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INFRASTRUCTURE AND VEHICLES FOR HEAVY LONG-HAUL TRANSPORTS FUELLED BY ELECTRICITY AND HYDROGEN – AN OVERVIEW

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities,
- Carries through system oriented research related to the entire renewable fuels value chain,
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

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SUMMARY

The overall aim with this report is to provide an updated view of the technical and economic development for long-haul road transports fuelled by electricity and hydrogen in a Swedish context. A lot of research, development and demonstration efforts are directed towards electric roads and fuel cell vehicles and two of the major demonstration projects worldwide are situated in Sweden (in Sandviken and Arlanda). Several main actors involved in the electric road system technologies in the Swedish projects have been interviewed, as well as heavy vehicle manufacturers and hydrogen fuel suppliers.

Three different types of electric road systems – overhead conductive, rail conductive and dynamic inductive – have been studied together with fuel cells. Estimates for the present and future vehicle and infrastructure costs have been derived from literature sources and adapted, and these estimates have been compared to the costs of conventional long-haul diesel lorries. Estimations for the energy costs of the different solutions have been made. The energy costs of comparison are without taxes, since we have assumed that the taxes per km in the future will be similar for different means of propulsion. This assumption is in turn based on an assumption that the fiscal impact for a major shift towards some specific way of propulsion otherwise would be considerable, which would not be tolerated by any government.

In the beginning of the considered time period (2017 to 2030), the vehicle costs of the new technologies, especially for the fuel cell vehicles, were found to be much higher than for conventional diesel vehicles. Towards the end of this period, the differences were not as significant according to the cost projections. The infrastructure costs of the electric road systems were found to be high and the costs of the dynamic inductive solutions were the highest.

The energy costs per km were estimated for three different electricity prices and three different diesel prices. The lower and upper ends of these prices represented extremes during the last decade. As expected, the energy costs were found to be the lowest for the electric road system with the lowest of the three considered electricity prices. The energy cost of hydrogen was only lower than all corresponding diesel costs at the lowest of the electricity prices. Somewhat unexpectedly, the estimated energy costs were actually found to be the highest for the fuel cell long-haul lorry at the highest of the considered electricity prices.

SAMMANFATTNING

Det övergripande syftet med föreliggande rapport är att ge en samlad och uppdaterad bild av det tekniska och ekonomiska utvecklingsläget för långväga tunga vägtransporter med el och vätgas som drivmedel utifrån svenska förutsättningar. Globalt sett pågår intensiv forskning om samt utveckling och demonstration av elvägar och bränsleceller för vägbundna transporter och två av demonstrationsprojekten för elvägar finns i Sverige (Sandviken och Arlanda). Flera aktörer kopplade till dessa projekt har blivit intervjuade under arbetet med rapporten och det har också representanter från tunga fordonstillverkare och vätgasleverantörer.

Tre olika tekniker för elvägar har studerats närmare: konduktiv överföring via hängande tråd och räls i vägen samt induktiv överföring. Dessutom har information om bränsleceller för drift av tunga vägtransporter inhämtats från litteraturen. Uppskattningar av nuvarande och framtida kostnader för fordon, infrastruktur och drift har inhämtats och kostnadsupp-skattningarna för fordon har anpassats för jämförelser med konventionella dieseldrivna långtradare. Jämförelser av drivmedelskostnader har gjorts utan några skattepåslag eftersom vi har utgått från att alla tekniska sätt att transportera gods på vägar kommer att beskattas likartat av fiskala skäl när tekniken väl har nått en viss volym.

De uppskattade kostnaderna för fordon med nya tekniker var högre än för de konventionella fordonen i början av den tidsperiod som studerats (2017 till 2030) och det gäller framför allt bränslecellsfordonen. Den uppskattade skillnaden mot slutet av perioden var betydligt mindre. De kostnadsuppskattningar för infrastruktur som erhållits från litteraturen eller intervjuer visade att kostnaden för nya elvägar är hög och att kostnaderna för induktiv överföring är högst av de studerade teknikerna.

De specifika kostnaderna för drivmedel per kilometer uppskattade för tre olika elpriser och tre olika dieselpriser. Kostnadsuppskattningarna gjordes bara utifrån kostnader för diesel respektive el in till elväg eller elektrolys (för vätgasfallet), inga fasta kostnader togs alltså med i beräkningarna. De högsta och lästa priserna för el och diesel motsvarade ytterligheter gällande priser för dessa drivmedel under det senaste decenniet. Det visade sig föga förvånande att elvägar hade den lägsta uppskattade specifika drivmedelskostnaden vid det lägsta elpriset. Drivmedelskostnaderna för de vätgasdrivna bränslecellerna var bara lägre än kostnaderna för den konventionella långtradaren vid samtliga studerade dieselpriser när det lägsta elpriset användes i kostnadsuppskattningen för vätgasproduktionen. När det högsta av de tre elpriserna användes vid vätgasproduktionen, visade sig bränslecellerna ha de högsta specifika drivmedelskostnaderna av samtliga av de studerade alternativen.

ABBREVIATIONS

AC	Alternating current
ARS	Additional required system
APS	Aesthetic Power Supply (Alstom trademark)
DC	Direct current
DI	Dynamic inductive
ERS	Electric road system
GHG	Greenhouse gases
ICE	Internal combustion engine
OC	Overhead catenary
RC	Rail conductive

CONTENTS

1 INTRODUCTION

The ambitions considering reductions of greenhouse gas (GHG) emissions in Sweden are high and the latest overall goal expressed by the Swedish Government are zero net emissions of GHG by 2045 (Government of Sweden, 2017). The relative importance of the transport sector in achieving this goal is more obvious in Sweden than in most other countries, mostly due to the relatively minor GHG emissions from the energy utility sector. Thus, the government has set a sectoral sub-target to reduce the GHG emissions from the domestic transport sector by 70% in 2030 compared to 2010 (ibid.). After cars, the road-bound transports of goods emit the largest share of GHG from the Swedish transport sector (Statistics Sweden, 2017). There are several strategies to reduce GHG emