due to the lower requirements for power or range for example. At what time the technology would be ready for market and thus, series application takes place, cannot be foreseen.

In contrast to the subsequent and parallel steps of technology development, infrastructure availability has to be realized step by step as shown in Figure 30. A development from currently available individual fuelling stations to corridors by the linkage of regions can result in nationwide interconnection. The state of infrastructure availability is described in the following chapter.

2.5 Energy infrastructure for hydrogen trucks

Hydrogen fueling stations by today are relatively scarce in Europe but new stations are being created, mainly in Germany, Italy and Scandinavian countries (see Figure 31). In this section the main task is to illustrate the current status of existing hydrogen infrastructure and will not discuss sources of hydrogen. The cost as well as the GHG reduction tasks production pathways of hydrogen are mentioned due to different production costs and greenhouse gas emissions.

The EU-wide collaboration HyER (formerly HyRaMP), covering local authorities and industry players from the automotive, gas-industry and energy sector aims at coordinating projects on hydrogen and fuel cell in Europe, facilitating also the introduction of an accurate hydrogen infrastructure.

The association's objective is the installation of up to 1,000 hydrogen refueling stations in Germany until 2020, with a focus on automotive applications. As of 2012, approximately 58 refueling stations are under operation in Europe, mostly in Germany. Approximately 30 additional stations are in preparation through 2015 throughout Europe.

The size of the actual stations and the level of realization can vary considerably. There are early test applications and semi-professional units with a large variety of production and storage technology as well as a low demand (for niche applications like research and municipal fleets). 90% of the existing stations deliver less than 50 kg hydrogen a day (HyRaMP, 2010). Figure 31 gives an overview of operational and planned fueling stations in 2012 in Europe.

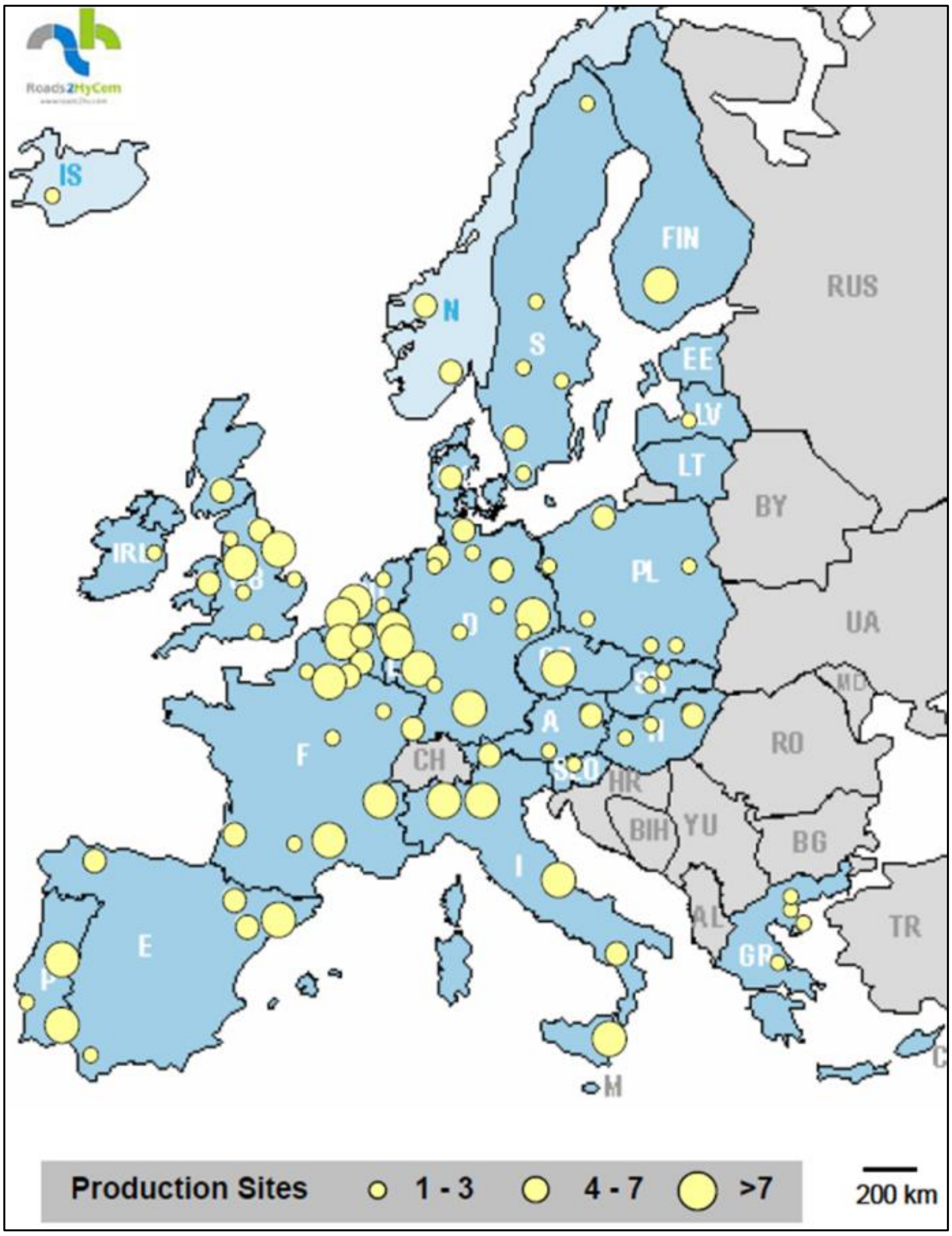
Figure 31 Overview about operable and planned fueling stations for 2012 in Europe

Source: Fuelcellsworks, 2012.

Most of the stations in Figure 31 deliver only compressed hydrogen gas at 350 bar and some at 700 bar. The hydrogen production is mainly based on-site (Roads2Hycom, 2007). In addition, nearly 1,600 km of hydrogen pipelines in Europe exist which are mainly owned by Air Liquid S.A., Linde AG and Air Products AG. Further details regarding the pipelines (location, length, etc.) can be looked up in (Roads2Hycom, 2007).

Figure 32 displays quantity and distribution of European production sites as of 2007 on an aggregated level.

Figure 32 Hydrogen production sites in Europe



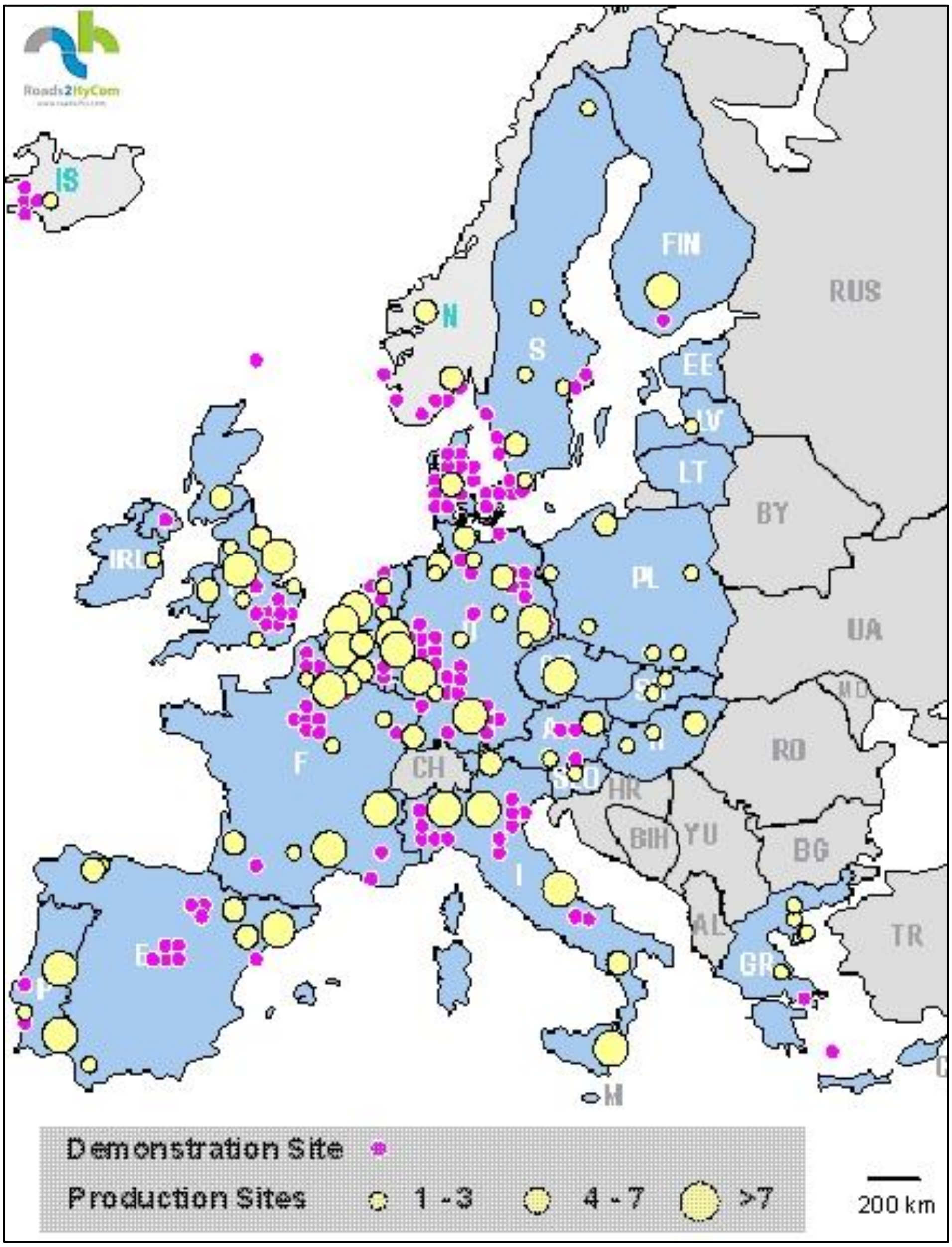
Source: Roads2HyCom, 2007a.

Production clusters are mainly based in the Benelux and Rhein-Main area and in the north of Italy.

Adding on-going hydrogen demonstration projects to the map it is shown that demonstration projects are locate near hydrogen production sites, see Figure 33.

The 128 demonstration projects shown are divided into various types of applications: Multiple (projects where more than one of the mentioned application types are demonstrated), portable (i.e. APU, mobile phone power devices), stationary (not moving applications) and transport (moving applications). Transport (62 projects) and stationary (55 projects) applications dominate the field widely (Roads2HyCom, 2007c).

Figure 33 Hydrogen demonstration projects



Source: Roads2HyCom, 2007b.

In the future, it is expected, that the hydrogen fueling infrastructure will expand to also more rural areas, potentially opening up also to end-users.

The creation of ‘green’ corridors by building belts of closely linked fueling stations enables uninterrupted long-haul traffic in different regions. This is seen as another path toward widespread H_2 implementation (HyRaMP, 2010).

3 Analysis of expected costs

In this chapter a cost analysis from a Total Cost of Ownership (TCO) perspective for different distribution and long haul truck configurations over time will be presented. The aim is to illustrate the cost differences of different vehicle configurations over a specific time frame. The focus is set on zero tailpipe emission drivetrains. Internal combustion hybrid vehicles are not included in the cost analysis.

A TCO analysis takes all costs of a capital asset into account, which accrue to the owner during the expected life cycle. TCO includes the retail price, fixed and running costs. In addition, infrastructure costs will be discussed in this chapter.

In the following sections (Section 3.1 - Section 3.3) the individual assumptions and methods used will be explained. The vehicle specific total costs of ownership are illustrated in Section 3.5.

3.1 Vehicle production costs

The production costs depend to a large degree on the main components of the drivetrain. A simplified breakdown is used to calculate the vehicle production costs.

For distribution trucks (7.5-16 tonnes gross vehicle weight), three vehicle configurations are defined and investigated: the reference internal combustion engine direct injection compressed ignition (ICE-DICI), the battery electric (BEV) and the fuel cell hybrid electric (FCHEV) vehicle. The years under consideration are 2012, 2020, and 2030.

For long haul trucks (40 tonnes gross vehicle weight), four vehicle configurations are defined and investigated: the reference internal combustion engine direct injection compressed ignition (ICE-DICI), the dynamic inductive grid-integrated vehicle (DI-GIV), the overhead catenary grid-integrated vehicle (OC-GIV) and the fuel cell hybrid electric (FCHEV) vehicle. Similar to distribution trucks, the years under consideration are 2012, 2020, and 2030.

Cost developments over time are reflected by the definition of specific cost rates for the relevant drivetrain components (see Table 14). All costs are price base 2010 (not inflated).

Table 14 **Specific costs of vehicle components**

Components		2012	2020	2030
Internal combustion engine[1]	(€$_{2010}$/kW)	53	60	67
Battery system[2]	(€$_{2010}$/kWh)	450	240	161
Electric motor[1]	(€$_{2010}$/kW)	19	17	15
Fuel cell system[2]	(€$_{2010}$/kW)	975	190	80
Hydrogen storage (700 bar)[1]	(€$_{2010}$/kWh)	26	18	10
Additional required BEV systems (ARS are the power electronic, battery management system, etc.)[1]	(€$_{2010}$/kW)	26	21.5	17
Additional required FCHEV systems (ARS are the power electronic, battery management system, etc.)[1]	(€$_{2010}$/kW)	19	16	13

Sources: [1] Özdemir, 2012; [2] derived from available literature data. Battery pack costs are given for the total battery capacity.

Specific costs of the internal combustion engine are expected to increase over time due to the integration of new technology mainly to meet tightening exhaust after-treatment regulations (Özdemir, 2012).

Battery system costs vary widely depending on production rates considered. Cost ranges have been determined with different literature sources, including McKinsey (2012), ICF (2011), Howell (2012), Element Energy (2011) and Roland Berger (2011). The chosen values for this study are shown in Table 14 (second row) and implicate rising production rates of up to 100,000 units as well as continual increasing of future investments.

As highlighted in Section 2.2.1, huge uncertainties in the development of future battery technology exist. Currently, it is not clear which technology will succeed in terms of automotive requirements and production costs. Future costs are difficult to predict, but it is estimated that the battery costs will decrease due to effects on volume and scale as well as introducing new technologies. Battery costs are generally similar for light- and heavy-duty vehicle applications. The specific battery system costs should decrease with increasing battery size, but based on current existing huge uncertainties, the battery system cost for light and heavy duty vehicles as well as for battery and fuel cell hybrid electric vehicles were assumed to be equivalent. Likewise, the costs of electric motors are expected to decrease due to economies of scales and learning curve effects over time (Özdemir, 2012).

Fuel cell system costs[13] also vary widely within the available literature. Following NEXTHYLIGHTS (2011) two approaches are being developed. One approach uses dedicated long life stacks where stack operation is expected to exceed 20,000 hours. The other approach involves automotive stacks where shorter warranties will be more likely, but with reduced stack replacement costs. Note that there is not yet a consensus within the industry regarding the dedicated long life stack approach (NEXTHYLIGHT, 2011). In this study the fuel cell system costs are derived from available literature based on DOE (2012), Özdemir (2012), IEA (2012) and Schmid (2009). The chosen values for this study are shown in Table 14 (fourth row).

[13] The fuel cell system costs cover the costs for the stack and the balance of plant.

At present, fuel cell system costs are very high mainly due to the limited quantity produced. Assuming a rise in production, innovations in production technology, a reduction in platinum used and economies of scale, costs per kW are predicted to decrease as shown in Table 14.

In addition to the fuel cell itself, costs of compressed 700 bar hydrogen storage were calculated (700 bar was chosen as reference since this technology is state of the art). Due to an anticipated increase of units produced (same as assumed for the fuel cell system) the costs per kWh are predicted to decrease as well (Özdemir, 2012).

Cost development of additional required systems (ARS), which are electrified systems like power electronics, the battery management system, etc., necessary to manage the power transfer for the BEV and for the FCHEV are estimated to decrease over time as shown in Table 14 based on Özdemir (2012).

3.1.1 Distribution trucks

Internal Combustion Engine Distribution Vehicle

Table 15 gives a simplified breakdown of the production costs for the internal combustion diesel engine reference vehicle. Reference vehicle costs are 48,400 euro in 2010, 49,500 euro in 2020 and 50,550 euro in 2030. The rise of vehicle costs over time is based on the integration of new powerpack technology mainly to meet tightening exhaust after-treatment regulations. All total vehicle costs examined consist of the sum of the specific costs for the glider, drivetrain and storage system. The glider cost is kept constant for simplification reasons. It comprises all parts which are necessary for a standard vehicle but not outlined in the tables (e.g. chassis, cabin exhaust system, etc.). Note that the following vehicle configurations are based on the coverage of the range requirements outlined in Section 2.1.

Table 15 Production costs of distribution trucks with ICE

Distribution vehicle production costs		ICE - DICI		
		2012	2020	2030
Total vehicle costs	(€2010)	48,400	49,500	50,550
Vehicle				
Glider	(€2010)	40,000	40,000	40,000
Drivetrain				
Powerpack	(€2010)	7,950	9,000	10,050
Power	(kW)	150	150	150
Battery	(€2010)	200	200	200
Storage system				
Fuel tank	(€2010)	300	300	300

Battery electric distribution vehicle

The configuration of the battery electric vehicle is illustrated in Table 16. For the battery electric and fuel cell hybrid electric vehicles additional required system (ARS) like controllers and converters for example have to be taken into account and thus were added within the vehicle category. For the pure battery electric configuration, 80% depth of discharge is considered.

A battery capacity of 250 kWh is necessary to reach the required range of 200 km at an estimated average energy consumption of 1 kWh/km and 80% depth of discharge (MAN, 2012). Due to assumed fuel consumption improvements over time (detailed information in Section 3.3) battery capacity may be reduced enabling the same driving range.

Current battery prices are the main cost driving factor resulting in approximately 3.3 times higher production costs compared to a conventional ICE vehicle. This is in-line with the statements gathered in the expert interviews. If battery prices decrease as predicted in Table 14, BEV-distribution vehicle production costs could be nearly halved by 2030.

Table 16 BEV distribution vehicle production costs

Distribution vehicle production costs		BEV 2012	BEV 2020	BEV 2030
Total vehicle costs	(€2010)	159,250	100,975	78,208
Vehicle				
Glider	(€2010)	40,000	40,000	40,000
ARS*	(€2010)	3,900	3,225	2,550
Drivetrain				
Electric motor	(€2010)	2,850	2,550	2,250
Power	(kW)	150	150	150
Storage system				
Battery	(€2010)	112,500	55,200	33,408
Capacity	(kWh)	250	230	208
Fuel tank	(€2010)	-	-	-

* Additional required BEV systems.

Fuel cell hybrid electric distribution vehicle

Table 17 shows the production costs of the fuel cell hybrid distribution vehicle. The main power unit is the fuel cell system and the additional battery is regulated at high state of charge (SOC) percentages (i.e. between 70 and 90%) to buffer high peak power demand and to enhance battery lifetime. The fuel cell configuration of 2012 used within this report is approximately 4.2 times more expensive than the ICE reference vehicle. Experts mentioned a scaling factor of approximately 6. Achieving the experts scaling factor, fuel cell system costs has to be approximately at 1,500 EUR_{2010}/kW which is at the upper end of the fuel cell system cost data available. This shows again the uncertainty of fuel cell system cost.

The high production costs are mainly caused by the current high costs of the fuel cell system as shown in Table 14. If production units will increase, fuel cell system costs might decrease as assumed in Table 14. Further cost reduction effects are expected for the battery and the electric motor.
Fuel consumption improvements are considered within the required storage capacities over time. The hydrogen storage capacity is sufficient to meet the driving range requirements of 200 km.

Anticipated cost reduction leads to a distribution fuel cell hybrid electric vehicle cost of 201,826 euro in 2012, 79,294 euro in 2020, and 59,498 euro in 2030. The production price is expected to decline by a factor of approximately 3.4 by 2030 compared to 2012 levels.

Table 17 FCHEV distribution vehicle production costs

Distribution vehicle production costs		FCHEV		
		2012	2020	2030
Total vehicle costs	(€2010)	201,826	79,294	59,498
Vehicle				
Glider	(€2010)	40,000	40,000	40,000
ARS*	(€2010)	2,850	2,400	1,950
Drivetrain				
Fuel cell system	(€2010)	146,250	28,500	12,000
Power	(kW)	150	150	150
Electric motor	(€2010)	2,850	2,550	2,250
Power	(kW)	150	150	150
Storage system				
Battery	(€2010)	2,250	1,200	805
Capacity	(kWh)	5	5	5
Hydrogen storage	(€2010)	7,626	4,644	2,493
Capacity	(kWh)	293	258	249

* Additional required FCHEV systems.

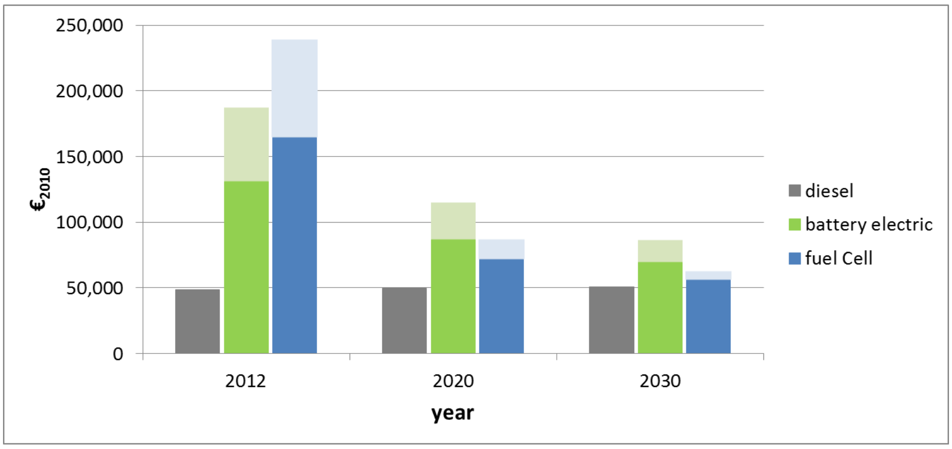
3.1.2 Overview of distribution truck production costs development

Figure 34 shows an aggregated overview of the considered distribution truck production costs. Since future cost developments are uncertain, a variation of the main influencing component costs was done. The battery and fuel cell system costs outlined in Table 14 were changed by ± 25%.

The bright bars denote the high cost (+25%) scenario and the dark bars the low cost (-25%) scenario. The margin of uncertainty is currently very high and will decrease over time as will overall production costs. Production costs of the alternative vehicles decrease until 2030 but will not reach the ICE reference vehicle cost level.

Fuel cell hybrid production cost decrease from 4.2 times higher to approximately 1.2 times higher production costs in comparison to the ICE reference vehicle by 2030. Battery electric vehicle production costs decrease from 3.3 times higher to approximately 1.4 times higher production costs in comparison to the ICE reference vehicle by 2030. The difference between the alternative vehicles is due to the actual higher cost of a fuel cell system compared to the battery. Over time, the fuel cell system costs are expected to decrease faster than the battery costs per kWh (see Table 14).

Figure 34 Distribution truck production cost development



Note: The bright bars denote the high cost (+25%) scenario and the dark bars the low cost (-25%) scenario.

3.1.3 Long haul trucks

Drivetrain configurations considered for long haul trucks (40 tonnes) are similar to the distribution truck drivetrain configurations. The internal combustion engine direct injection compressed ignition (ICE-DICI) is the reference vehicle. Three zero tailpipe emission configurations were defined: the dynamic inductive grid-integrated vehicle (DI-GIV), the overhead catenary grid-integrated vehicle (OC-GIV) and the fuel cell hybrid electric vehicle (FCHEV). Similar to the distribution vehicles, the years under consideration are 2012, 2020 and 2030. The specific cost rates of Table 14 are applied for the calculation of the drivetrain costs as well.

Internal Combustion Engine long haul vehicle

The production costs of 79,800 euro in 2012, 82,250 euro in 2020 and 84,700 euro in 2030, as outlined in Table 18, refer to the long haul reference vehicle.

The glider is 20,000 euro more expensive compared to the distribution truck due to higher payloads and thus greater chassis requirements. The driver cab for long haul applications contains better equipment and additional configurations like more driving assistance systems.

Table 18 ICE long haul vehicle production costs

Long haul vehicle production costs		ICE-DICI 2012	2020	2030
Total vehicle costs	(€2010)	79,800	82,250	84,700
Vehicle				
Glider	(€2010)	60,000	60,000	60,000
Drivetrain				
Powerpack	(€2010)	18,550	21,000	23,450
Power	(kW)	350	350	350
Battery	(€2010)	250	250	250
Storage system				
Fuel tank	(€2010)	1,000	1,000	1,000

Dynamic inductive grid-integrated long haul vehicle

The assumed concept of both the dynamic inductive as well as the overhead catenary grid-integrated vehicle is that they mainly operate on roads with a constant energy supply. For this operation mode, the grid is responsible for supplying the traction power. But when thinking of last mile delivery[14] it is supposable that no grid connection will be installed. In this case, configuration chosen allows a driving range of 60 km, which means a 30 km radius of operation.

Two cases of pure battery operation are estimated. The first case is the operation range from the fleet operator basis to get to the grid connection. The second case of pure battery electric driving is during hub delivery. It is assumed, that this underlying concept could be an interesting application option for the grid integrated vehicles. The defined pure electric operation range is based on best guess estimation because fleet operators unfortunately did not provide any ranges. Furthermore, note that the defined pure electric driving range is strongly linked to the vehicle overall production costs. For the grid integrated vehicles 80% depth of discharge regarding the battery capacity is considered as well.

Based on the used configuration of the dynamic inductive grid integrated long haul vehicle, the production costs of 159,588 euro in 2012 are approximately 2 times more expensive in comparison to the reference ICE-DICI vehicle; see Table 19. The dynamic inductive grid-integrated vehicle is, however, dependent on a respective inductive energy supply infrastructure. The main portion of the required power is transferred to the vehicle via induction from the copper coils in the motorway, which are connected to the grid. Experts stated that all electrical components necessary for realizing dynamic inductive driving amount to 20,000-30,000 euro. This comprises the electric motor, receiver coil, controller and converters, etc. Based on this 25,000 euro for ARS, grid connection and electric motor in 2012 is assumed. Additional required systems (ARS), which are the controller and converters, amount to 9,100 euro in 2012. The cost for the electric motor in 2012 is 6,650 euro. Thus, the difference between the total assumed costs less costs for electric motor and less costs for the additional required systems are the estimated costs for the grid connection which amount to 9,250 euro in 2012. Future grid connection costs are assumed to decline mainly due to technology improvement and economies of scale as illustrated in Table 19.

The additional battery capacity of 166 kWh allows pure electric last mile operations without grid connection within a radius of 30 km when fuel consumption is assumed to be 2.21 kWh/km from the battery, as described previously. Battery capacity declines to 152 kWh in 2020 and 137 kWh in 2030 due to estimated fuel consumption improvements.

Applying the specific cost rates of Table 14, the production costs results in 159,588 euro in 2012, 118,540 euro in 2020 and 101,097 euro in 2030.

[14] Last mile delivery is, therefore, defined as a 30 km operation radius.

Table 19 DI-GIV long haul vehicle production costs

Long haul vehicle production costs		DI-GIV		
		2012	2020	2030
Total vehicle costs	(€2010)	159,588	118,540	101,097
Vehicle				
Glider	(€2010)	60,000	60,000	60,000
ARS*	(€2010)	9,100	7,525	5,950
Drivetrain				
Grid connection	(€2010)	9,250	8,525	7,800
Electric motor	(€2010)	6,650	5,950	5,250
Power	(kW)	350	350	350
Storage system				
Battery	(€2010)	74,588	36,540	22,097
Capacity	(kWh)	166	152	137
Fuel tank	(€2010)	-	-	-

* Additional required BEV systems.

Overhead catenary grid-integrated long haul vehicle

The same concept as described previously in the dynamic inductive grid-integration section is assumed. Thus, the configuration of the overhead catenary grid-integrated long haul vehicle is approximately 2.4 times more expensive than the reference ICE-DICI vehicle in 2012; see Table 20.

The overhead catenary grid connection contains similar parts as the dynamic inductive grid connection like controllers and converters, etc. Hence, cost differences in comparison to the dynamic inductive vehicle originate only due to additional costs for the very complex pantograph (contact-based current collector). Experts say that the overall cost of the whole equipment, which includes the pantograph, the electric motor/generator as well as the controller and converters, are in the mid five-digit euro area. The future target is 20,000 Euro within the next 10 years. Thus, in this configuration, the costs for the named equipment are at 55,750 euro in 2012 and assumed to be 21,200 euro in 2030. Through linear interpolation, 36,808 euro are assumed in 2020.

The OC-GIV is also dependent on a dedicated wayside energy supply infrastructure, the overhead catenary system. The main portion of the required power is transferred to the vehicle via the pantograph from the overhead catenary wire, which is connected to the grid. The additional battery capacity of 166 kWh takes 80% depth of discharge into account and allows pure electric last mile operations without grid connection within a radius of 30 km, as described before, when fuel consumption is assumed to be 2.21 kWh/km from the battery, which is the same as for the DI-GIV. Battery capacity declines due to fuel consumption improvements to 152 kWh in 2020 and 137 kWh in 2030.

Applying the specific cost rates of Table 14, the production costs result in 190,338 euro in 2012, 133,348 euro in 2020, and 103,297 euro in 2030.

Table 20 **OC-GIV long haul vehicle production costs**

Long haul vehicle production costs		OC-GIV		
		2012	2020	2030
Total vehicle costs	(€2010)	190,338	133,348	103,297
Vehicle				
Glider	(€2010)	60,000	60,000	60,000
ARS*	(€2010)	9,100	7,525	5,950
Drivetrain				
Grid connection	(€2010)	40,000	23,333	10,000
Electric motor	(€2010)	6,650	5,950	5,250
Power	(kW)	350	350	350
Storage system				
Battery	(€2010)	74,588	36,540	22,097
Capacity	(kWh)	166	152	137
Fuel tank	(€2010)	-	-	-

* Additional required BEV systems.

Fuel cell hybrid electric long haul vehicle

The fuel cell hybrid electric vehicle configuration is shown in Table 21. The main power unit is the fuel cell system and the additional battery is regulated at high state of charge (SOC) percentages (i.e. between 70 and 90%) to buffer high peak power demand and to enhance battery life. Battery capacity chosen within this report is 5 kWh, the same as distribution trucks. Different capacities between the distribution and long haul truck may be possible but require a definition of the underlying cycle profile regarding altitude or velocity, for example, to understand the overall recuperation energy potential.

The configuration is approximately 5.6 times more expensive compared to the ICE-DICI. The high costs of 443,962 euro in 2012 are mainly due to the cost intensive fuel cell system.

Fuel consumption improvements are considered within the required storage capacities over time. The FCHEV production costs in 2020 and 2030 are 176,005 euro and 119,436 euro respectively.

Table 21 **FCHEV long haul vehicle production costs**

Long haul vehicle production costs		FCHEV		
		2012	2020	2030
Total vehicle costs	(€2010)	443,962	176,005	119,436
Vehicle				
Glider	(€2010)	60,000	60,000	60,000
ARS*	(€2010)	6,650	5,600	4,550
Drivetrain				
Fuel cell system	(€2010)	292,500	57,000	24,000
Power	(kW)	300	300	300
Electric motor	(€2010)	6,650	5,950	5,250
Power	(kW)	350	350	350
Storage system				
Battery	(€2010)	2,250	1,200	805
Capacity	(kWh)	5	5	5
Hydrogen storage	(€2010)	75,912	46,255	24,831
Capacity	(kWh)	2,920	2,570	2,483

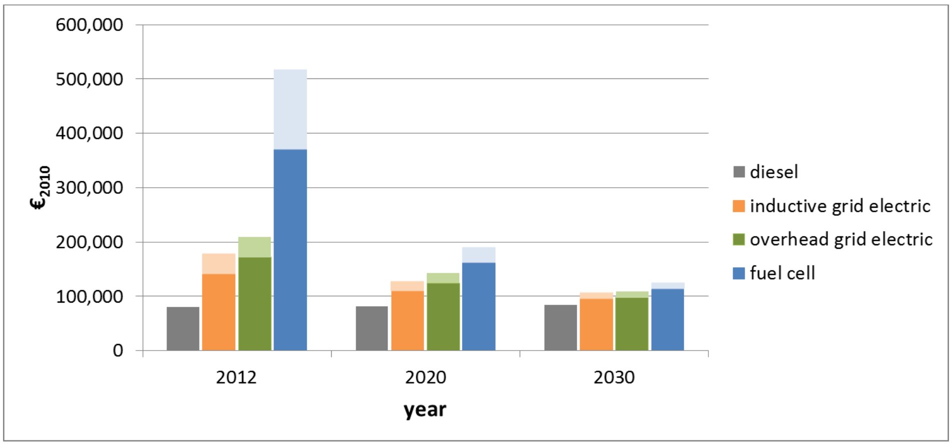
* Additional required FCHEV systems.

3.1.4 Overview of long haul truck production costs development

Figure 35 shows an aggregated overview of the different long haul truck production costs. Due to an existing uncertainty of production, costs of the main influencing components were varied. The battery and the fuel cell system costs outlined in Table 14 were changed by ± 25%. The bright bars reflect the high cost (+25%) scenario and the dark bars reflect the low cost (-25%) scenario. As illustrated, the margin of uncertainty is currently very high and will decrease over time as will the overall production costs. In addition, the main impact of the variation is related to the fuel cell hybrid vehicle due to the different configuration in comparison to the grid-integrated vehicles.

The production costs of the alternative vehicles decrease by 2030 but do not reach the ICE reference vehicle level. Fuel cell hybrid average production cost (illustrated in the tables above) decrease from approximately 5.6 times higher in 2012 to approximately 1.4 times higher in comparison to the ICE reference vehicle in 2030. Grid integrated vehicle production costs converge nearly on the ICE reference vehicle level by 2030. The immense difference between the grid integrated vehicles and the fuel cell hybrid electric vehicle is due to the specific concept and the specific configuration. The OC-GIV in comparison to the DI-GIV is more cost intensive due to the high costs of the pantograph.

Figure 35 Long haul truck production cost development



Note: The bright bars denote the high cost (+25%) scenario and the dark bars the low cost (-25%) scenario.

3.2 Fixed costs

Total costs of ownership of the vehicle are split into fixed and running costs. Fixed costs in this report include the annualized capital costs, the motor vehicle tax and insurance costs.

Table 22 shows an overview of the assumptions and methods concerning the fixed costs in this report.

Table 22 **Overview of fixed cost assumptions and methods used**

	Delivery truck (7.5 ton-16 ton)	Long haul truck (40 ton)
Vehicle lifetime	10 years	8 years
Annualized capital	Annuity method	
Interest rate	4%	
Retail Price Equivalent factor (RPE)	1.53	
Motor vehicle tax	0.01 €/km	
Insurance	1.5% per year of the vehicle retail price	

Annualized capital costs

The annualized capital costs are calculated using the annuity method, see Equation 1. The residual value is set to zero.

Equation 1 **Annualized capital**

$$Annualized\ capital = \sum_{z=1}^{k} I_z * (ANF_{n,i})_z$$

with: $I = C * RPE = retail\ price$

$C = production\ costs$

$RPE = retail\ price\ equivalent\ multiplier$

$i = interest\ rate$

$n = specific\ life\ time$

$ANF_{n,i} = \frac{(1+i)^n * i}{(1+i)^n - 1} = annuity\ factor$

$z = number\ of\ specific\ components$

$k = maximum\ number\ of\ components\ required$

The annualized capital is the sum over the product of different retail prices and the specific annuity factors. The latter is a theoretical annual regular payment being a function of specific lifetime and interest rate. The interest rate is set to 4%.

Based on statistical data from the ANFAC[15], the life of heavy-duty vehicles is less than 10 years (Tosca, 2008). This is in line with statistical data from the German Federal Transport Authority (KBA)[16] giving an average lifetime of a heavy-duty vehicle of 7.6 years (KBA, 2012). Thus, vehicle lifetime of 8 years is assumed for the long haul vehicle in this report. A vehicle life of 10 years is given for conventional distribution vehicles in GEMIS (2009).

Referring to interviews with battery manufacturers, current battery lifetime is 1,000-2,000 cycles. In Europe (EU 27), average yearly working days are 260 days[17] based on EUF (2011). Thus, battery lifetime is expected to be 6 years,[18] based on this average. Within the next 5 years, interviewed experts expect 4,000 cycles, equivalent to a battery lifetime of 15 years. Note the expected

15 Asociación Española de Fabricantes de Automóviles y Camiones.

16 Kraftfahrt-Bundesamt.

17 Average yearly working days (260 days) = Average yearly working hours (1,976 hours) divided by average daily working hours (7.6 hours).

18 Battery lifetime = Average of 1,500 cycles divided by 260 average yearly working days.

battery lifetimes are calculated for the case of one cycle per day. Taking the lifetime expectations above into account, the battery needs to be replaced for the current vehicles but not for the vehicle calculations regarding the years 2020 and 2030.

Fuel cell lifetime has reached 10,000 hours of real world operation as shown in Section 2.4.1. Fuel cell operation hours necessary in this study for distribution trucks are 10,400 hours.[19] Thus, fuel cell system replacement is required for the actual fuel cell hybrid vehicle. Regarding the vehicles in 2020 and 2030, fuel cell system replacement is not taken into account due to anticipated improvements in terms of durability. Fuel cell operation hours necessary in this study for long haul trucks are 14,560 hours.[20] Hence, fuel cell system replacement is required for the actual fuel cell hybrid vehicle as well as for the 2020 vehicle. In 2030, fuel cell system replacement is not taken into account due to the anticipated improvements.

Retail prices are gained via multiplication of the vehicle production costs with the retail price equivalent multiplier (RPE). The RPE is historically based and compares the direct manufacturing costs with all other cost factors like dealer support, research and development or profit margins which are difficult to allocate but influence the final price of a vehicle. Unfortunately, there are no studies that investigate RPE for commercial vehicles.

For passenger cars, the U.S. Environmental Protection Agency (EPA) reported the industry-weighted average RPE in 2007 was 1.46 (EPA, 2009). Other papers give an RPE for commercial vehicles of 1.49 (Tosca, 2008) and 1.66 (NAP, 2010). The average of 1.53 is used within this report.

Motor vehicle tax

Tax burdens of conventional commercial vehicles depend mainly on the gross vehicle weight, and the emission and noise classes. For simplification reasons, vehicle tax for the conventional vehicles is assumed to be 0.01 €/km (NANUPOT, 2010). For the alternative drivetrain vehicles the tax is adopted, as current legislation does not differ from the conventional vehicles. Of course, the drivetrains investigated are zero tailpipe emission vehicles operating at a lower noise level. Lower tax levels (or subsidies) may, therefore, be realistic.

Insurance

Annual insurance costs are assumed to be 1.5% of the vehicle retail price (Tosca, 2008). This approach takes the higher risk of a new technology into account, leading to higher insurance costs for the alternative vehicle configurations.

[19] Fuel cell required operation hours for the distribution truck: 520,000 km over lifetime divided by average velocity of 50 km/h.

[20] Fuel cell required operation hours for the long haul truck: 1,135,680 km over lifetime divided by average velocity of 78 km/h.

3.3 Running costs

Running costs
to hubs. Thus, average speed is 78 km/h.[21]
Assuming 4 hours[22] of daily driving regarding the distribution truck annual distance traveled is 52,000 km.[23] For the long haul truck annual mileage is 141,960 km[24] assuming 7 hours[25] of daily driving. Maximum daily driving hours for truck drivers restricted in the European Union are 9 hours (RSA, 2013).

Annual fuel costs

The assumed fuel consumptions regarding the different vehicle configurations are shown in Table 24. Fuel consumption regarding the grid-integrated vehicles (DI-GIV and OC-GIV) is assumed to be higher in comparison to the battery electric vehicles (BEV – 2 kWh/km for long haul trucks based on MAN, 2012) due to the dynamic loading via induction or catenary wires is not very efficient. Thus, efficiency loss of 10% is assumed, which lead to an overall tank-to-wheel within this report include annual expenses for fuel, maintenance and repair, tires, tolls and driver wages. Table 23 shows an overview of the assumptions.

Table 23 Overview of running cost assumptions

	Delivery truck (7.5 t-16 t)	Long haul truck (40 t)
Annual distance traveled	52,000 km	141,960 km
Annual Fuel costs	See Table 24, Table 25 and Table 26	
Driver wage (incl. 50% indirect labour costs)	28,800 €/a	55,800 €/a
Maintenance and repair	0.06 €/km (ICE) 0.04 €/km (BEV) 0.04 €/km (FCHEV)	
Tires	0.01 €/km	
Toll	0.169 €/km	0.183 €/km

Annual distance traveled

The EU 27 yearly working days are 260 days with an average working hours of 7.6 hours per day and 1,976 hours per year (EUF, 2011).

Average speed of the distribution vehicle within Europe is approximately 50 km/h (ERC, 1999). The underlying concept for long haul trucks is that they mainly operate on motorways, with an assumption of 80% and an average speed of 85 km/h.[26] To a small part, an assumption of 20%, long haul trucks operate on local streets with an average speed of 50 km/h during delivery (30 km radius of operation) efficiency of 66% instead of 73%.

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21 Average speed: 85 km/h*0.8 + 50 km/h*0.2 = 78 km/h.

22 It is estimated that cargo pick-up and drop-off time are 3.6 hours a day.

23 Annual milage distribution truck: 50 km/h*4h*260 working days/year = 52,000 km/year.

24 Annual milage long haul truck: 78 km/h*7h*260 working days/year = 141,960 km/year.

25 It is estimated that pick-up and drop-off time are 2 hours a day.

26 In reference to (ERC, 1999).

Table 24 **Assumed fuel consumptions regarding different vehicle configurations for 2012**

Fuel consumption		Distribution truck (7.5-16 t)	Long haul truck (40 t)
ICE - DICI[1]	(kWh/100 km)	179 (18 l diesel)	348 (35 l diesel)
BEV[2]	(kWh/100 km)	100	-
DI-GIV[3]	(kWh/100 km)	-	221
OC-GIV[3]	(kWh/100 km)	-	221
FCHEV[4]	(kWh/100 km)	146	292

1 Calculation values: 0.83 kg/l; 11.97 kWh/kg; fuel consumption as illustrated in Section 2.1.
2 MAN, 2012.
3 Own assumption see above.
4 Own calculation (see Section 2.4.1).

Truck fuel consumption has declined 1.1% per year on average since 1995, according to DAIMLER (2012) on the basis of vehicle tests performed by Lastauto Omnibus. This is due to technological advances of the driveline and reduction of frictions. The EU transport model TREMOVE[27] assumes comparable reductions for the future. For the battery electric vehicles and the grid integrated vehicles, a yearly fuel reduction potential of 1% is assumed due to the current high research intensities, which is in line with Özdemir (2012). For the fuel cell hybrid electric vehicles fuel consumption reduction potential is set to 0.83% yearly based on assumed fuel consumptions in McKinsey (2012). Table 25 shows the data for relative fuel consumption. The fuel consumption reduction depicted is assumed to apply to all the different vehicle configurations. Increased drivetrain efficiency and lower air resistance may contribute most to lower fuel consumption.

Table 25 **Relative fuel consumption development over time per vkm (2012 is equivalent to 100%)**

Vehicle	2012	2020	2030
ICE[1]	100%	90%	82%
BEV[2]	100%	92%	83%
DI-GIV[3]	100%	92%	83%
OC-GIV[3]	100%	92%	83%
FCHEV[4]	100%	88%	85%

Sources: [1] TREMOVE; DAIMLER (2012); [2] Özdemir (2012); [3] same reduction as for BEV is assumed; [4] McKinsey (2012).

Table 26 shows the assumed fuel prices over the different time frames. Prices are all exclusive of value added tax (VAT). The prices for electricity and hydrogen are based on linear decarbonisation, with 75% reduction of emissions over time, as proposed by the EU energy roadmap (EC, 2011a).

27 TREMOVE is a transport model for the European Union, covering transport demand, mode shares and vehicle stock forecasts until 2030, see http://www.tremove.org/.

Table 26 **Assumed fuel prices at the filling station**

Fuels		2012	2020	2030
Diesel (including taxes, excluding VAT)	Low (€$_{2010}$/l)	1.19	1.18	1.35
	High (€$_{2010}$/l)	1.19	1.46	1.64
Electricity (including limited taxes, excluding VAT)	Low (€$_{2010}$/kWh)	0.105	0.127	0.136
	High (€$_{2010}$/kWh)	0.135	0.157	0.166
Hydrogen (excluding taxes, excluding VAT)	Low (€$_{2010}$/kg H_2)	3.29	4.77	5.23
	High (€$_{2010}$/kg H_2)	7.41	10.73	11.76

Diesel prices
The diesel price is based on the long-term correlation between the oil price (UK Brent) and the raw sales weighted EU fuel price. Excise duty has been added on the basis of the sales EU weighted excise duty.

The weighted average diesel price for 2012 has been calculated by using the long-term correlation between the oil price and the raw diesel price, using the average oil price for 2012 (110 $\$_{2012}$/barrel). The excise duty is based on the excise duty for 2010 (0.43 €$_{2010}$/l), with an assumed increase of 2% per year[28] for the following periods. The fuel price for 2020 and 2030 are based on the average long-term oil price estimates of IEA and EIA (EIA, 2012). For 2020 and 2030, the expected oil price is estimated at 120 and 130 dollar per barrel respectively. The excise duties for these years are calculated on the basis of the 2010 excise duty, assuming a yearly 2% real price increase. Since the oil price is highly volatile, depending on many (geo)political and technological factors and thus difficult to predict. Therefore, an uncertainty range of 25 $\$_{2012}$/barrel is used.

Table 27 **Low and high diesel price estimates for this study (corresponding oil price between brackets)**

	Average in €$_{2010}$/l	Low estimate in €$_{2010}$/l	High estimate in €$_{2010}$/l
2012		1.19 (110 $\$_{2012}$/barrel)	
2020	1.32 (120 $\$_{2012}$/barrel)	1.18 (95 $\$_{2012}$/barrel)	1.46 (145 $\$_{2012}$/barrel)
2030	1.49 (130 $\$_{2012}$/barrel)	1.35 (105 $\$_{2012}$/barrel)	1.64 (155 $\$_{2012}$/barrel)

Electricity prices
For electricity, prices strongly differ between households and industrial consumers due to higher taxes and grid costs. Based on fast charging as a starting point, the calculation is based on large consumption industrial prices. However, additional grid investment costs may have to be accounted.

The average industrial electricity price differs strongly over Europe (DG Energy, 2011) and with the type of contract. Therefore, it is difficult to define a price for electricity. Thus, two rates for electricity were used.

28 The assumed 2% real excise duty respresents a government policy with strong focus on climate change prevention. The 2% increase corresponds with 2% real income growth.

The calculated average price is 0.105 €/kWh[29] including taxes but excluding VAT, as reported by Eurostat; see Table 28. This price represents large-scale introduction of electricity for trucks through grid integration or fast plug-in charging. However, for overnight charging for small and medium sized companies, this price may be too low. Therefore, a second electricity rate of 0.135 €/kWh was used.

Table 28 EU 27 average electricity prices as reported by Eurostat (2012)

	Excluding Taxes ($€_{2010}$/kWh)	Including Taxes, excluding VAT ($€_{2010}$/kWh)
Band IA : Consumption < 20 MWh	0.148	0.168
Band IB : 20 MWh < Consumption < 500 MWh	0.108	0.123
Band IC : 500 MWh < Consumption < 2,000 MWh	0.091	0.105
Band ID : 2,000 MWh < Consumption < 20,000 MWh	0.081	0.092
Band IE : 20,000 MWh < Consumption < 70,000 MWh	0.073	0.083
Band IF : 70,000 MWh < Consumption < 150,000 MWh	0.069	0.077

Non-recoverable taxes are relatively limited, taken into account by using the prices stated above in comparison with road diesel. If the diesel taxation is applied using the same price per unit of energy carrier, the tax rate would be 0.045-0.065 €/kWh instead of 0.008-0.02 €/kWh.

Over time, electricity will need to be decarbonised. Both ECF (2011) and Eurelectric (2011) claim that the price for electricity will not necessarily increase significantly over time as a result of this process. However, the EU energy roadmap EC (2011) indicates an average price increase of 35% between 2010 and 2030, with price remaining constant after 2030. The price increase of this latter mentioned source has been applied in this study.

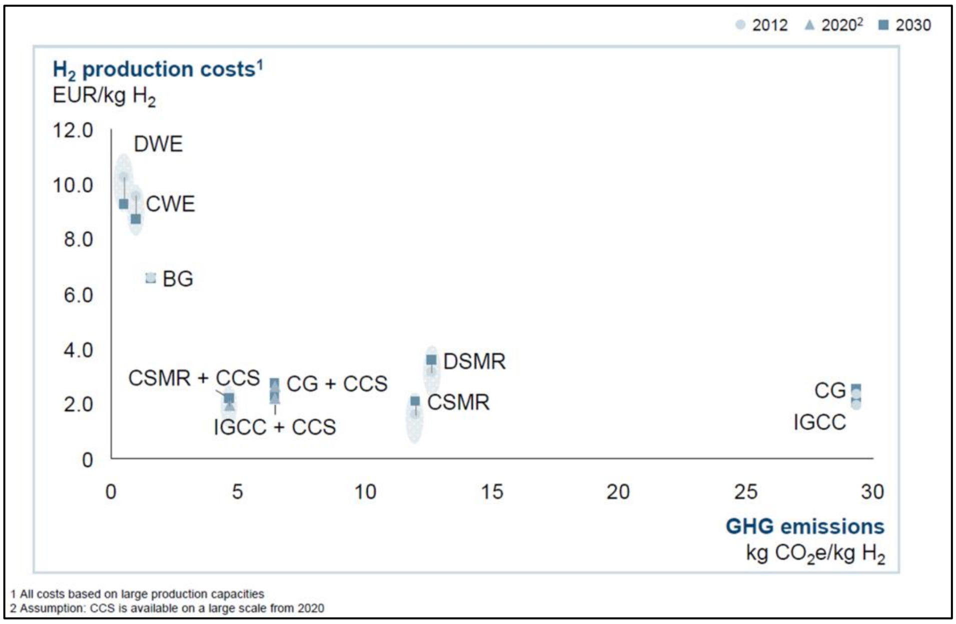
Hydrogen prices

Several literature sources provide information about the costs of hydrogen production. Hill (2010) assumes a price increase for the production of hydrogen as a result of a change from steam methane reforming (SMR) to distributed or central water electrolysis (DWE/CWE). Gül (2008) and McKinsey (2012) cite costs for hydrogen produced from renewable electricity. Figure 36 shows hydrogen production costs based on the latest study from McKinsey (2012).

Based on mature technologies, the production costs of hydrogen from biomass will be lower than hydrogen from wind electricity. Furthermore, the production costs of hydrogen produced from natural gas by CSMR or DSMR is lower to those of hydrogen produced from bio gasification (BG).

[29] This price is for consumption of 500-2,000 MWh. Taxes represent 1.4 €cents.

Figure 36 An overview of costs and GHG Emissions for all production methods

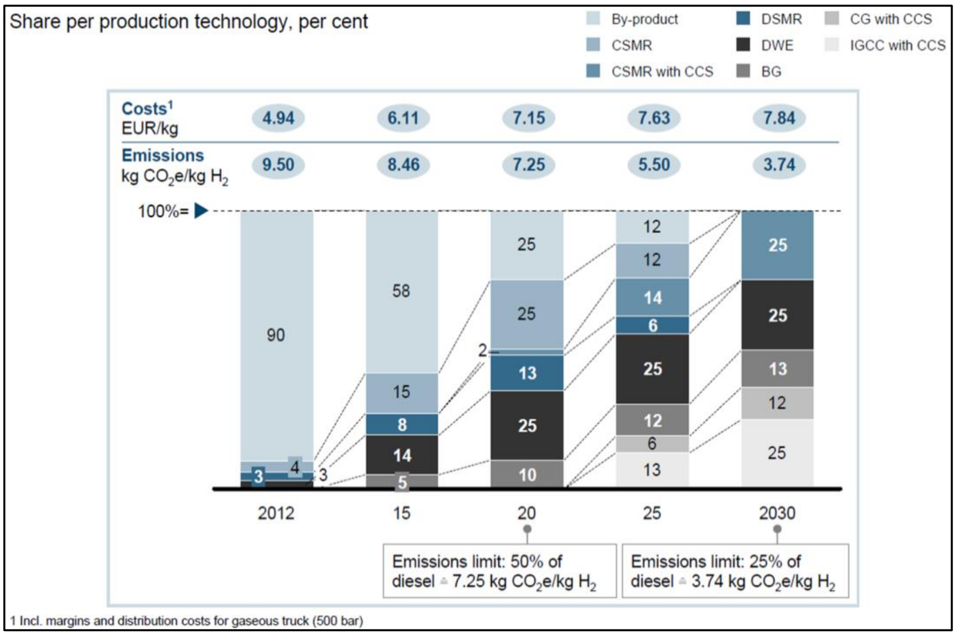


Abbreviations: CSMR: Central Steam Methane Reforming; CCS: CO_2 Capture and Storage; DSMR: Distributed Steam Methane Reforming; DWE: Distributed Water Electrolysis; CWE: Central Water Electrolysis; BG: Biomass Gasification; CG: Coal Gasification; IGCC: Integrated Gasification Combined Cycle.

Source: McKinsey, 2012.

The available literature (Hart et al., 2003; ANL, 2005; Gül, 2008; McKinsey, 2010; Hill et al., 2010; McKinsey, 2012) shows a range of data for different production processes. The older literature presents lower production costs than more recent literature. Note that these are just production costs. Therefore, latest costs calculations were based on a defined production mix from McKinsey (2012) for this study due to the costs outlined are inclusive margins and costs for distribution (500 bar truck distribution); see Figure 37. Furthermore, the costs of 4.94 euro/kgH_2 in 2012, 7.15 euro/kgH_2 in 2020 and 7.84 euro/kgH_2 in 2030, are in the mid-range of all the sources available.

Figure 37 **Overview of the hydrogen production mix used in this study**



Abbreviations: CSMR: Central Steam Methane Reforming; CCS: CO_2 Capture and Storage; DSMR: Distributed Steam Methane Reforming; DWE: Distributed Water Electrolysis; BG: Biomass Gasification; CG: Coal Gasification; IGCC: Integrated Gasification Combined Cycle.

Source: McKinsey, 2012.

For the purpose of reflection of the bandwidth in the various literature, the costs shown in Figure 37 are scaled up or down by a defined factor of 1.5 to illustrate a low and a high scenario; see Table 26.

Energy carrier taxes

The hydrogen costs cited exclude taxes, and the electricity costs represent only limited taxes in comparison with diesel. If the diesel taxes applied in this study, the taxes on electricity and hydrogen would be 0.05-0.06 €/kWh and 1.39-1.99 €/kg H_2 respectively. In Table 29 an overview of the assumed fuel taxes is given, including an assumed real price increase of 2% per year.

Table 29 **Fuel excise duties for different energy carriers**

	Diesel ($€_{2010}$/l)	Electricity ($€_{2010}$/kWh)	Hydrogen ($€_{2010}$/kg H_2)
2012	0.45	0.05	1.39
2020	0.53	0.05	1.63
2030	0.64	0.06	1.99

Note: If the taxes would all be expressed per kWh, the figures for the different energy carriers would be equal.

Driver wage

Driver wages are an integral element of the TCO calculation. An annual gross wage of 37,200 euro for long-distance truck drivers and 19,200 euro for distribution truck drivers is assumed (Bergrath, 2007 and BVT, 2004). Additional indirect labor costs, assumed to be 50% of the monthly gross wage, accrue due to expenses, vocational benefits, social contributions, etc. (BVT, 2004). This approach is to a large extent in line with the approach of the NANUPOT (2011) analysis.

Maintenance and repair

Data on costs regarding maintenance and repair of conventional vehicles were taken from an analysis of the American Transportation Research Institute (ATRI, 2011). The survey gives operation costs per mile. Maintenance and repair costs in 2012 were converted to 0.06 €/km.

In general, electrified vehicle configurations do not need as much maintenance efforts as mechanical diesel engines due to less parts being exposed to friction and associated wear and tear. Thus, maintenance and repair costs of the alternative, electrified vehicle are assumed to be lower than the ICE vehicles. Based on interviews with experts maintenance and repair costs are a third less than the ICE vehicles. Therefore, 0.04 €/km are used for the alternative vehicle configurations.

Tires

Tire costs are calculated as 0.01 €/km, based on ATRI (2011), and is used for all powertrains.

Toll

Toll costs per kilometre depend on the number of axels and on the emission class. Furthermore, these road charges vary from country to country. In this study, German toll rates were applied. The toll for distribution trucks is set to 0.169 €/km and for the long-haul truck to 0.183 €/km (BGL, 2012). Assumed distribution vehicle travel is 10,000 km per year and the long-haul truck travels 114,000 km[30] on roads subject to toll. These toll rates apply for every vehicle configuration. Differences due to environmental charges (congestion charge in London and Amsterdam) or subsidies are not taken into account.

3.4 Infrastructure costs

A comprehensive appraisal of the implementation of alternative drivetrains needs the analysis of not only the vehicle but also the required energy infrastructure. Possible zero tailpipe emission vehicle and infrastructure combinations are listed in Table 30.

As the exact investment costs are uncertain, particularly for large-scale applications, quantitative (€/km) cost estimates will not be generated for all technologies within this report. The overall cost situation is illustrated to speculate on technology specific cost ranges.

[30] 80% of yearly distance travelled on motorways and all subjected to toll.

Table 30 Vehicle - infrastructure combinations for distribution and long haul truck configurations

	Distribution trucks			Long haul trucks			
Infrastructure	ICE-DICI	BEV	FCHEV	ICE-DICI	DI-GIV	OC-GIV	FCHEV
Diesel							
Plug-In							
Battery swapping							
Dynamic inductive							
Overhead catenary							
Hydrogen							

Diesel infrastructure costs

Additional infrastructure costs do not occur for conventional diesel driven vehicles due to the assumption that all costs are allocated to the fuel price.

Plug-in charging infrastructure cost estimation

As battery electric distribution trucks are fully recharged overnight, each distribution truck will need its own charging point. One charging point for a battery electric distribution truck costs approximately 6,200 (based on data provided by one of the interviews). However, this concerns a charging facility for a BEV with a battery capacity of 120 kWh. Our reference case has a usable battery capacity of 200 kWh, so the actual costs of one charging point may be somewhat higher. Currently, the yearly maintenance costs are 35 USD for one charging point for passenger cars (Rocky Mountain Institute, 2009), which is approximately 25 euros. However, these maintenance costs may be higher for HDVs. Table 31 summarises this cost data and shows the costs per HDV-km:

Table 31 Infrastructure costs for plug-in charging

Cost item	Cost (euros)	Source/Calculation
Plug-in charging point	8,000	Data from interviewee combined with own estimate to upgrade to a higher battery capacity
Annual maintenance costs of plug-in point	125	Rocky Mountain Institute (2009) combined with own estimate to upgrade to higher power transfer of HDVs
Total costs of infrastructure over lifetime of vehicle (10 years)	9,250	8,000/10 is 800 investment costs per year. (800+125) * 10 = 9,250
Total costs per HDV kilometer (52.000 km per year)	0.02 euro/km	9,250/(10*52.000)

Battery swapping infrastructure cost estimation

Not much is known about the costs of building one battery swap station that can (also) be used by HDVs. For passenger cars, it is argued that the costs of building one automated swap station are about 3 million USD (NY Times, 2011), which is approximately 2.2 million euros. It is unclear how much capacity this swap station has and the costs factors included in this figure (Table 32). It may be the case that the costs for a similar station for HDVs will be higher, as the batteries are larger and heavier.

The overall infrastructure costs then depend on the number of stations that are needed, which in turn is influenced by the size of the country and its urban areas, the number of distribution trucks, and other relevant aspects.

Table 32 **Infrastructure costs for battery swap infrastructure**

Cost item	Cost	Source
Battery swap station	3.2 million euros	NY times (2011) Own estimate to upgrade to a HDV swapping station
Costs of ensuring a stock of charged batteries	Information not available	
Energy infrastructure annual maintenance costs	1-2.5% of initial investment cost per year	Own estimate (life expectancy: 20 years)

Overhead catenary infrastructure cost estimation
In general, an overhead catenary system provides continuous energy transfer to the vehicles. Considerably expensive wayside energy infrastructure is necessary. In addition, the infrastructure may not be fully utilized to a high degree, as not all trucks can be expected to be catenary vehicles on an electrified road. The overhead catenary technology for on-road vehicles is not new, as mining trucks and trolley busses have been in operation for more than a couple of decades. However, mainly due to higher speeds, highway operable trucks need adapted technologies (active pantograph).

The infrastructure costs of equipping two highway lanes with an overhead catenary and building up an energy supply infrastructure (substations, connection to the grid, transformers and rectifiers) is estimated to be in the range of 2–3 million € per km in total, based mainly on Siemens' estimations. Maintenance costs of the wayside equipment range from 1 to 2.5% of the initial catenary and energy supply investment costs. See Table 33.

Table 33 **Overhead Catenary System Costs**

Cost item	Cost	Source
Energy infrastructure investment costs	2-3 Mio. euro/km	Trafikverket, 2012 GNA, 2012 SRU, 2012
Energy infrastructure annual maintenance costs	1-2.5% of initial investment cost per year	Own estimate (life expectancy: 20 years)

Dynamic inductive infrastructure cost estimation
There are no cost estimates available on dynamic inductive charging. Several studies do point out that these costs will be high (Chawla and Tosunoglu, 2012). It is assumed that the costs will be in the same order of magnitude as the overhead catenary wire, as the interviewees on this topic argued that the energy supply to the road is the main cost driver, which is also the case for the overhead catenary system. The costs per km may be somewhat higher in reality, considering that the changes that need to be made to the existing infrastructure will be more invasive, as some aspects of the inductive charging infrastructure needs to be placed underground, compared to the catenary wire, which can be added to existing roads. However, it will not be necessary to electrify the whole road network, but only a small portion (Lee, 2012). According to the interviewees, approximately 50% would be sufficient. This

will reduce the total investment costs needed significantly. Further reducing the overall costs of the investment is the fact that inductive charging systems have low maintenance costs, as there is no wear and tear of components (AEA, 2010). The assumed costs are shown in Table 35.

Table 34 **Infrastructure costs for dynamic inductive charging**

Cost item	Cost	Source
Energy infrastructure investment costs	2-3 Mio. euro/km (for 50% of the network)	Trafikverket, 2012 GNA, 2012 SRU, 2012 Interview data
Energy infrastructure annual maintenance costs	1% of initial investment cost per year	Own estimate (life expectancy: 20 years)

Hydrogen infrastructure cost estimation

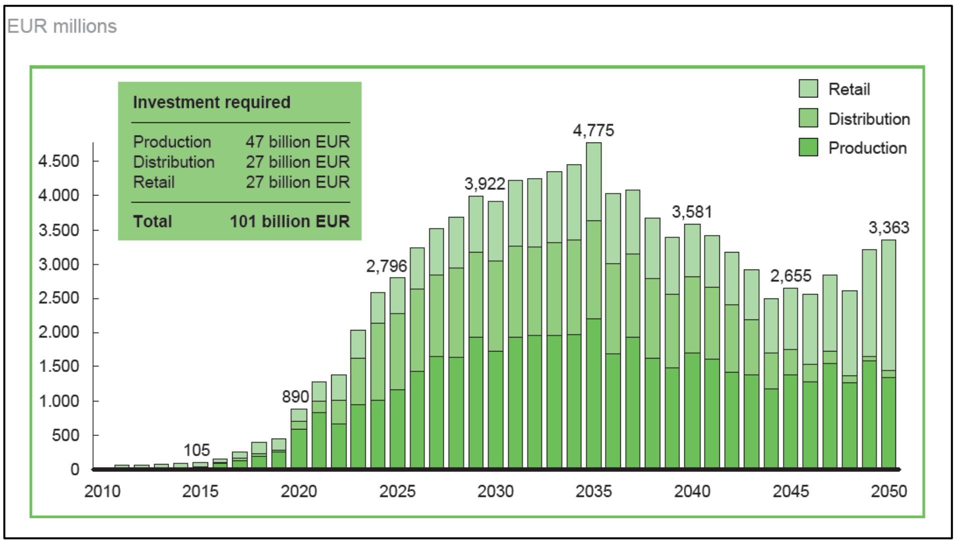
Hydrogen infrastructure costs are very difficult to estimate as different production pathways, delivery options, and plant installations/ capacity utilization methods exist. Furthermore, as the hydrogen technology is still in the development phase and has not yet been implemented in a larger scale, experience on costs is very rare. However, total costs of ownership for passenger cars have been investigated by leading industrial companies and organisations supported by McKinsey. Participants of the study were Daimler, BMW, Vattenfall, Linde Group, Air Liquide, European Climate Foundation European Fuel Cells, Hydrogen Joint Undertaking (FCH JU), NOW GmbH, etc.

The study showed that the costs for a hydrogen infrastructure are approximately 5% of the passenger vehicle TCO (McKinsey, 2010), equivalent to 1,000–2,000 euro per passenger vehicle. Therefore, the business case of FCHEVs is hardly affected by the additional costs of the infrastructure. Unfortunately, the aggregated results are based on confidential data, making it impossible to reproduce.

In the following calculations, the illustrated hydrogen costs (in Section 3.3) includes margin and distribution (500 bar truck distribution) costs and thus not all existing infrastructure costs (costs for fuelling station for example) are allocated to the hydrogen price.

Total investments for large scale commercialization of hydrogen supply infrastructure required for Europe are shown in Figure 38. 100 billion euros over 40 years are estimated to be necessary (McKinsey, 2010). However, the number of stations assumed for that scenario is not stated. These figures are based on a 25% market share of fuel cell passenger vehicles in Europe until 2050 (McKinsey, 2010).

Figure 38 Total capital investment for large-scale roll-out of hydrogen supply infrastructure in Europe



Source: McKinsey, 2010.

3.5 Total Costs of ownership

In contrast to the rising oil price, battery and fuel cell system costs are expected to decline due to economies of scale and learning effects over time. This is the main reason why alternative technologies could become competitive in the future.

A TCO analysis for the reviewed distribution and long haul truck drivetrains is performed below. Two scenarios, one with low fuel price and low component (only for battery capacity and fuel cell system) cost estimations and the other with high fuel price and high component (only for battery capacity and fuel cell system) cost estimations were calculated. This is due to the unclear future development and thus should illustrate possible bandwidths over time.

The different fuel prices are outlined in Section 3.3 and the basic component costs of variation (± 25%) are outlined in Section 3.1. In the following, the low and high scenarios are illustrated and discussed in detail.

3.5.1 Distribution trucks

Table 35 shows the calculation results (low and high scenarios) for the distribution truck taking the year 2012 as basis. In the low and high scenarios at present, TCO of the zero tailpipe emissions drivetrains are not competitive in comparison to the ICE. The total costs of ownership of the BEV and the FCHEV in the low scenario are 35 and 37% higher in comparison to the ICE reference vehicle. This is due to the high retail prices caused by the technology costs of the battery and the fuel cell system. Furthermore, lower operational costs, particularly fuel costs, of the battery and the fuel cell hybrid electric vehicles do not outweigh the higher retail price.

The TCO of the BEV and the FCHEV in the high scenario are 69 and 83% higher in comparison to the ICE reference vehicle. Greater annual fixed costs and depending on the energy carrier, little lower or higher operating costs, are the main reason for this development. Note that the fuel calculations are based on the assumed fuel prices shown in Section 3.3.

Table 35 TCO distribution truck calculation results for 2012 (€$_{2010}$)

		low scenario			high scenario		
TCO Distribution Truck		2012			2012		
	unit	**ICE-DICI**	**BEV**	**FCHEV**	**ICE-DICI**	**BEV**	**FCHEV**
life time	year	10	10	10	10	10	10
Travelled distance per year	km/a	52,000	52,000	52,000	52,000	52,000	52,000
Retail price	€	74,052	200,621	251,992	74,052	286,684	365,595
Fixed costs							
Annualized capital	€/a	9,130	33,445	31,910	9,130	49,862	46,478
Motor vehicle tax	€/a	520	520	520	520	520	520
Insurance	€/a	1,111	3,009	3,780	1,111	4,300	5,484
Total fixed costs	€/a	10,761	36,974	36,210	10,761	54,683	52,482
Running costs							
Fuel	€/a	11,138	5,460	7,528	11,138	7,020	16,954
Driver wages incl. Indirect labor costs	€/a	28,800	28,800	28,800	28,800	28,800	28,800
Maintenance and repair	€/a	3,120	2,080	2,080	3,120	2,080	2,080
Tires	€/a	520	520	520	520	520	520
Toll	€/a	1,690	1,690	1,690	1,690	1,690	1,690
Total running costs	€/a	45,268	38,550	40,618	45,268	40,110	50,044
Total Costs of Ownership vehicle	€/a	56,029	75,524	76,828	56,029	94,793	102,526
Total Costs of Ownership vehicle	€/km	1.08	1.45	1.48	1.08	1.82	1.97
Total Costs of Ownership vehicle differences	%	100	135	137	100	169	183

Note: TCO of the vehicle only. Infrastructure costs are not included for BEV and FCHEV.

The calculation results for the year 2020 are illustrated in Table 36. It is seen that due to raising production units of the battery and the fuel cell systems, retail price cost differences in comparison to the conventional vehicle decline in a radical manner. In the low scenario, TCO of the BEV and the FCHEV differ at 6% compared to the reference vehicle. Thus, battery electric vehicles and FCHEV are nearly competitive despite 1.8 times and 1.45 times higher retail prices. Main reason for this trend is the price decline assumption shown in Table 14. The fuel cell system costs declines faster than the battery costs, whereas the costs for operation, especially the fuel costs of the BEV, are much lower in comparison to the FCHEV costs. This is mainly caused by the lowest price increase over time for electricity. The assumed hydrogen prices in Table 26 are subjected to the highest percental increase. Furthermore, the lowest fuel consumption improvement potential for FCHEV is assumed (see Table 25).

In the high price scenario, the BEV is not competitive due to a 2.3 times higher retail price. Fuel costs savings do not outweigh the higher annual capital costs. The FCHEV is also not competitive due to the greater annual and greater fuel costs.

Table 36 **TCO distribution truck calculation results for 2020 (€$_{2010}$)**

		low scenario			high scenario		
TCO Distribution Truck		2020			2020		
	unit	**ICE-DICI**	**BEV**	**FCHEV**	**ICE-DICI**	**BEV**	**FCHEV**
life time	year	10	10	10	10	10	10
Travelled distance per year	km/a	52,000	52,000	52,000	52,000	52,000	52,000
Retail price	€	75,735	133,378	109,959	75,735	175,606	132,679
Fixed costs							
Annualized capital	€/a	9,337	16,444	13,557	9,337	21,651	16,358
Motor vehicle tax	€/a	520	520	520	520	520	520
Insurance	€/a	1,136	2,001	1,649	1,136	2,634	1,990
Total fixed costs	€/a	10,993	18,965	15,726	10,993	24,805	18,868
Running costs							
Fuel	€/a	9,940	6,076	9,599	12,299	7,511	21,593
Driver wages incl. Indirect labor costs	€/a	28,800	28,800	28,800	28,800	28,800	28,800
Maintenance and repair	€/a	3,120	2,080	2,080	3,120	2,080	2,080
Tires	€/a	520	520	520	520	520	520
Toll	€/a	1,690	1,690	1,690	1,690	1,690	1,690
Total running costs	€/a	44,070	39,166	42,689	46,429	40,601	54,683
Total Costs of Ownership vehicle	€/a	55,064	58,131	58,415	57,423	65,406	73,551
Total Costs of Ownership vehicle	€/km	1.06	1.12	1.12	1.10	1.26	1.41
Total Costs of Ownership vehicle differences	%	100	106	106	100	114	128

Note: Only TCO regarding the vehicle. Infrastructure costs are not included for BEV and FCHEV.

In 2030, BEV vehicle cost regarding the low scenario on a per-km base are 3% less than the costs regarding the reference vehicle (see Table 37). The TCO of the FCHEV are at the ICE reference vehicle level in 2030. Thus, the alternative drivetrains especially the BEV will become seriously competitive. The main driver behind it is the strong reduction of the battery and fuel cell system costs as well as the stronger rise of the diesel fuel costs compared to the costs of electricity whereas the hydrogen costs are subjected to the highest percental increase, as described previously. Nevertheless, FCHEV fuel costs are slightly lower than the reference vehicle ones. Hence, crucial factors are fuel price as well as production cost developments. Ultimately, the retail price of the reference ICE vehicle is still the lowest one.

In the high scenario the BEV is seriously competitive as well, whereas the FCHEV still is not. The high hydrogen fuel costs lead to the loss of competitiveness.

Table 37 **TCO distribution truck calculation results for 2030 (€$_{2010}$)**

		low scenario			high scenario		
TCO Distribution Truck		2030			2030		
	unit	**ICE-DICI**	**BEV**	**FCHEV**	**ICE-DICI**	**BEV**	**FCHEV**
life time	year	10	10	10	10	10	10
Travelled distance per year	km/a	52,000	52,000	52,000	52,000	52,000	52,000
Retail price	€	77,342	106,879	86,134	77,342	132,436	95,930
Fixed costs							
Annualized capital	€/a	9,536	13,177	10,620	9,536	16,328	11,827
Motor vehicle tax	€/a	520	520	520	520	520	520
Insurance	€/a	1,160	1,603	1,292	1,160	1,987	1,439
Total fixed costs	€/a	11,216	15,300	12,432	11,216	18,835	13,786
Running costs							
Fuel	€/a	10,362	5,870	10,171	12,587	7,165	22,871
Driver wages incl. Indirect labor costs	€/a	28,800	28,800	28,800	28,800	28,800	28,800
Maintenance and repair	€/a	3,120	2,080	2,080	3,120	2,080	2,080
Tires	€/a	520	520	520	520	520	520
Toll	€/a	1,690	1,690	1,690	1,690	1,690	1,690
Total running costs	€/a	44,492	38,960	43,261	46,717	40,255	55,961
Total Costs of Ownership vehicle	€/a	55,707	54,260	55,693	57,933	59,089	69,747
Total Costs of Ownership vehicle	€/km	1.07	1.04	1.07	1.11	1.14	1.34
Total Costs of Ownership vehicle differences	%	100	97	100	100	102	120

Note: Only TCO regarding the vehicle. Infrastructure costs are not included for BEV and FCHEV.

3.5.2 Long haul trucks

Table 38 illustrates the long haul vehicles TCO in 2012. In the low scenario, the grid-integrated vehicles are currently superior to the ICE in spite of the 1.8 (DI-GIV) and 2.2 (OC-GIV) times higher retail prices. The fuel costs are nearly half of the conventional vehicle fuel costs. Therefore, it is taken into account that the results of the grid-integrated vehicles are strongly linked to the best guess configuration regarding these vehicles illustrated in Section 3.1.3. The battery capacity sufficiently allows battery-operation within a 30 km radius. Thus, the chosen configuration may not fully replace a conventional ICE vehicle in terms of driving dynamics and will nearly always need a continuous external power supply for driving (80% of its driving operations). It needs also to be taken into account that the infrastructure costs are not included or allocated in this calculation.

Considering the infrastructure-dependency of the grid-integrated vehicles in the full road-network, the lower costs per km may no longer be advantageous. The fuel cell hybrid electric vehicle is to 41% more expensive compared to the ICE reference vehicle and thus not competitive due to the high retail price. Lower operational costs, in particular fuel costs, of the FCHEV vehicle do not outweigh the higher retail price.

In the high price scenario, the DI-GIV is nearly on the same TCO level as the reference vehicle whereas the OC-GIV and the FCHEV is not competitive.

Table 38 TCO long haul Truck calculation results for 2012 (€$_{2010}$)

		low scenario				high scenario			
TCO long haul Truck		2012				2012			
	unit	**ICE-DICI**	**DI-GIV**	**OC-GIV**	**FCHEV**	**ICE-DICI**	**DI-GIV**	**OC-GIV**	**FCHEV**
life time	year	8	8	8	8	8	8	8	8
Travelled distance per year	km/a	141,960	141,960	141,960	141,960	141,960	141,960	141,960	141,960
Retail price	€	122,094	215,639	262,687	566,521	122,094	272,699	319,746	792,004
Fixed costs									
Annualized capital	€/a	18,134	35,643	42,631	103,593	18,134	46,528	53,516	150,050
Motor vehicle tax	€/a	3,420	1,420	1,420	1,420	3,420	1,420	1,420	1,420
Insurance	€/a	1,831	3,235	3,940	8,498	1,831	4,090	4,796	11,880
Total fixed costs	€/a	23,385	40,297	47,991	113,511	23,385	52,038	59,732	163,350
Running costs									
Fuel	€/a	59,126	32,942	32,942	40,913	59,126	42,354	42,354	92,149
Driver wages incl. indirect labor costs	€/a	55,800	55,800	55,800	55,800	55,800	55,800	55,800	55,800
Maintenance and repair	€/a	8,518	5,678	5,678	5,678	8,518	5,678	5,678	5,678
Tires	€/a	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Toll	€/a	20,862	20,862	20,862	20,862	20,862	20,862	20,862	20,862
Total running costs	€/a	145,726	116,702	116,702	124,673	145,726	126,114	126,114	175,909
Total Costs of Ownership vehicle	€/a	169,111	156,999	164,693	238,184	169,111	178,152	185,845	339,258
Total Costs of Ownership vehicle	€/km	1.19	1.11	1.16	1.68	1.19	1.25	1.31	2.39
Total Costs of Ownership vehicle differences	%	100	93	97	141	100	105	110	201

Note: Only TCO regarding the vehicle. Infrastructure costs are not included for DI-GIV, OC-GIV and FCHEV.

Calculation results for 2020 are shown in Table 39. The configurations with the lowest costs per kilometre are the grid-integrated vehicles for both scenarios and is mainly due to the chosen vehicle configuration explained above. The costs for the fuel cell hybrid electric vehicle converge toward the reference vehicle. The TCO of the FCHEV in the low scenario is 11% higher compared to 46% higher in the high scenario in comparison to the ICE reference vehicle. The differences result mainly from the high costs of the fuel cell technology and thus retail price is approximately 2 times (low scenario) and 2.3 times (high scenario) higher. The fuel costs in the low scenario are nearly the same but in the high scenario, fuel costs are nearly twice the reference vehicle fuel costs.

Table 39 TCO long haul Truck calculation results for 2020 (€$_{2010}$)

		low scenario				high scenario			
TCO long haul Truck		2020				2020			
	unit	**ICE-DICI**	**DI-GIV**	**OC-GIV**	**FCHEV**	**ICE-DICI**	**DI-GIV**	**OC-GIV**	**FCHEV**
life time	year	8	8	8	8	8	8	8	8
Travelled distance per year	km/a	141,960	141,960	141,960	141,960	141,960	141,960	141,960	141,960
Retail price	€	125,843	167,390	190,046	247,027	125,843	195,343	217,999	291,550
Fixed costs									
Annualized capital	€/a	18,691	24,862	28,227	40,459	18,691	29,014	32,379	49,585
Motor vehicle tax	€/a	3,420	1,420	1,420	1,420	3,420	1,420	1,420	1,420
Insurance	€/a	1,888	2,511	2,851	3,705	1,888	2,930	3,270	4,373
Total fixed costs	€/a	23,998	28,792	32,497	45,584	23,998	33,364	37,069	55,378
Running costs									
Fuel	€/a	52,767	36,599	36,599	52,208	65,287	45,244	45,244	117,441
Driver wages incl. indirect labor costs	€/a	55,800	55,800	55,800	55,800	55,800	55,800	55,800	55,800
Maintenance and repair	€/a	8,518	5,678	5,678	5,678	8,518	5,678	5,678	5,678
Tires	€/a	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Toll	€/a	20,862	20,862	20,862	20,862	20,862	20,862	20,862	20,862
Total running costs	€/a	139,366	120,359	120,359	135,968	151,887	129,004	129,004	201,201
Total Costs of Ownership vehicle	€/a	163,364	149,151	152,856	181,552	175,885	162,368	166,073	256,579
Total Costs of Ownership vehicle	€/km	1.15	1.05	1.08	1.28	1.24	1.14	1.17	1.81
Total Costs of Ownership vehicle differences	%	100	91	94	111	100	92	94	146

Note: Only TCO regarding the vehicle. Infrastructure costs are not included for DI-GIV, OC-GIV and FCHEV.

Table 40 shows the result for the year 2030. The grid-integrated vehicles in both scenarios are still at the lowest price level. In the low scenario, the FCHEV reaches a cost competitive level. The TCO of the FCHEV are 3% higher in comparison to the ICE reference vehicle despite an approximate 1.3 times higher retail price, though in contrast to 2020, the fuel costs for the FCHEV are slightly higher. This relates mainly to the higher fuel consumption improvement assumed for the conventional ICE-DICI reference vehicle as well as the minimal percental increase of the diesel price compared to the hydrogen price. In the high scenario, the FCHEV is not competitive until 2030.

Table 40 **TCO long haul Truck calculation result for 2030 (€$_{2010}$)**

		low scenario				high scenario			
TCO long haul Truck		2030				2030			
	unit	ICE-DICI	DI-GIV	OC-GIV	FCHEV	ICE-DICI	DI-GIV	OC-GIV	FCHEV
life time	year	8	8	8	8	8	8	8	8
Travelled distance per year	km/a	141,960	141,960	141,960	141,960	141,960	141,960	141,960	141,960
Retail price	€	129,591	146,227	149,593	173,249	129,591	163,131	166,497	192,225
Fixed costs									
Annualized capital	€/a	19,248	21,719	22,219	25,732	19,248	24,229	24,729	28,551
Motor vehicle tax	€/a	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Insurance	€/a	1,944	2,193	2,244	2,599	1,944	2,447	2,497	2,883
Total fixed costs	€/a	22,611	25,332	25,882	29,751	22,611	28,096	28,646	32,854
Running costs									
Fuel	€/a	55,002	35,331	35,331	55,313	66,818	43,125	43,125	124,374
Driver wages incl. indirect labor costs	€/a	55,800	55,800	55,800	55,800	55,800	55,800	55,800	55,800
Maintenance and repair	€/a	8,518	5,678	5,678	5,678	8,518	5,678	5,678	5,678
Tires	€/a	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Toll	€/a	20,862	20,862	20,862	20,862	20,862	20,862	20,862	20,862
Total running costs	€/a	141,602	119,091	119,091	139,073	153,417	126,885	126,885	208,134
Total Costs of Ownership vehicle	€/a	164,213	144,423	144,973	168,823	176,028	154,981	155,531	240,988
Total Costs of Ownership vehicle	€/km	1.16	1.02	1.02	1.19	1.24	1.09	1.10	1.70
Total Costs of Ownership vehicle differences	%	100	88	88	103	100	88	88	137

Note: TCO regarding the vehicle only. Infrastructure costs are not included for DI-GIV, OC-GIV and FCHEV.

3.6 Impact of fuel taxation on electricity and hydrogen

In this chapter, an analysis of the current diesel taxes (see Table 29) applied to electricity and hydrogen was made. It may not be realistic to assume that they will remain low or zero. Table 41 illustrated the different fuel prices considering taxes equivalent to current diesel excise duty, per MJ energy carrier.

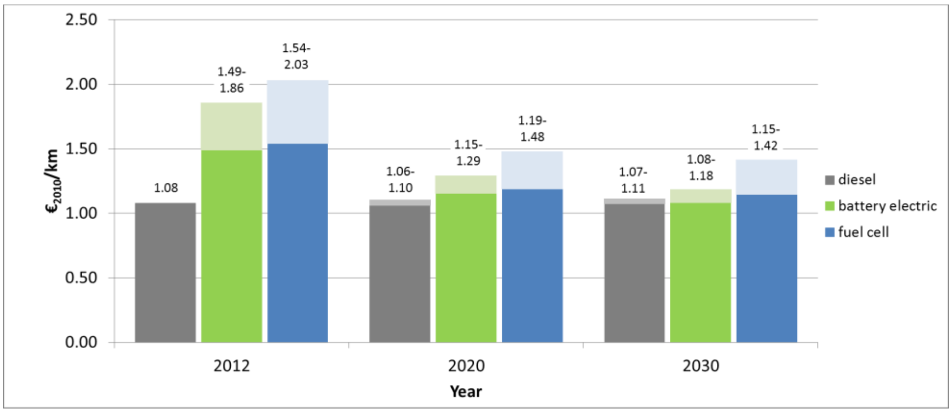
Table 41 **Assumed fuel prices at the filling station including taxes (excluding VAT)**

Fuels		2012	2020	2030
Diesel	Low (€$_{2010}$/l)	1.19	1.18	1.35
	High (€$_{2010}$/l)	1.19	1.46	1.64
Electricity	Low (€$_{2010}$/kWh)	0.141	0.163	0.182
	High (€$_{2010}$/kWh)	0.171	0.193	0.224
Hydrogen	Low (€$_{2010}$/kg H_2)	4.68	6.40	7.22
	High (€$_{2010}$/kg H_2)	8.80	12.36	13.75

In Figure 39 and Figure 40, the TCO of the distribution and long haul trucks including the full amount of tax, is equivalent to diesel (per MJ energy carrier) is illustrated. As expected, when considering the full amount of tax equivalent to diesel, the TCO of alternative distribution vehicles, such as BEV and FCHEV, increases by approximately 0.04 euro/km and 0.07 euro/km respectively.

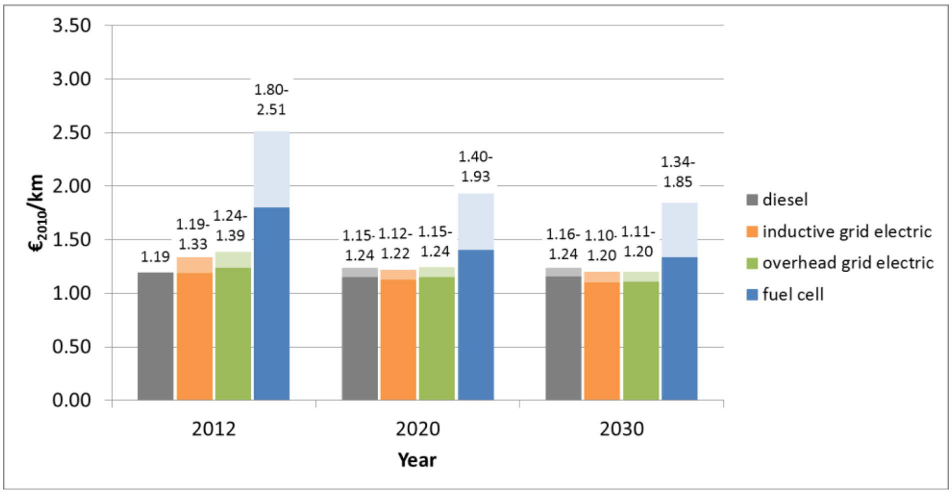
The TCO of alternative long haul vehicles increase between 0.08 euro/km and 0.12 euro/km. Thus, the leverage is not negligible.

Figure 39 Conclusion of the total cost of ownership of distribution trucks (including taxes)



Note: TCO regarding the vehicle only. Infrastructure costs are not included for battery electric and fuel cell vehicles.

Figure 40 Conclusion of the total cost of ownership of long trucks (including taxes)



Note: TCO regarding the vehicle only. Infrastructure costs are not included for inductive grid electric, overhead grid electric and fuel cell vehicles.

3.7 Conclusion and discussion

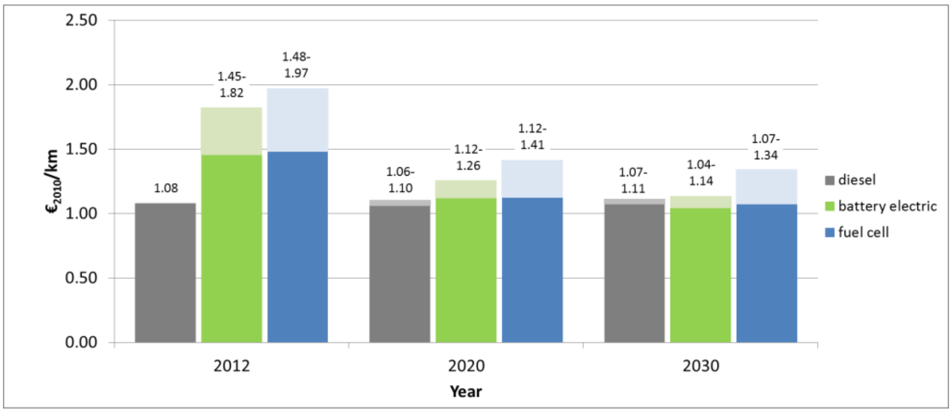
The following conclusions can be drawn from the calculated results:
- The results outlined depend on the chosen vehicle configuration, to a certain degree.
- The order of convergence of the alternative vehicles to the conventional ICE vehicle cost per kilometre level is strongly linked to the estimated costs for the different vehicle components, to the assumed battery and fuel cell system replacements and to the fuel cost estimations over time.
- For some vehicle configurations, such as BEV, FCHEV, and GIV, the infrastructure costs must also be taken into account and may change the order of precedence.

The analysis of the expected costs show that the production costs vary significantly over the years of consideration, which is mainly influenced by the costs for the required battery and/or fuel cell system. When looking at the total costs of ownership, it is interesting that the running/fixed cost ratio of the reference vehicle is around 80/20 whereas the ratios of the alternative vehicles are around 55/45. By reducing the production costs over the years of consideration, the ratio will change to be nearly the same ratio as the conventional vehicle. This implies that the first step is to reduce the production costs so that the fleet operator will generate more benefits during operation. Regarding the TCO of the BEV distribution vehicle, production costs can be approximately 1.6 times higher to reach nearly the ICE reference vehicle level, respectively to the assumed conditions for 2030. Regarding the FCHEV distribution vehicle the production costs can be 1.2 times higher.
GIV Long haul vehicle production cost can vary by 2.2 times and FCHEV production costs can be approximately 1.2 to times higher, respectively for the assumed conditions for 2030.

Due to the high uncertainty of real costs, two scenarios were calculated. A low scenario based on low fuel prices combined with low component costs and a high scenario based on high fuel prices combined with high component costs; only battery and fuel cell system costs were changed in both scenarios. Figure 41 and Figure 42 illustrate the results of both scenarios in an aggregated overview. The dark colours represent the results of the low scenario and the bright colours shows the additional costs accrued by using the fuel prices and component costs regarding the high scenario. The low and the high scenario overlap in many cases.

On the total cost of ownership level, the alternative distribution vehicle configurations will converge on the conventional reference vehicle level. Based on the assumptions, the battery electric vehicle will be nearly cost competitive by 2020. By 2030, the battery vehicle configuration is cost-effective. The FCHEV will become a competitive option between 2020 and 2030 due to the TCO reaching the same level as the reference vehicle. The competitiveness of the FCHEV is strongly linked with the assumed fuel prices for hydrogen as well as the assumed fuel cell system costs. The same applies to the BEV. It is interesting that the battery electric vehicle has a low uncertainty rate in comparison to the fuel cell hybrid vehicle by variation of the two parameters – fuel price and component costs.

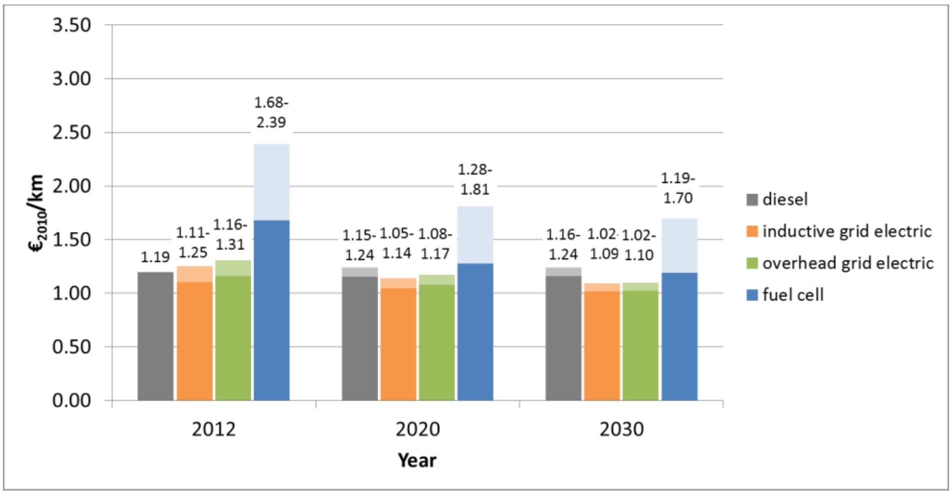
Figure 41 Conclusion of the total cost of ownership regarding the distribution trucks (no non-existing taxes)



Note: TCO regarding the vehicle only. Infrastructure costs are not included for battery electric and fuel cell vehicles.

The long haul fuel cell hybrid electric vehicle costs converges to the ICE vehicle by 2020 until it is at a nearly cost competitive level in 2030 when looking only at the low scenario (dark bars). Of course, the grid integrate vehicles are the most cost-effective by now and in the future due to the special used configuration. The cost difference between the DI-GIV and the OC-GIV are due to the higher production cost of the OC-GIV mainly influenced by the additional costs of the pantograph. It is important to note that the fuel cell hybrid electric vehicle can fully replace a conventional vehicle whereas the grid-integrated vehicle cannot due to its limited range and the requirement of a continuous power supply. Furthermore, additional infrastructure costs which are required for the grid-integrated vehicles may change the order of precedence.

Figure 42 Conclusion of the total cost of ownership regarding the long haul trucks (no non-existing taxes)



Note: TCO regarding the vehicle only. Infrastructure costs are not included for inductive grid electric, overhead grid electric and fuel cell vehicles.

The results in this study show the TCO developments on a vehicle basis for zero tailpipe emission vehicles and do not take any infrastructure costs into account. When considering full tax equivalent of diesel, TCO of alternative distribution vehicles such as BEV and FCHEV increase by approximately 4 €cents per km and approximately 7 €cents per km respectively. Regarding alternative long haul vehicles, the TCO increase by between 8 €cents per km and 12 €cents per km. Thus, the leverage is not negligible.

It can be concluded that the total vehicle operation costs (infrastructure not included) should not significantly increase (less than 10%) with the introduction of zero tailpipe emission vehicles, limiting the impact on the EU economy when these technologies are introduced.

We note once more that this conclusion is based upon the assumption of large production numbers, implying a technology shift away from conventional vehicles.

4 The role of policy instruments

Government policy will play a critical role in catalysing the market for zero emission trucks until the technology costs are reduced to levels that make zero emission technologies competitive with their conventional counterparts.

In order to achieve a significant uptake of zero emission trucks, several barriers need to be overcome as discussed in Chapter 2. Recent research has also shown that the transport industry is currently reluctant to adopt certain technological measures that reduce fuel consumption (CE Delft, 2012). Therefore, government policies are needed to reduce the effects of certain barriers, and to promote the uptake of zero emissions trucks.

In some niche segments, such as city distribution, zero emission trucks may result in a more promising business case than for long haul applications in the nearer term. As a result, zero emission technologies can be introduced at an earlier stage for such truck types. Examples of the types of vehicles that may be good matches for the characteristics described above include garbage trucks or local delivery fleets. This is mainly due to lower upfront investments, fewer technological barriers, and liveability arguments, such as reduced pollutant emissions and noise. Consequently, advanced concepts are already being introduced in many countries for both urban bus transport and for the city distribution of goods. Therefore, policy incentives could first be directed to these urban applications and increasingly expanded to intercity and long haul applications after implementation success is seen in urban applications.

In Figure 43, four stages of application are shown. Most current projects can be defined as niche applications. Evolution beyond these pilot projects to a corridor or region will need a refuelling infrastructure.

Figure 43 Overview of options vehicle and fuel regulation

Urban captive fleets → Corridor/ region → National → EU wide

From an infrastructure point of view, it is important to develop an integrated policy that covers both freight and passenger transport. If infrastructure costs can be allocated to both the passenger and freight sector, the per-vehicle-km costs will be lower and initial investments easier to bear.

In the next sections the role of different levels of government is discussed, starting with local governments, since most zero emission truck deployments are currently concentrated in urban areas. In addition, different types of policy measures will be discussed, such as voucher programs, tax incentives, performance standards, and low-emission zones.

4.1 Research and development

In the next decades, research and development (R&D) will be an important condition for the upscale of the use of zero emission vehicles. R&D subsidies need to be aimed at both bench-scale fundamental research and real-world applications of early generation vehicles. Researchers, OEMs, and technology suppliers need to be encouraged to invest in the development of zero emission technologies. Governments can consider subsidising these investments in a technology neutral way (i.e. not favour a specific technology at this point), as the industry has the best knowledge about the advantages and disadvantages of different options, and the relative strengths of particular technologies in specific truck applications. To motivate accelerated levels of private sector R&D, governments can provide research grants or other incentives such as low interest loans or co-investment opportunities (i.e. industry-government cost-share projects). This is especially important when considering the limited public funds that governments can allocate to zero emission vehicles.

Governments could also assist in experimental programmes where the technologies will be developed and tested. Such programmes will provide significant new knowledge, which will not only help the industry to develop the technology, but also will provide both governments and stakeholders with the necessary information about which types of infrastructure will be needed in the future. In addition, this type of expenditure helps train new engineers and project leaders to continue to make progress in applying these advanced technologies to vehicles in the decades ahead.

R&D needs to be financed by both the EU and by the individual Member States. The EU and Member States need to support scientific research aimed at the development and the improvement of infrastructure-related technologies, such as inductive and overhead grid charging. In addition it is critical to provide engineering support for vehicle component suppliers, such as manufacturers of the batteries, fuel cell stacks, and electric motors. Because many automobile manufacturers are further along in their light-duty applications of these electric drive technologies, the government research programmes could be focused on extending and scaling up these technologies to medium-duty, urban applications. Furthermore, more practical projects aimed at vehicle testing, standardisation, and financing would also need to be supported to help ensure several-vehicle projects can be scaled up to vehicle pilot demonstrations of tens and hundreds of vehicles.

4.2 Infrastructure development

The calculations that have been made for this project suggest that the TCO of the different technologies converge over time. That is to say, the findings indicate that the initial upfront vehicle technology costs for the electric drive vehicles are approximately outweighed by the technologies energy costs savings over their vehicle lifetimes in the 2030 timeframe. As a result, from a single vehicle user (or fleet operator) cost point of view, the adoption of zero emissions truck technologies would not appear to be a large problem. However, there are many other factors that influence adoption, such as preferences, experiences of other companies, and payback time. Additionally, the availability of an adequate fuel supply and refuelling infrastructure is key to the adoption of zero emission vehicles. Problematically, this is a well-known ‘chicken and egg’ problem, which implies that infrastructure investments need to be made prior, or at least simultaneously, to the widespread introduction of zero emissions vehicles.

This barrier will be difficult to overcome considering the scale of the infrastructure costs that are needed. A study by McKinsey (2010) estimates the electricity infrastructure costs for serving 200 million electric passenger cars at 500 billion euro for example. Total infrastructure costs for HDVs may be somewhat lower, as it concerns less and more concentrated vehicles. There may be a role for governments to assist the industry in making such investments, at least in early stages of development. There are several examples of government subsidies for alternative fuel fuelling stations such as compressed natural gas (CNG), liquefied natural gas (LNG), and electric vehicle charging ports in several European countries. Governments and industry may also co-operate in public-private partnerships, which help spread the risks and benefits of developing infrastructure.

When a certain market share has been reached, industry may see new business cases and will be interested in infrastructure investment. An example of this is the development of charging points for electric vehicles by the Dutch electric grid owners.

The European Commission recently published a proposal for a Directive (COM(2013)18)) on the development of an alternative fuels infrastructure. The Commission obliges the Member States to develop a plan and sets a target for electric vehicle charging points, to be met by Member States. It is up to the Member States to attract and incentivise industry to develop the networks.

4.3 Local policies

Policies from governments at all levels are needed to make zero emission vehicles a success. However, at the moment, local policies contribute most to the introduction of electric distribution trucks in cities. In several cities, local governments use a variety of instruments to promote the deployment of less-polluting vehicles, such as easing the inner city access[31], subsidies, and differentiation of city access charges. By implementing such instruments, viable business models for electric distribution trucks can be realised. London and Amsterdam offer two such city-level examples to accelerate electric vehicle deployment.

Amsterdam: subsidised electric vehicle investment
The city of Amsterdam reimburses business in Amsterdam 40,000 euro when purchasing a full electric distribution truck. The local government has reserved 8.6 million euro for this (including subsidies for electric cars or vans) from the start of the scheme in 2012 through 2015 (Amsterdam, 2013). With this scheme, viable business models can be made for distribution trucks that do not need a large range and return to a regular home base for recharging at night.

London: Low Emission Zone tax exemption
The city of London can only be accessed by paying the congestion charge. For distribution trucks, this charge is 10 Pound per day per vehicle. Green vehicles, including electric vehicles, are exempted from the charge. By using an electric distribution truck in the city of London, 2,500 Pound per year can be saved, in comparison to a conventional vehicle.

[31] In the Netherlands, there are examples of relaxation of the time window for distribution of goods in shopping areas, resulting in less vehicles and less staff needed.

The above examples show that local policies can help to make zero emission vehicles more financially attractive. This is not only important from a user's fiscal perspective, but also from the industry perspective, as it will help to advance the maturity of the technology, it will give manufacturers and fleets experience with the new technology, and it will lower the vehicle production costs. In addition, local governments should lead by example and adopt zero emission technologies to green their own fleets, helping to establish an early market for zero emission vehicles. The city of Rotterdam has replaced several of its conventional vehicles with full electric garbage vehicles since 2009; several other cities, such as The Hague and Breda have followed this example (Van Gansewinkel, 2013).

Environmental zoning could be used in a later stage to completely ban conventional diesel and gasoline combustion trucks from city centres, which is already the case for highly polluting trucks in many EU cities. The European Commission has mentioned a measure of this kind in the Transport White Paper when they announced the ambition to obtain CO_2-free city freight logistics in 2030.

4.4 National policies

In addition to local subsidies, national subsidies can be useful in order to develop larger scale applications on particular corridors (e.g. Trans-European Transport Network) or at a targeted regional scale. The supply of an actual infrastructure will be more important in these type of projects, as these typically require a larger scale energy supply infrastructure, since vehicles are travelling over larger distances. This separation of national funding may also be used for local projects, as well as align with cost-sharing schemes between national and local entities.

National governments can use several policy measures to stimulate the development and uptake of zero emission vehicles. Fiscal policies for example, can help to close the gap between the user costs of conventional and zero-emissions vehicles. Fiscal policies can accomplish this in two ways: by generating benefits for (and thus reducing the costs of) zero emissions trucks and energy, or by increasing the cost for conventional trucks and fuels. Several fiscal policies can be designed. An increase in the taxation of diesel fuel for example, would be an appropriate way to close the gap in user costs between conventional and zero emissions trucks. Similar effects can be obtained when the fuel of zero emission trucks (electricity or hydrogen) is exempted from fuel taxes until the vehicle technologies become the new standard. A feebate system (e.g. implementing a high fee for new conventional vehicles and a rebate for zero emission vehicles) would be a combination of both ways and, in theory, has a neutral effect on governmental budgets.

Vehicle circulation taxes (e.g. Eurovignet) could be used as well. Since there is a trend towards distance based charging systems for trucks in Europe, the exemption or reduction of distance based charging (e.g. MAUT in Germany[32]) may lead to significant benefits for zero emission trucks.

[32] The MAUT is 0.16-0.28 euro per vehicle-km for large trucks. Assuming 50,000 km of tolled kms would result in a benefit of 8,000 to 13,000 per year.

A disadvantage of most fiscal measures described above is that such measures have an impact on the government budget. Exemptions from zero-emission fuels may negatively affect the governmental income. This may be a problem as fuel excise duties represent typically around 5% of the government income. When the exemption is combined with an increase in diesel taxes, this loss can be (partially) compensated. Another potential disadvantage of fiscal measures, particularly in contrast to regulatory measures, is that it will not be known in advance what the effects will be on the adoption of zero emission vehicles (i.e. whether it will increase their adoption rate and to what extent).

In addition to fiscal policies, national governments should also be aware of their own procurement policy. National governments could act as an early adopter of zero emission technologies by replacing vehicles in their own fleet with zero-emission alternatives. These national vehicle procurement guidelines can be explicitly linked with manufacturer and infrastructure funding and incentives described above, in order to simultaneously promote the supply of advanced technologies and ensure the demanded uptake of the first tens, hundreds, or thousands of vehicle units.

National policies may also be used to stimulate industry program initiatives for sustainable transport. Several initiatives have already been initiated worldwide, such as Green Freight Europe and SmartWay in the U.S. These initiatives are focused on best practise sharing, technology verification, support of carrier purchase, carrier certification and carbon monitoring and reporting, and may be useful to increase the awareness of people that are working in the sector. As new advanced electric drive technologies, as described above, arrive on EU road programs like Green Freight Europe could take an active role in supporting fleet’s decision-making about the new technologies.

4.5 European policies

Local and national governments can only support the development and introduction of zero emissions vehicles to a limited extent, since the transport industry has an international scope. The widespread uptake of zero emissions vehicles and the distribution of a fuel/charging network therefore requires support by an EU strategy that provides clear long term signals to the trucking industry. Therefore, a roadmap for the introduction of zero emissions trucks needs to be developed and needs to be supported by a full policy package. This policy package should swiftly change from stimulation to regulations in order to reach the European goal of reducing GHG emissions from transport with 60% by 2050 as compared to 1990, a goal set in the European Commission’s White Paper on Transport.

Although not specifically aimed at transport, the UK Climate Change Act is a good example of such a road map. The Act obligates local UK governments to reduce the net carbon Kyoto GHG emissions by at least 80% in 2050 than 1990 levels. The Act obligates local governments to set five yearly carbon budgets at least 12 years in advance, including a transition plan. The principle of making a binding long term transition plan could be very useful to decarbonise the EU freight transport sector, as it could help decision-makers form regulatory policy with clearer goals in mind.

Another goal that has been set in the European Commission's White Paper on transport is zero emission city distribution of goods in major urban centres by 2030. It was not precisely prescribed in the White Paper how zero emission city transport should be realised. The Commission should therefore develop a framework that clearly indicates what will be required from the industry with respect to their emissions. This framework should not only cover the emissions of road vehicles, but also cover the fuel chain as this becomes more important when discussing zero emissions vehicles. The findings from this report provide initial steps toward trucks types, vehicle technologies, and fuels that would make sense for these urban zero emission truck programs.

4.5.1 Development of a portfolio of CO_2 standards that includes the fuel supply pathway

To promote the use of zero emission trucks, a portfolio of CO_2 standards would need to be implemented that reflects both the energy carrier and the vehicle. Vehicle regulation is important as it reduces the energy consumption of the vehicle and stimulates innovation. However, the GHG content of the energy carrier is also important in order to obtain truly zero emission vehicles. For example, in the case that electric vehicles use primarily coal-fired electricity as an energy source, no net GHG reductions will be achieved.

Several policy instruments already exist, or are under development, that can be used for the development of a CO_2 standard for trucks. With respect to the energy carrier, the Renewable Energy Directive (RED), the Fuel Quality Directive (FQD) and the European Emissions Trading System (EU ETS) are well-known examples. The text box below describes these policy measures in more detail.

FQD
The Fuel Quality Directive has been implemented by DG Clima and sets a target of 6% reduction of the carbon intensity of transport fuels that are supplied in the European Union between 2010 and 2020. The FQD is therefore aimed at fuel suppliers. The reduction in carbon intensity can either be achieved by reducing upstream GHG emissions or by supplying low carbon fuel options, such as hydrogen or electricity. It is widely expected that the bulk of the target will be met by the use of biofuels. The FQD promotes biofuels with a high GHG reduction potential (i.e. more than 35% GHG emission saving as compared to fossil fuel) and excludes biofuels with a GHG reduction potential below the threshold of 35%. With the 6% target that has currently been set, oil companies may decide what measures they take to reduce emissions. This can be either biofuels or efficiency improvement in the fuel chain (e.g. refinery).

RED
The Renewable Energy Directive has been implemented by DG Energy and sets mandates for the use of renewable energy in the European Union. This includes a mandatory target for European Member States that 10% of the energy in land transport should be from renewable sources by 2020. The RED excludes biofuels with a GHG reduction potential below the threshold. Regarding overall energy (i.e. electricity, heat and transport energy combined), the target is 20% renewable energy for 2020. It is expected that this will be met with an average renewable electricity share of about 35%.

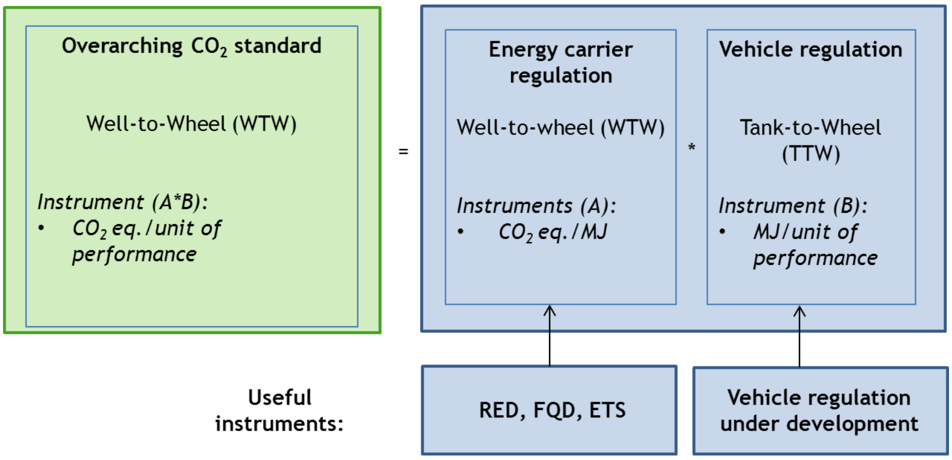
Both the FQD and RED contain default values (gCO_2 eq./MJ) for biofuel production pathways, the calculation methodology to determine the emission factor of fossil fuels, electricity and hydrogen (relevant to the FQD) has not yet been defined.

EU ETS
The European Union Emissions Trading System (EU ETS), is the largest emissions trading scheme in the world. It was launched by DG Clima in 2005 to combat climate change and is a major pillar of the EU's climate policy. The EU ETS covers more than 11,000 factories, power stations, and other installations with a net heat excess of 20 MW in EU 27. The stationary sources that are regulated by the EU ETS are collectively responsible for approximately half of the EU's CO_2 emissions. Under the 'cap and trade' principle, a cap is set on the total amount of greenhouse gases that can be emitted by all participating installations. 'Allowances' for emissions are then auctioned or allocated for free, and can subsequently be traded. At the moment the CO_2 price might be too low to realise that all electricity that is delivered to electric vehicles has zero-emissions. However, this might change if the cap becomes stricter.

In addition to vehicle and energy carrier regulation, also an overarching standard needs to be implemented. If only the vehicle and the fuel are regulated, the uptake of zero emission vehicles in the fleet may not be ensured.

Figure 43 provides an overview of the elements that need to be covered by a CO_2 standard for HDV that covers both the vehicle and the energy carrier.

Figure 44 **Overview of options vehicle and fuel regulation**



Below, several options are discussed that cover both vehicle and fuel regulation and are necessary to reduce vehicles' energy consumption and to decarbonise their energy carriers.

Application of RED/FQD framework for ZEV energy carriers
The framework that is used in the FQD/RED, can be used to gradually reduce the GHG emissions of electricity and hydrogen production for transport in the next decades:
– the RED/FQD should be used to phase out the use of unsustainable fuel pathways;
– the 6% reduction by 2020 from the FQD needs to be gradually increased after that year, to increase the production of sustainable energy carriers;
– after 2020, the production of renewable electricity needs to increase substantially when electric and hydrogen vehicles are widely adopted.

In order to lower the average carbon intensity of transport energy carriers with instruments like those mentioned above, default values for carbon intensity per energy carrier are needed. As better fuel pathways are developed, promoted, and expanded, these values should drop over time as a result of tightening the RED and FQD criteria aforementioned.

Firstly, biodiesel may be an attractive alternative. However, as soon as the FQD target increases, biodiesel (with its relatively high default carbon intensity in comparison to renewable electricity and hydrogen) will be a less attractive fuel for trucks. As a result, vehicles that use energy carriers with lower default carbon intensity values will become more attractive and replace the current biodiesel. This also implies that the share of hydrogen produced from natural gas gradually decreases, while the share of hydrogen produced from renewable sources increases. This is a necessary shift, since hydrogen produced from renewable sources contributes to a much lower carbon intensity compared to hydrogen that is produced from natural gas.

EU ETS
Europe has an Emissions Trading System (EU ETS) for the resource intensive industry, power plants, and other installations since 2008. This system can also be used to reduce the average emissions of power production. By lowering the emission cap, the GHG emissions of electricity production may decrease, through a phase out of coal fired power production for example. However, this does depend on the cap that is set and what CO_2 price will result as a consequence. If the price is low, the power sector may merely buy credits from other sectors, which would not stimulate the generation of renewable electricity.

Vehicle regulation
EU legislation for passenger vehicles has been recently implemented, mandating car manufacturers to produce cars that emit 130 g/km or less on average by 2015 and 95 g/km by 2020. For vans similar limits have been set at 175 g/Km by 2017 and 147 g/km by 2020. The European Commission is now evaluating the options for a similar fuel efficiency measure for trucks. A proposal for such a measure has been developed by TU Graz (2012). This proposal entails a computer model that includes the main components that affect the fuel efficiency of a truck, such as the engine, driving resistance, gearbox and auxiliaries. The fuel consumption that results from the combination of the aforementioned components should be tightened over time for different technologies, in order to reduce vehicle energy consumption.

If the overall energy consumption is expressed per km or tkm, such a computer model will also be able to evaluate the TTW emissions of a potentially zero emission truck, since the engine is the only component that will be different. If the model that will be developed can be applied to both conventional as well as to zero emissions vehicles, and, in addition, can include the GHG emissions that result from fuel production, the entire well-to-wheel chain can be regulated. This latter mentioned aspect is important to include, as the production of conventional fuels and renewable hydrogen or electricity strongly differ in their GHG impact.

Zero-counting, super credits,[33] or alike could be used to promote the development of zero emission trucks by manufacturers in earlier stages of the truck regulations. Super credits make zero emission vehicles attractive as the manufacturer would be rewarded with a bonus, making it easier to achieve the targets set. The gradual tightening of the fuel efficiency measure in combination with fiscal measures will lead to the introduction of conventional vehicles with lower fuel consumption. The use of zero-counting from a regulatory perspective can initially help stimulate electric vehicles at their most expensive early development phase to lead to the introduction of alternatively fuelled vehicles in the market. This could be especially important in vehicle truck regulations if the 2020 and earlier timeframe require only small CO_2 percentage reductions than can be achieved with engine, tire and aerodynamic changes to conventional diesel vehicles.

An advantage of combining vehicle and energy carrier regulation over the long term is that the potential of fuel decarbonisation will be reflected in the overall well-to-wheel value, while only looking at the vehicle does not reflect the actual well-to-wheel emissions of zero emission vehicles. Combining both vehicle regulation and energy carrier regulation would require the cooperation of different departments (DG Clima and DG Energy) of the European Commission.

Another potential issue of note with the enforcement of a standard is that at the moment of vehicle registration and certification, fuel information is based on recent history, while such a vehicle will be in the fleet for the next decade. With such an approach, decarbonisation of fuels over time will not be taken into account. This might be resolved by taking estimations of fuel development into account. An effective example of vehicle-fuel policy integration is shown in the California light-duty vehicle and fuel carbon regulations. In the California framework, grams of CO_2 per unit energy carrier (e.g. gCO_2 per kWh for electricity, and gCO_2 per kg of hydrogen) are estimated from the projected implementation of the fuel regulations, and these are applied in the vehicle regulation (CARB, 2012).

4.6 Conclusion and discussion

This section has provided an overview of a large number of policy instruments that can be used to increase the share of zero emission vehicles. Many of the instruments can be used at the same time, or can be built sequentially upon one other.

In some niche segments, such as city distribution, zero emission trucks could be introduced in earlier stages than for long haul applications, due to more limited up-front investments, fewer technological difficulties, liveability arguments (reduced pollutant emissions and noise) and consequently better business cases. When defining policies, this should be taken into account.

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[33] The passenger car CO_2 regulation gives manufacturers additional incentives to produce vehicles with extremely low emissions (below 50g/km). Each low-emitting car will be counted as 3.5 vehicles in 2012 and 2013, 2.5 in 2014, 1.5 vehicles in 2015 and then 1 vehicle from 2016 onwards. This positively impacts the manufacturers average emission.

Larger uptake of zero emissions vehicles requires support by a broad EU strategy that provides clear signals to the trucking industry. Therefore, a roadmap of the introduction of zero emissions trucks needs to be developed and needs to be supported by a serious policy package that targets electric drive suppliers, truck manufacturers, fuel and electricity providers, and local fleets. This policy package should swiftly change from stimulation to regulation for substantial volumes of zero emission trucks to be realised.

Introduction of the portfolio of CO_2 standards, including coverage of both the vehicle and the energy carrier over the long-term, is very important. Such standards should be established with very long regulatory lead-time (e.g. to 2030) to encourage large sustained investments by industry, and the standards would best be tightened over time to promote zero emission vehicles. These standards should be aligned with long term national and EU-level scoping activities to ensure that annual actions are linked to long-term climate stabilization goals.

5 GHG Reduction scenario

The previous chapters have indicated that several uncertainties exist, which play a role in the breakthrough of zero emissions trucks regarding the kind of technology and why a specific technology will be preferred above another. The most important uncertainties are:
- vehicle component technology development;
- vehicle component cost development;
- infrastructure availability;
- fuel prices and taxes;
- developments in the passenger car sector.

It is, therefore, not possible to definitively conclude what technology or mix of technologies will prevail for 2030-2050 for distribution and long-haul trucks. As a result, the scenarios in this chapter have an explorative character rather than a precise prediction of the future. In other words, the scenarios are based on a '*what-if'* analysis and are not derived through a logic model.

5.1 Methodology

Figure 45 shows the steps of the GHG reduction calculation starting at number one. Different exogenous input data is required to calculate by simple multiplication sequences the total well-to-wheel (WTW) GHG emissions. The calculation steps, variables and data sources employed are outlined in more detail below the illustrated overview of the calculation flow chart and variables in
Table 42.

Figure 45 GHG reduction calculation flow chart

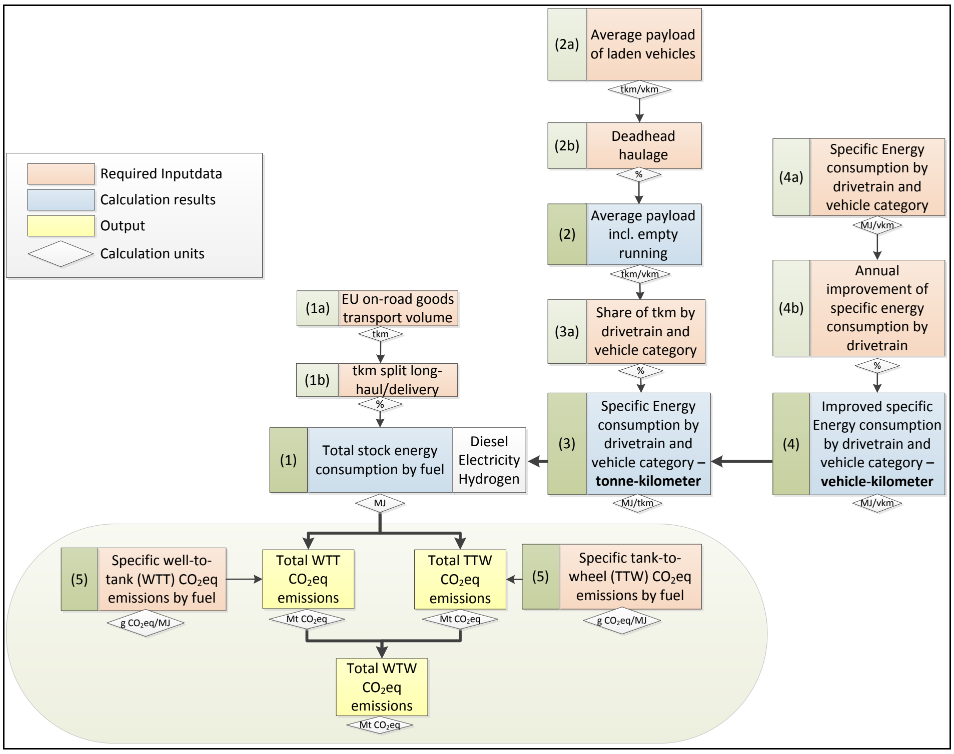


Table 42 Variables of the GHG scenarios calculation

	Variable	Unit	Source
(1a)	EU on-road goods transport	Tkm	European Commission (2012)
(1b)	tkm split long-haul/delivery	%	TREMOVE (2012), v3.3.2
(2a)	Average payload of laden vehicles	tkm/vkm	Ecoinvent (2007)
(2b)	Deadhead haulage (share of empty trips)	%	European Commission (2011)
(3a)	Share of tkm by drivetrain and vehicle category	%	Section 5.2
(4a)	Specific energy consumption by drivetrain and vehicle category	MJ/vkm	See Chapter 2 and Table 43
(4b)	Annual improvement of specific energy consumption by drivetrain	%	Table 43
(5)	Specific well-to-tank (WTT) GHG equivalent emissions	g CO_2 eq./MJ	JEC (2011); EC (2011a)
(5)	Specific tank-to-wheel (TTW) GHG equivalent emissions	g CO_2 eq./MJ	Sultan (2010)

The steps displayed in the GHG scenario calculation flow chart are explained in more detail.

1. Total stock energy consumption by fuel is calculated on the basis of the EU on-road goods transport volume (1a). In 2010, the volume was 1.76 trillion tonne-kilometres (tkm) reported by Eurostat[34] (European Commission, 2012). Taking the tkm split with regard to long-haul and delivery trucks (1b)[35] into account, the sum of long-haul tkm and delivery truck tkm, each having a specific energy demand can be identified. Furthermore, using the specific energy consumption per tkm, which depends on drivetrain and vehicle category, total stock on energy consumed by fuel (1), that is diesel, electricity or hydrogen, can be calculated. Future transport volume is derived from Tremove version 3.3.2 (Tremove, 2012).
2. Average payload inclusive of empty running is calculated by multiplying the average payload of laden vehicles (2a) with the deadhead haulage (share of empty trips) (2b). Ecoinvent[36] provides the required data. The average vehicle payload of laden distribution and heavy-duty trucks in the EU is 6.4 tkm/vkm (i.e. tonnes per vehicle) and 15 tkm/vkm respectively (Ecoinvent, 2007). Following Eurostat data for the average share of national and international deadhead haulage, a 27% share of empty running is assumed for distribution and 13% for long haul trucks (European Commission, 2011b). This results in an average vehicle payload of 4.7 tkm/vkm for distribution and 13.1 tkm/vkm for long haul trucks.
3. Specific energy consumed per tkm depends on the estimated share of tkm by drivetrain and vehicle category (3a), which is linked to the average payload (2). It also depends on the improved specific energy consumption per drivetrain and vehicle category (4) on a vehicle kilometre basis. Dividing (4) through (2) by taking (3a) into account results in the specific energy consumed per tkm (3), which is required for the GHG scenario calculation.

   Note that through (3a) different scenarios can be realized. In this study, one business-as-usual (BAU) scenario and two alternative scenarios (ALT 1 and ALT 2) were constructed to show the impact of variations in the drivetrain-tkm-shares on the GHG emissions. The scenarios are discussed in detail in Section 5.2.

   Table 43 shows the calculated specific energy consumptions per tkm and their annual improvements over time. Hybrid electric vehicles (HEV) were additionally included in the GHG calculation since hybrid drivetrains are seen as a transitional technology from internal combustion engines to pure-electric drivetrains.

[34] Eurostat is the European statistic agency, see http://epp.eurostat.ec.europa.eu.

[35] Based on TREMOVE v.3.3.2 (a transport model for the European Union, covering transport demand, mode shares and vehicle stock forecasts until 2030), the tkm split regarding long-haul and delivery trucks (1b) indicates that the great majority (more than 90%) of the transport performance is covered by heavy trucks (>16 t GVW) and the rest by delivery trucks with a GVW of 7.5-16 t, see http://www.tremove.org/.

[36] Ecoinvent is a transport modelling tool for environmental analysis covering European road-, rail, air and water based transport, see http://www.ecoinvent.ch/.

Table 43 Specific energy consumption and annual improvement rates

	Specific energy consumption (MJ/tkm) as of 2012	Annual improvement in specific energy consumption until 2050*
Long haul Trucks		
ICE-DICI	0.93	1.1%
OC-GIV	0.61	1.0%
DI-GIV	0.61	1.0%
FCHEV	0.80	0.83%
Distribution Trucks		
ICE-DICI	1.35	1.1%
HEV	1.08	1.0%
BEV	0.77	1.0%
FCHEV	1.12	0.83%

* See Section 3.3 for explanation on these figures.

1. Specific energy consumption by drivetrain and vehicle category (4a) is discussed in Section 3.3. In addition to the illustrated specific energy consumption, specific energy consumption of HEVs is added to Table 43. Specific energy consumption of an HEV is 5.25 MJ on a per vehicle kilometre basis, a 20% lower energy consumption than the reference ICE vehicle following data of AEA (2011) and NAP (2010). Using the specific energy consumptions as a starting point and taking the annual improvement rates of specific energy consumption by drivetrain (4b) into account, the improved specific energy consumption by drivetrain and vehicle category on a vehicle-kilometre basis over time (4) can be calculated. Thus, the specific energy consumption and the related improvements over the years describe the development regarding the vehicle fleet.

2. Having calculated the well-to-tank (WTT) and tank-to-wheel (TTW) CO_2 eq. emissions, total well-to-wheel (WTW) CO_2 eq. emissions can be derived from the total stock energy consumption by fuel (1).

In general, GHG emissions are split into a (production) well-to-tank (WTT) and a (consumption) tank-to-wheel (TTW) part. For calculating these two parts, specific intensities in gCO_2 eq./MJ need to be known. In the following, the intensities for the WTT and TTW part are outlined in detail:

WTT intensities

WTT carbon intensities of diesel were taken from JEC (2011). It is set to 15.9 gCO_2 eq./MJ (without considering biodiesel blending share). The WTT carbon intensity might evolve in two directions. Under the increased use of non-conventional oil, the GHG emissions associated with oil production may increase. However, the fuel quality directive (see Chapter 4) may contribute to lower emissions of oil production. The values were held constant over time, as a compromise between both scenarios.

For electricity production and transport, GHG emission factors are based on the EU Roadmap 2050 (EC, 2011a). As depicted in the Roadmap, power generation in the EU will be almost completely decarbonized by 2050.

EU energy roadmap
The EU is committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 in the context of necessary reductions by developed countries in order to remain below a 2°C temperature increase. The Commission analysed the implications of this in its 'Roadmap for moving to a competitive low-carbon economy in 2050.' The report focuses on the reduction of energy demand and the improvement of energy efficiency. At the moment, natural gas, coal, nuclear and renewables are the most import energy sources for power production. Several scenarios have been developed within the context of the EU energy roadmap. All imply major changes in, for example, carbon prices, technology and networks.

The reference scenario developed for the Roadmap 2050 in EC (2011a) is used in this study as a starting point. This reference scenario is based on a 7% GHG emission reduction for electricity power production. Table 44 provides an overview of the carbon intensity of electricity production of the EC reference scenario.[37]

Table 44 Carbon intensities for electricity generation in the EU 27 (reference scenario EC energy roadmap)

	Carbon intensity of electricity production, including network losses (10%)	
Unit	gCO_2 eq./kWh	gCO_2 eq./MJ
2012	456	127
2020	378	105
2030	278	77
2040	167	46
2050	98	27

When estimating the WTW GHG intensity of hydrogen, the key questions are:
- What energy source is used to produce the hydrogen?
- With what efficiency is the hydrogen produced?

Today, most of the world's hydrogen is produced from reforming natural gas (about 90%). Most of this hydrogen is used in refineries (ECN, 2011). However, a large range of potential production routes exists, such as coal gasification, biomass processing (e.g. gasification of wood) and hydrogen production from electrolysis (i.e. from electricity).

For the year 2012, hydrogen produced from natural gas by steam methane reforming (SMR) is assumed. The figure for 2012 is based on JRC (2011).

The GHG intensity of hydrogen (like other energy carriers) will need to be gradually reduced over time because of further tightening of policies such as the FQD GHG emission reduction target, as indicated in Chapter 4. Thus, it is assumed that during the coming decades, hydrogen production for transport fuels will gradually shift from the current SMR practice to either production from renewable energy sources like biomass and wind, or that fossil fuels remain the main energy source by applying CCS.

[37] The reference scenario takes into account the upward trend of import fuel prices in a highly volatile world energy price environment. Economic decisions are driven by market forces and technological progress in the framework of concrete national and EU policies and measures implemented by March 2010. The 2020 targets for RES and GHG will be achieved in this scenario, but there is no assumption on targets for later years besides annual reduction of the cap in the ETS directive.

A mix of these two options would, of course, also be possible, depending on the development of cost and GHG intensity of these routes.

Based on the further tightening of the FQD requirements, a scenario has been developed that shows similarities with the decarbonisation of electricity. As for electricity, the production of hydrogen will be decarbonised by around 75%. The figures given in Table 45 are representative for the production mix illustrated by McKinsey (2012), depicted in Figure 37.

Table 45 EU 27 carbon intensities for hydrogen use in transport

Hydrogen production emissions	
Unit	gCO_2 eq./MJ
2012	111
2020	100
2030	60
2040	35
2050	24

TTW intensities

The study concentrates on zero-tailpipe emission vehicles, emitting no TTW GHG emissions at all. In the case of the reference vehicle (ICE-DICI) and the HEV, however, the TTW CO_2 eq. intensity of diesel needs to be included; thereby, it is assumed, that all HEVs have a diesel ICE. Current TTW carbon intensity of diesel fuel (without considering biodiesel blending share) is 73.2 gCO_2 eq./MJ (Sultan, 2010).

5.2 GHG reduction scenario

On the basis of the GHG reduction calculation flow chart (Figure 45) different scenarios were developed to illustrate the potential of various drivetrain technologies to phase into the market. The long haul truck drivetrain technologies under consideration are: the direct injection compressed ignition (DICI), the overhead catenary grid integrated vehicle (OC-GIV),[38] and the fuel-cell hybrid electric vehicle (FHEV). The dynamic inductive grid integrated vehicle is not taken into account.

For distribution trucks, direct injection compressed ignition (ICE-DICI) vehicles, hybrid electric vehicles (HEV), battery electric vehicles (BEV) and fuel cell hybrid electric vehicles (FHEV) are taken into account. HEVs were considered because experts expect the hybrid technology will become cost competitive within the next 5-7 years whereas the battery electric and fuel cell hybrid vehicle will not. The latter was demonstrated in Chapter 3. HEV technology only makes sense in applications where they reach a better fuel consumption in comparison to conventional diesel vehicles. Furthermore, note that in this study the HEV covers all kinds of hybridisation technology (micro-, mild-, full-hybrids, and plug-in hybrids as well as electric range extender

[38] Firstly, it is expected that in the future only one of the competing technologies (overhead catenary or dynamic inductive loading) will be realized for long haul applications. The fact, that the overhead catenary technology currently exists as illustrated within Chapter 2 and moreover under testing leads to preferring this technology.

vehicles). This aggregation is necessary due to an intensive consideration of the hybrid technology was beyond the scope of the current study.

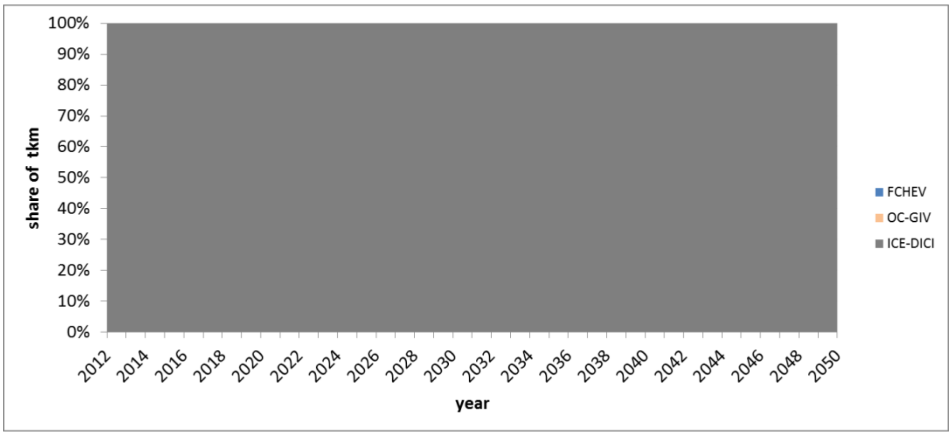
Three scenarios that reflect different mileage shares of the drive trains were developed:
- Business-as-usual (BAU) - conservative scenario;
- Alternative 1 (ALT 1) - favorable scenario;
- Alternative 2 (ALT 2) - ambitious scenario.

5.2.1 Business-as-usual (BAU) conservative scenario

In general, the y-axis illustrates the share of tkm generated by different drivetrain technology and the x-axis illustrates the timeframe of consideration (2012-2050).

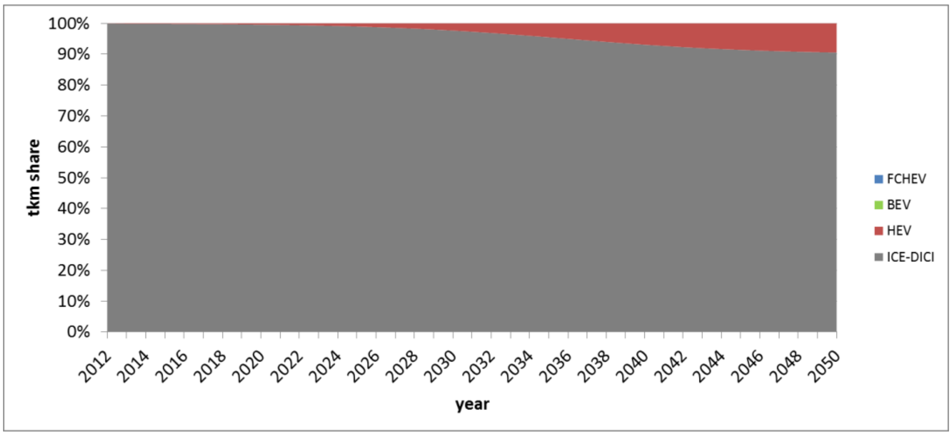
The BAU scenario mirrors a transport scenario with only minor penetration rates of alternative drivetrain technologies. Thus, in case of the long haul trucks in Figure 46, a share of 100% tkm generated by long haul diesel drivetrains until 2050 is predicted. This implies that no alternative vehicle configuration investigated in this study will be competitive until 2050, as the current bottlenecks identified in the previous chapters cannot be overcome in the next 40 years.

Figure 46 **Long haul trucks BAU scenario**



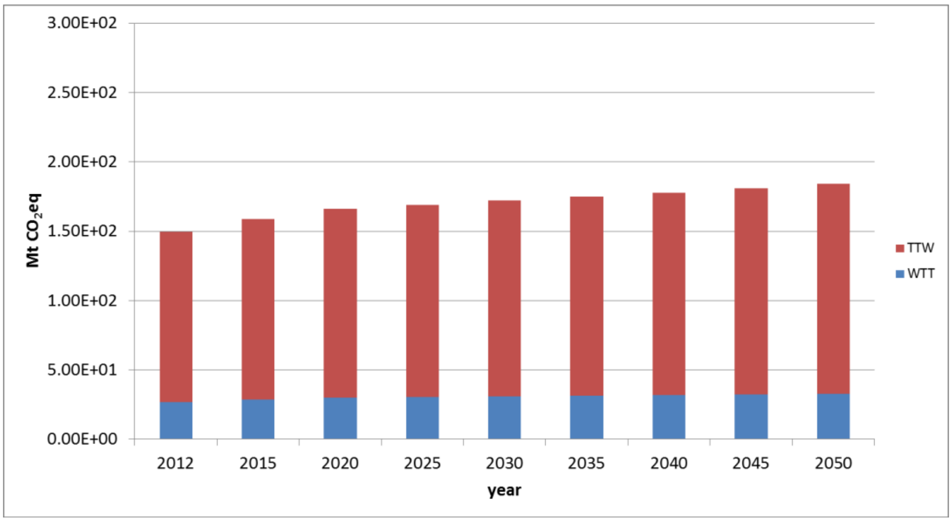
In contrast to the long haul trucks, in the delivery truck BAU scenario, a 10% tkm share of hybrid drivetrains in 2050 is anticipated (see Figure 47). Experts expect that HEV will have a positive business case within the following 5-7 years. Thus, slow HEV diffusion into the market starts in 2020. Furthermore, it is assumed that current cost, technology and infrastructure bottlenecks will not be satisfactorily solved and thus, alternative vehicles like BEV and FCHEV will not penetrate the market until 2050.

Figure 47 Delivery trucks BAU scenario



The specific GHG emissions factors discussed above were applied to compute the well-to-tank (WTT) and tank-to-wheel (TTW) CO_2 eq. emissions and combined total well-to-wheel WTW CO_2 eq. emissions. Incremental drivetrain efficiency improvements over time cannot offset the diesel dominance and the increase of the hauling capacity in this scenario. Hence the GHG emissions in Figure 48 will increase by approximately 23% until 2050 compared to the 2012 level (from 149 Mt CO_2 eq. to 184 Mt CO_2 eq.).

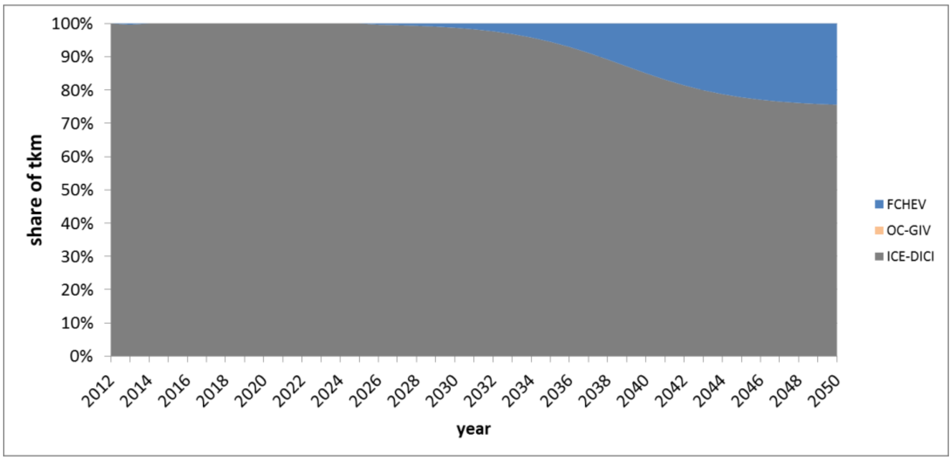
Figure 48 BAU scenario and the related emissions in Mt CO_2 equivalent



5.2.2 Alternative 1 (ALT 1) favourable scenario

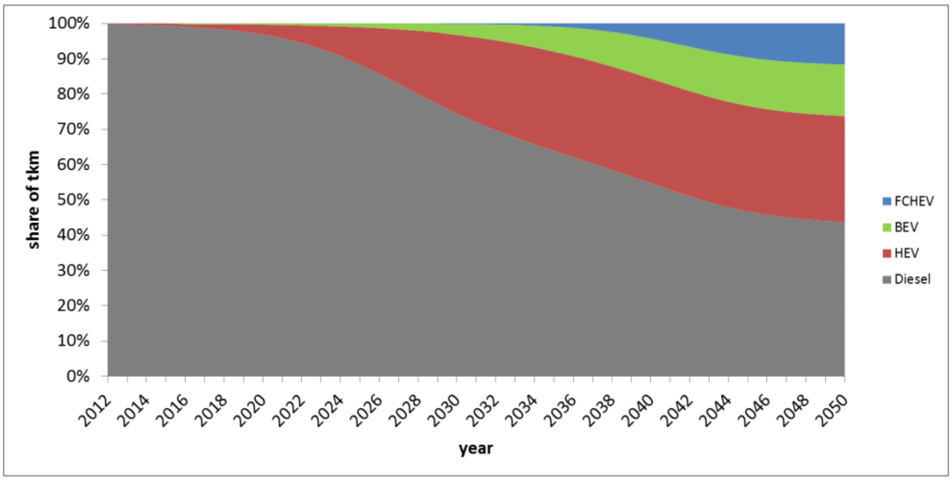
In the ALT 1 long haul scenario, FCHEV will enter the market in 2030 onward due to the convergence towards the TCO level of the ICE-DICI (see Section 3.7). The OC-GIV is more cost-effective from a vehicle point of view but not when taking infrastructure costs into account. Thus, the FCHEV will reach a tkm share of 25% by 2050 (see Figure 49).

Figure 49 Long-haul trucks ALT 1 scenario



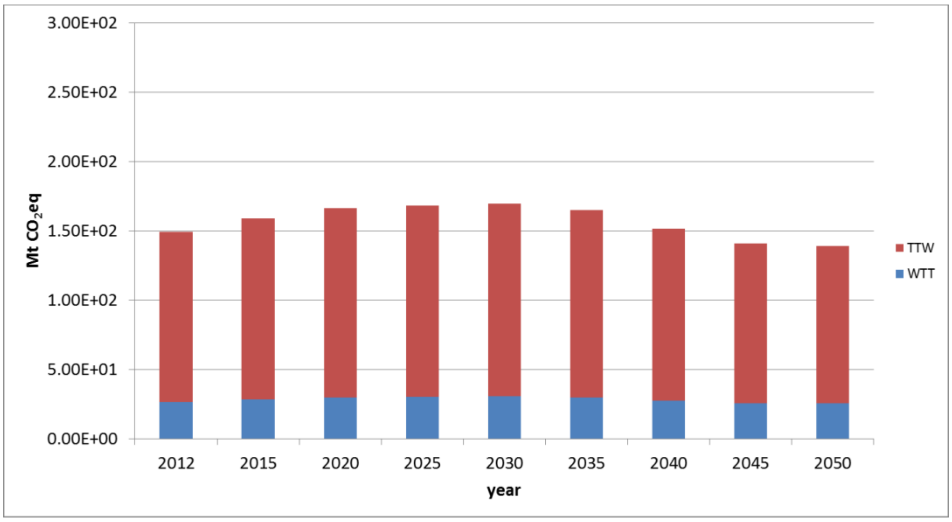
In the sector of delivery trucks, HEV have a rising tkm share of up to 10% until 2025 caused by the anticipated positive business case as described before. After 2025 the BEV technology will penetrate the market as they become cost competitive and thus, tkm share will increase. From 2035 onward, also FCHEV will start to gain greater market shares. As a result of the strong competitiveness through 2050 and therefore a rising market penetration of the HEV and the zero tailpipe emission vehicles, tkm share of the conventional ICE-DICI vehicles decline. By 2050, the alternative vehicles reach a combined tkm share of 56% (see Figure 50).

Figure 50 Delivery trucks ALT 1 scenario



Phasing in of the alternative vehicles leads to a slight reduction of GHG emissions starting in 2030. By 2050, GHG emissions are reduced by approximately 7% from 149 Mt CO_2 eq. to 139 Mt CO_2 eq. (see Figure 51).

Figure 51 ALT 1 scenario and the related emissions in Mt CO_2 equivalent

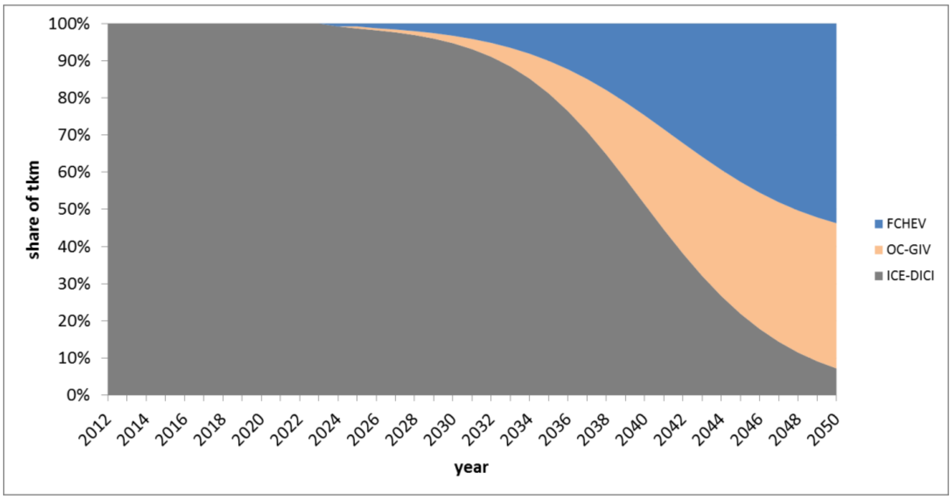


5.2.3 Alternative 2 (ALT 2) ambitious scenario

In this ambitious ALT 2 scenario, alternative drivetrains penetrate the long-haul market more rapidly and with higher penetration rates than in the ALT 1 scenario.

Not only will FCHEV reach competitiveness but the OC-GIV vehicles will also have a positive business case. This implies that the difficulty of infrastructure funding will be overcome. Thus, the OC-GIV technology will have a significant tkm share in 2050 through extension of motorway corridors in which OC-GIV can operate. Due to higher learning rates as well as accelerated progress in technology development, FCHEV will enter the market in 2025 and will reach a significant tkm share as well by 2050. In total, more than 90% of all long haul transport is then performed with zero tailpipe emission vehicles (see Figure 52).

Figure 52 Long-haul trucks ALT 2 scenario



In the delivery truck sector, it is assumed that a large share of transport is comprised of FCHEV and BEV. Hybrid electric and conventional ICE-DICI trucks will only play a minor role until 2050. HEV slowly enter the market and reach a peak of tkm share in 2020. BEV will play a significant role after 2020 and FCHEV will play a significant role starting in 2025. As a consequence, zero tailpipe emission vehicles will dominate the tkm share from 2030 onwards. Together they will perform 93% of the total delivery transport by 2050. Furthermore, the strong focus on zero tailpipe emission leads to a phase out of HEV and even more of ICE-DICI vehicles. Hence, hybrid technology is anticipated to be only a bridge technology (see Figure 53).

Figure 53 Delivery trucks ALT 2 scenario

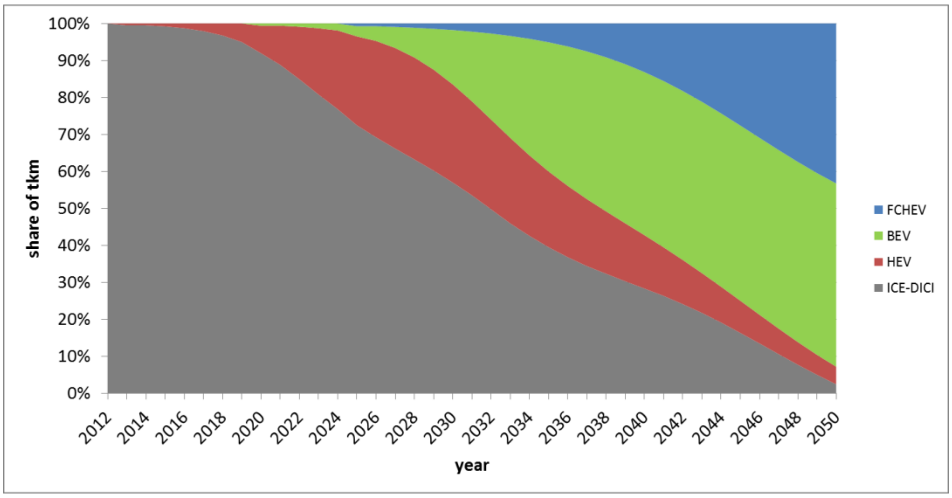
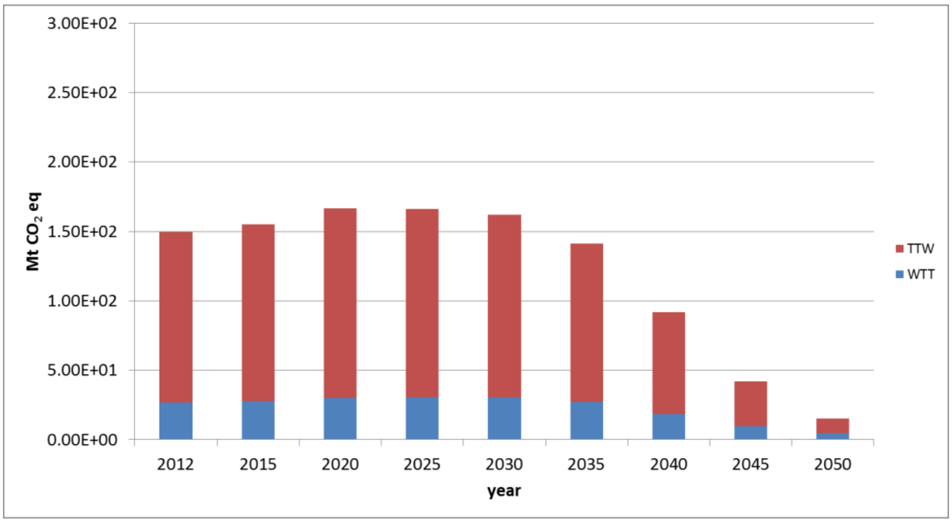


Figure 54 shows the GHG emission reduction in the ALT 2 scenario. The focus on zero tailpipe emission vehicles is crucial for the strong reduction of the GHG emission. Until 2050, GHG emission is reduced by approximately 90% from 149 Mt CO_2 eq. to 15 Mt CO_2 eq.

Figure 54 ALT 2 scenario and the related emissions in Mt CO_2 equivalent



5.3 Conclusion and discussion

The scenarios and the related results showed in this chapter have an explorative character and are not a prediction of the future. The aim is rather to show through different scenarios how zero emission vehicles can influence GHG emission levels.

With an increasing share of alternative low-emission drivetrains, both WTT and TTW emissions decrease at a faster pace. Starting from 149 Mt CO_2 in 2012, emissions increase in the BAU scenario steadily to about 184 Mt CO_2 in 2050. This is mainly due to the fact that no zero tailpipe emission vehicles will enter the market. The GHG emissions rise by 23%, meaning that fuel consumption improvement cannot outweigh the rising demand within the transport sector.

In the ALT 1 scenario, emissions rise until 2030 and then decrease again, reflecting an increasing share of alternative drivetrains starting to penetrate the market from about 2020 onwards. In 2050, annual GHG emissions are 7% lower than in 2012.

The ambitious ALT 2 scenario shows a more sharp emission cut compared to the ALT 1 scenario - down to 15 Mt CO_2 eq. until 2050, meaning a decrease of 90% compared to the 2012 value. This dramatic GHG reduction is mainly due to a high share of overhead catenary and fuel cell hybrid vehicles in the long haul sector. Furthermore, due to a tkm share of more than 90% regarding zero tailpipe emission vehicles (FCHEV and BEV) in the delivery truck sector. However, it has to be stressed that the assumed GHG reduction will need significant tightening of the alternative energy carriers policy.

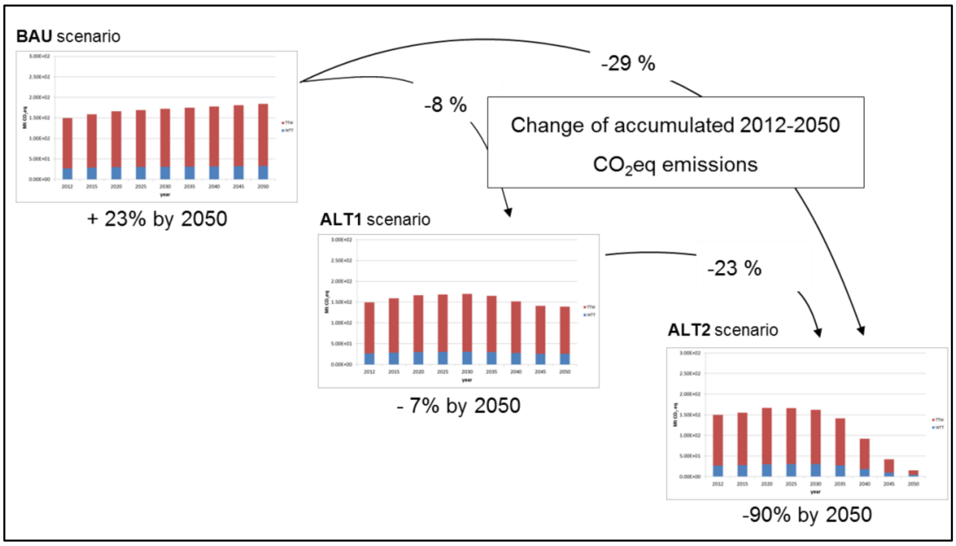
Table 46 illustrates the GHG emission levels in 2012 and in 2050 in the three scenarios, their relative changes, and the change of total GHG emissions in 2050 compared to the BAU scenario.

Table 46 Change of GHG emissions (WTT and TTW) in Mt CO_2eq. by scenario

	2012	2050	% change compared to 2012
BAU	149.4	184	+23%
ALT 1	149.4	139	-7%
ALT 2	149.4	15.2	-90%
	2050		**% change compared to BAU**
BAU	184		-
ALT 1	139		-25%
ALT 2	15.2		-92%

Although annual GHG emissions decrease considerably sharply in the ALT 2 scenario (by 90% until 2050 compared to 2012 levels), the accumulated 2012-2050 GHG emissions decrease only by 29% compared to the BAU scenario (see Figure 55). The accumulated GHG emissions in the ALT 1 scenario are 8% less than in the BAU scenario. The comparison of the ALT 1 with the ALT 2 scenario shows that in the ALT 2 scenario, GHG emissions are further reduced by 23%.

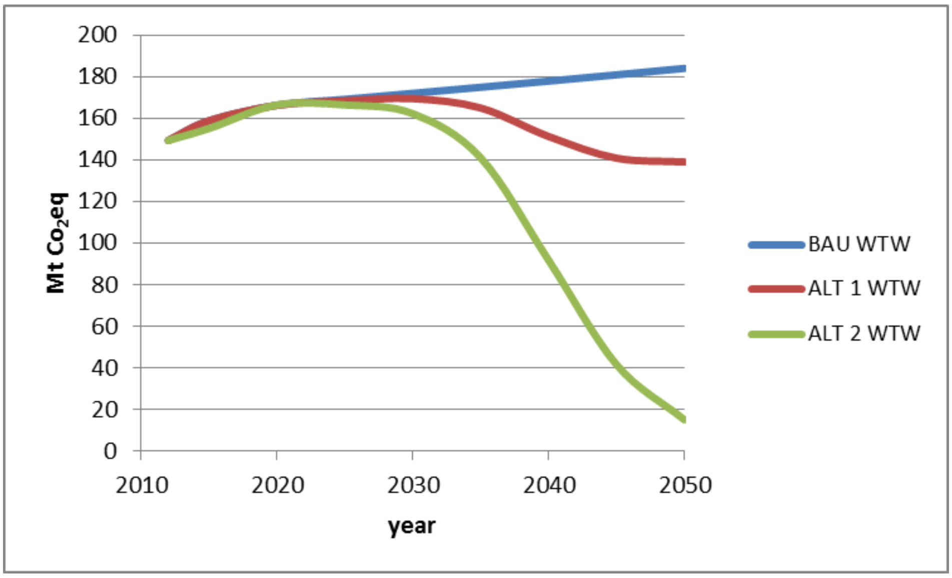
Figure 55 Comparison between the different scenarios



The comparison of the different GHG emissions by scenario showed, that decarbonisation of drivetrains is very important for reducing the on-road goods carbon footprint.

Furthermore, as a result of a large-scale zero-tailpipe emission vehicle phase-in that use hydrogen and electricity as energy sources, a serious decarbonisation over time can be achieved once the fuel production chain is decarbonised as well (see Figure 56).

Figure 56 Well-to-Wheel CO_2 eq. scenario development



6 Conclusions and discussion

The European Commission's White Paper on Transport states that the transport sector should reduce its emissions by 60% by 2050 compared to 1990 levels. Fuel cell electric and battery electric trucks are the most promising alternatives to supplant conventional diesel trucks by 2030 due to the ability of hydrogen and electricity, and the relative difficulties in achieving deep carbon reductions from biofuels with indirect land use change and sustainability concerns in the on-road freight sector

This assessment included four parts. The technical analysis included a technology assessment of available zero tailpipe electric and hydrogen vehicles. A cost analysis was conducted to estimate the TCO of these alternative vehicles. Hereafter, the role of different policy instruments and an assessment of different GHG reduction scenarios were evaluated. The data sources of this work included a survey of five truck manufacturers, expert consultations with 12 relevant organisations, and an extensive literature review.

To get an overview of the current and future product offerings of EU truck manufacturers, a questionnaire was sent to five of the largest truck manufacturers. Their feedback shows that manufacturers are currently starting to offer hybrid trucks for both distribution and long haul applications. Half of the manufacturers are developing electric distribution trucks. Currently, truck manufacturers are not developing fuel cell trucks. One manufacturer is investigating fuel cell drivetrains as an option, and another has on-going research in this area. The remainder of the manufacturers are not engaged in any research or development activities for fuel cell drivetrains. For battery electric trucks, technologies that are an alternative to the sole use of batteries, such as overhead catenary wires and inductive charging, receive limited attention from most manufacturers. This is a consequence of the absence of customer demand and the general uncertainty about the potential of these vehicle and infrastructure technologies. Due to these factors, truck manufacturers are reluctant to make any significant investments in zero tailpipe emissions alternatives other than battery plug-in vehicles that are now used for city distribution on small scales.

6.1 Technology assessment

6.1.1 Electric trucks

To date, electric truck deployment has generally been limited to urban areas. These vehicles can be charged overnight and offer a sufficient range; the electric trucks of Smith have a range of 80-190 kilometre for example. Currently, there are around 1,000 electric distribution trucks operated worldwide. Battery calendar life and deep cycle life are close to the requirements for distribution vehicle application. Significant technology improvements are expected within the next five years, especially with respect to the durability of current battery technologies. Also, costs of battery packs are expected to decrease.

Next generation batteries are being investigated at the moment, but no prototypes exist yet for heavy-duty vehicle applications. Their main advantage is that energy density may improve up to a factor 10 in the period after 2030. These batteries reduce problems with additional weight and limited driving range simultaneously. However, there are several challenges that need to be overcome before advanced batteries, such as Li-air, can be implemented. The most important barriers are the limited power density and cycle life (not fully reversible chemical reactions), the large volume of the cathode, and the need for air purification.

Experts do not agree about the degree of energy density improvement that can be obtained with these batteries. The commercial potential of these advanced battery concepts depends on how the current bottlenecks can be resolved. Even with significant improvements in energy density (Wh/kg) and the effective resolution of other technical barriers, batteries will not meet the requirements for long haul transport applications, as the significant projected weight penalty imposed by the batteries render this technology option impractical. If, for example, a factor of 5 to 10 increase in energy density could be achieved in batteries, the weight increase for a 40 tonne GVW truck would be around 2,000-4,000 kg. Battery electric drivetrains will likely not be used in long haul trucks unless alternative charging infrastructures, such as overhead catenary wires or dynamic inductive charging are widely developed and deployed. Industry experts confirm this view.

Current research is ongoing in the application of nano structures in the design of electrodes to allow for fast charging. However, this will increase battery volume. Some scientists have reached charging times under 10 minutes using this technology. However, batteries that allow for this kind of fast charging are not on the market yet.

6.1.2 Fuel cell trucks

Fuel cell drivetrains are generally less efficient than electric drivetrains, since hydrogen needs to be transformed into electricity before it can be used to drive the electric motor, and there are losses inherent to this transformation. However, as indicated above, hydrogen may be preferred over batteries due to the superior driving range provided by this technology, especially for long haul applications.

One of the most significant challenges for fuel cells is to reach adequate durability. At the moment, durability tests up to 10,000 hours have been not been performed. For distribution purposes, this is close to what is needed, but for long haul purposes approximately 14,500 hours of operation or more are needed.

The volume and weight of the hydrogen storage vessels are critical issues, especially for long haul transport. For a typical long haul truck with a range of 1,000 km, a hydrogen tank with a capacity of approximately 1,700 kg would be needed with 700 bar hydrogen storage. The corresponding required volume is about 3.8 m^3. 700 bar storage is currently state-of-the-art. Physical and chemical adsorption are being researched and offer the potential of increased gravimetric densities and smaller volumes.

Fuel cell introduction in the distribution truck segment over the next 10 years is possible from a technology perspective, but adoption is highly dependent on the availability of fuel infrastructure, improved economics, and customer acceptance. Penetration in the long haul trucking sector seems to be feasible in the long term but definitely requires more research in onboard hydrogen storage.

6.1.3 Infrastructure requirements

The development of a vehicle charging and hydrogen refuelling infrastructure is an important criterion for the introduction of electric and fuel cell vehicles, respectively.

For battery electric vehicles, several charging options are possible. For the wide-scale adoption of electric distribution trucks, fast-charging may be required in addition to overnight charging. However, this requires both batteries that allow for high power charging and a network of fast-charging stations. The latter will require significant investments.

Another option would be to deploy battery swapping, which has the potential to significantly reduce charging times and the upfront owner costs of electric vehicles. However, standardisation would be required for both the design of the battery swapping stations as well as the design of the electric vehicles so that all electric vehicles could make use of each swapping station. Creating an infrastructure of swapping stations and a stock of replacement batteries would require significant investments. Since the technology of batteries is expected to change significantly over time, several types of batteries would need to be available at every swapping station, to accommodate different types of vehicles. The swapping station itself and the large amount of battery inventory required make battery swapping a relatively expensive approach and may be less attractive if large-scale fast-charging infrastructure is developed.

For long haul applications, an onroad charging infrastructure could enable battery electric trucks since less energy will need to be stored onboard the vehicle. However, introducing sufficient coverage of overhead wire infrastructure or dynamic inductive charging requires massive investments. Both technologies have been tested in demonstration projects at a small scale. These field tests have shown that the technologies can work.

Fuel cell trucks require an adequate hydrogen refueling network that is not available at the moment. If such a network can be accomplished, fuel cell trucks can be applied to both truck segments.

Chicken and egg problem
The importance of sufficient charging and/or refuelling networks is not a topic of discussion. Unfortunately, a ‘chicken and egg problem’ applies to the introduction of zero tailpipe emissions vehicles and the necessary infrastructure, since the investments costs are high. As part of the roadmap, governments should carefully evaluate whether the availability of infrastructure becomes a bottleneck and whether the industry needs help from the government for developing this infrastructure. Governments and the industry may cooperate in public-private partnerships, which would share the risks and benefits of building an infrastructure.

The European Commission recently published a proposal for a Directive on the development of an alternative fuel infrastructure in Member States (European Commission, 2013). The Commission obligates the Member States to develop an action plan and sets a target for electric vehicle charging points to be met by Member States. While this is a necessary first step, the chicken and egg problem has yet to solved.

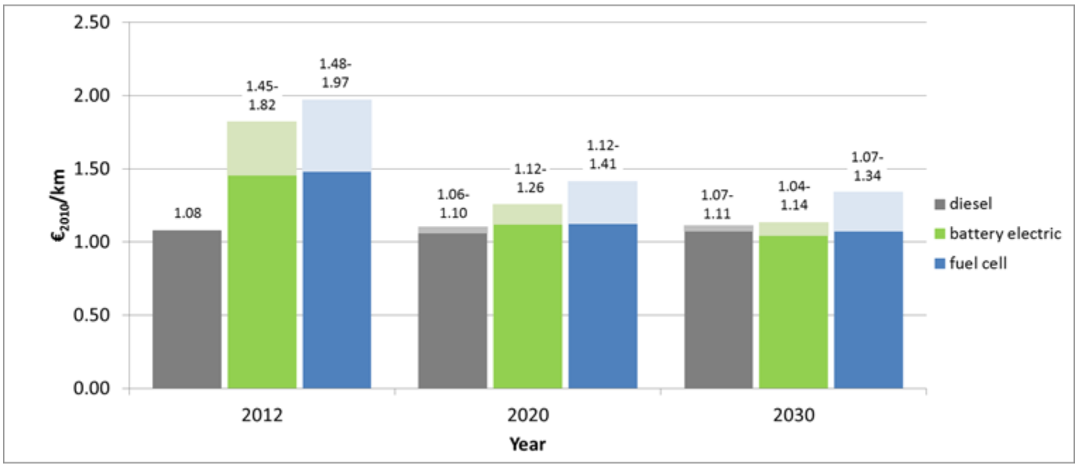
6.2 Estimate of total ownership costs

The total costs of ownership (TCO) analysis estimates that the costs of conventional vehicles and alternative vehicles will converge over the next two decades. However, the extent to which the costs will decrease is uncertain. Two parameters are especially uncertain: the energy carrier price and the costs of batteries and fuel cell systems. The first is uncertain due to demand and supply deviations, and the latter depends strongly on technological developments and expected economies of scale.

Interestingly, for the total costs of ownership, the operating-to-fixed-cost ratio is around 80/20 for the reference vehicle, whereas for alternative vehicles the ratios are around 40/60. Over time, as zero emission truck production volumes increase and the production costs decrease, the operating-to-fixed-cost ratio for alternative vehicles becomes closer to that of conventional vehicles.

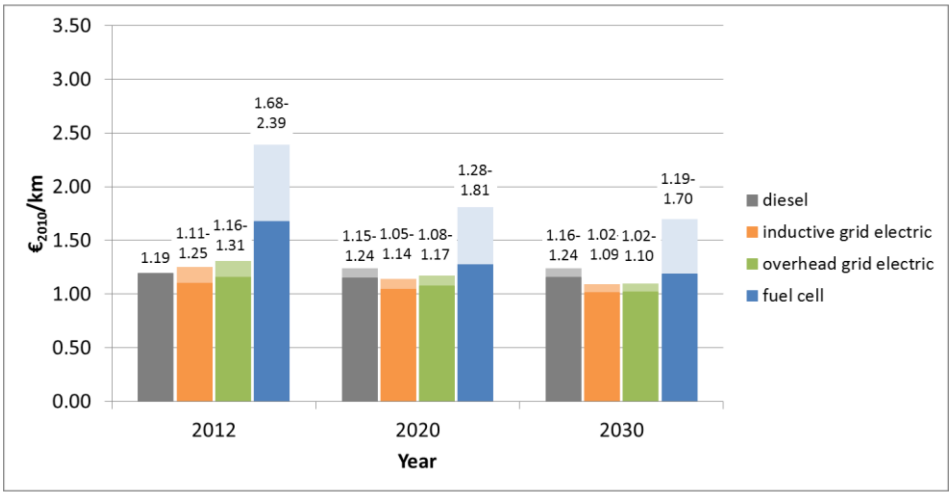
In Figure 57 and Figure 58 the costs of the different vehicle configurations are depicted for distribution and long haul trucks, respectively. The low-cost scenarios are shown with dark colours, while the high-cost scenarios have light colours.

Figure 57 TCO costs for distribution vehicles



Note: TCO of the vehicle only. Infrastructure costs of a battery charging and hydrogen refuelling network are not included for the battery electric and fuel cell vehicles, respectively. Non-existing taxes are not included.

Figure 58 TCO costs for long haul vehicles



Note: TCO of the vehicle only. Infrastructure costs are not included for the inductive grid electric, overhead grid electric and fuel cell electric vehicles. Non-existing taxes are not included.

As shown in the figures above, the TCO of fuel cell vehicles (FCHEV) are higher than those of electric vehicles (BEV). Both the electric and fuel cell vehicles only become competitive under the assumed scenario of battery and fuel cell system cost reduction with additional technology improvements. It should be noted that infrastructure costs are not included in these figures.

Additionally, fuel taxation (i.e. excise duty) is not included in the figures above. The large shares of alternative fuels that have been depicted in the GHG scenarios chapter may not be realistic without fuel taxation, since governments use the yields from fuel taxation for their budget expenditures. If all fuels are taxed in the same way as diesel per unit of energy, trucks fuelled by hydrogen and electricity would be more expensive, approximately 4-7 €cents per km for alternative distribution vehicles and 8-12 €cents per km for alternative long haul vehicle.

From Figure 57 and Figure 58 it can be concluded that the costs of zero tailpipe emission vehicles can become competitive with conventional vehicles within the next two decades. This is especially the case for the battery electric truck (distribution segment) and for the inductive and overhead grid electric vehicles (long haul segment). When taking into account the uncertainty ranges it seems likely that the total transport costs would not significantly increase (i.e. not increase more than 10%), limiting the impact on the EU economy when these technologies are introduced.

6.3 The role of policy instruments

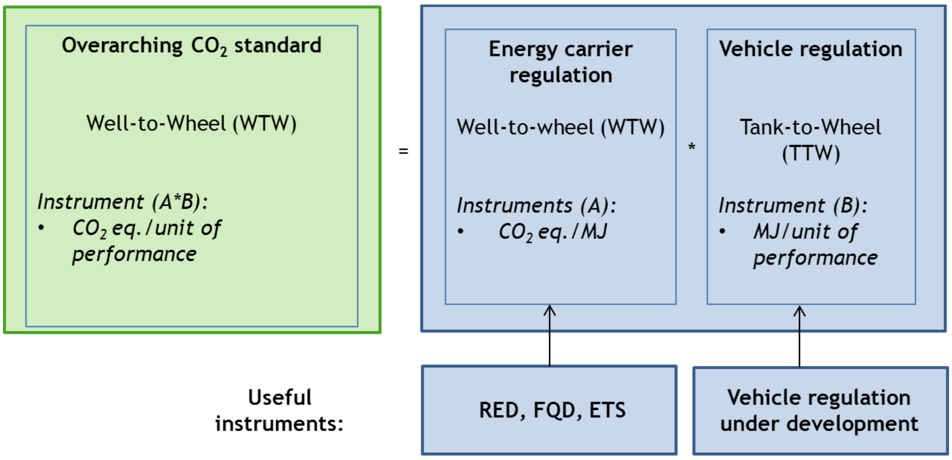
There is general consensus that governmental policies are a necessity for the large-scale development and introduction of zero emission vehicles and the introduction of energy carrier pathways that provide lower GHG emissions.

In some applications, such as city distribution, zero emission trucks can be introduced at an earlier stage than for long haul applications due to lower upfront investments, fewer technological barriers, liveability arguments (reduced pollutant emissions and noise), and better economics. Currently, advanced technologies are already being introduced in many countries for urban bus transport and in city goods distribution.

Policy incentives should be directed at the niche zero emission truck applications during early stages of deployment and then expanded to include mainstream applications as adoption of advanced technologies increases. Policy measures are needed in during early stages of commercialization to offset high capital costs and encourage early adopters. Local and national governments may play a significant role at this point. Policy instruments that can encourage the development and implementation of zero emission vehicles are subsidies, tax incentives ,and other fiscal instruments.

Larger uptake of zero emission vehicles requires an EU policy strategy that provides clear signals to the trucking industry on the way forward. This can be accomplished by developing a roadmap for the introduction of zero emissions trucks. This roadmap can be supported by a package of policy measures. This policy package should change from a stimulating character to a more regulatory character. This framework should not only cover the emissions of trucks (i.e. vehicle regulation), but also cover the fuel feedstock pathways, as this is important from a well-to-wheels perspective.[39] In other words, an overarching set of climate policies needs to be implemented that targets both the energy carrier and the vehicle. Figure 59 provides an overview of the elements that need to be covered by this set of policy measures.

Figure 59 Overview of set of vehicle and fuel regulations



As can be seen in the figure, several policy instruments already exist, or are under development, that are part of an overall CO_2 framework for heavy-duty vehicles. For the energy carrier, the Renewable Energy Directive (RED), the Fuel Quality Directive (FQD), and the European Emissions Trading System (EU ETS) are currently in place.

The framework used in the FQD/RED can be used to gradually reduce the GHG impact of electricity and hydrogen production for transport in the coming decades. The FQD requires a 6% reduction of GHG emissions in the carbon content of supplied fuels by 2020. After 2020, this value can be gradually

[39] A fuel cell truck powered by hydrogen from coal gasification does not reduce the vehicles emissions over the well-to-tank chain. The use of power for coal firing in electric vehicles does also not lead to lower emissions.

increased to stimulate the production of lower-carbon energy carriers. In addition, the EU ETS and the RED aim to lower emissions and increase the share of renewables in electricity production.

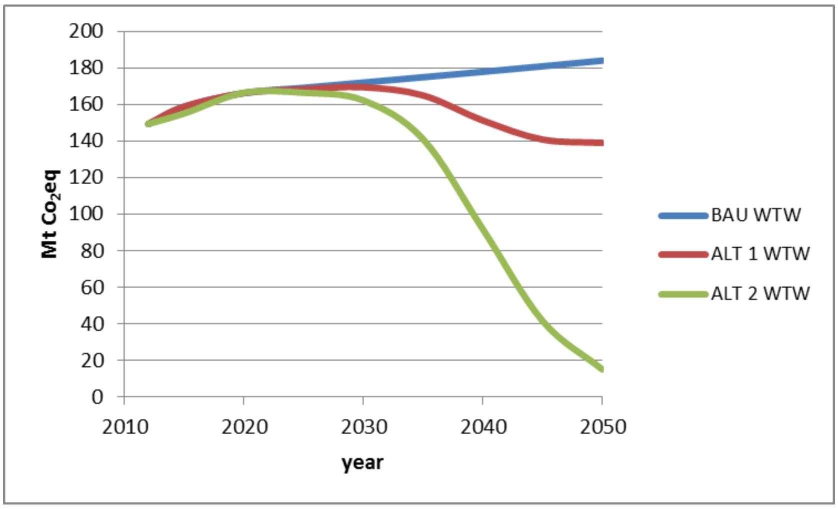
The European Commission is currently evaluating the options for regulating the vehicle energy consumption of trucks. The average fuel consumption of all sold vehicles, irrespective of technology, should be tightened over time in order to reduce vehicle's energy consumption.

6.4 GHG scenarios

Two GHG reduction scenarios have been developed to explore the potential of zero emission technologies. According to the EU's energy roadmap, electricity will be significantly decarbonised in the period up to 2050. This will result in an even larger GHG reduction impact for alternative vehicles than those that use conventional diesel. If the FQD requirements are tightened in the future, hydrogen pathways are decarbonised as well. Decarbonisation of the fuel supply is very important. If the fuel chains are not decarbonised, well-to-wheel emissions of zero tailpipe emission vehicles will not necessarily be lower than that of conventional vehicles.

Under the BAU scenario, the GHG emissions of truck transport in the EU will increase by 23%, due to increased transport volumes. Two alternative scenarios have been developed, as shown in Figure 60. The optimistic scenario assumes a 50% share of alternative vehicles (measured in tkm) in the fleet by 2050, including hybrid trucks. Under the ambitious scenario, this penetration rate is assumed to be even larger, around 90%. The results show that with increased transport activity, the GHG emissions still decrease by 8% in the optimistic scenario and by 90% in the ambitious scenario in 2050,[40] compared to 2012. This shows that the combination of zero emissions fuels and vehicles has the potential to decarbonise the freight transport sector.

Figure 60 Overview of the three scenarios explored



[40] The EU target for transport is -60% for transport as a whole between 1990 and 2050. If this target for trucks is used, the 90% reduction is not very different, since the growth between 1990 and 2012 has been significant.

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Annex A List of consulted organisations

- EU Truck manufacturers:
  - Daimler
  - Daf
  - Volvo
  - Scania
  - Renault
  - MAN
  - Iveco
- Spijkstaal
- Hytruck
- Johnsson Controls
- Eurobat
- PVI
- Delft University of Technology
- Bombardier
- IAV
- Siemens
- Hydrogenics
- NuCellSys
- Deutsche Post DHL

Annex B OEM Questionnaire

ZERO EMISSION TRUCKS

On behalf of the ICCT (International Council on Clean Transportation), research and consultancy company CE Delft and German Aerospace Center (DLR) carry out a study on current and future zero-emission technologies[1] in the EU on-road freight sector.

One focus of the analysis consists of mapping state of the art technologies and assessing the potential of prospective emission reducing drivetrain and energy storage technologies seen by OEMs and the relevant suppliers.

The study covers the following phases:

- survey of state-of-the-art zero-emission technologies
- technology roadmaps
- costs analysis
- life-cycle reduction potential compared to traditional trucks and fleet-wide scenarios
- policy measures to accelerate the adoption of zero-emission trucks

We developed a questionnaire for the first two phases described above on drivetrain concepts, energy storage and energy converter systems. The questionnaire is attached to this mail

We would be very grateful if you could tell us a the right person to contact in your company / forward the questionnaire to the right contact person in your organization.

Up to your preference you can answer the questions by filling the questionnaire or on the phone. We will of course employ your results anonymously.

In case of further questions, feel free to contact us anytime.
Thank you very much for your support.

Best regards,

[1] This implies that we take technologies into account that massively reduce fuel consumption.

List of Questions

1. What non-conventional trucks (hybrid/electric/CNG/LNG/hydrogen) is your company producing at the moment that might pave the road towards zero emissions trucking?

type	GVW (tonne)	power (kW)	technology	partners

2. What zero-emission technologies does you company believe to play a role for trucks in the period of 2030-2050. *Please indicate in the table: yes/no/unsure.*

	hybrid	Battery plug-in	Battery swapping	Overhead catenary wire	Stationary Inductive charging	Dynamic Inductive charging	hydrogen	---
Regional delivery trucks								
Long haul delivery trucks								

Please explain the view of your company:

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3. What technology does your company develop/follow these days?
Please fill out in the table: *implementing/engineering/researching/following/non*

	Regional delivery trucks	Long haul delivery trucks
hybrid		
Battery plug-in		
Battery swapping		
Overhead catenary wire		
Stationary Inductive charging		
Dynamic Inductive charging		
Hydrogen		
.....		

4. What do you believe are the main bottlenecks for the different options? How could these be overcome? *Please fill out the bottleneck per technology in the table below:*

	Main bottleneck	Steps needed to be overcome
Hybrid		
Battery plug-in		
Battery swapping		
Overhead catenary wire		
Stationary Inductive charging		
Dynamic Inductive charging		
Hydrogen		
....		

5. To what extent would vehicle weight increase due to batteries or other equipment be acceptable, especially in the segment of large trucks?

	none	<200 kg	400 kg	600 kg	800 kg	>1000 kg
Regional delivery trucks (<12 tonne)						
Long haul delivery (>12 tonne) trucks						

Annex C Specific H_2 storage data used

		350 bar technology	700 bar technology	liquid storage	physical and chemical adsorption
Vessel Type	[-]	III	IV	N.A.	N.A.
Nominal pressure	[bar]	350	700	1	N.A.
Netvolume	[m³]	0.10	0.12	N.A.	N.A.
Vessel weight	[kg]	48	84	150	N.A.
Vessel volume	[m³]	0.15	0.20	0.23	N.A.
H_2 density at 25°C	[kg/m³]	23.3	39.3	-	N.A.
H_2 density at -253°C	[kg/m³]	-	-	70.8	-
H_2 content	[kg]	1.68	4.54	9.00	N.A.
Gravimetric H_2 content	[kg H_2/kg storage]	0.035	0.054	0.06	0.03
Volumetric H_2 content	[kg H_2/m³ storage]	16	23	40	42

N.A.: Information not available

Source: with relation to Eichlseder (2008)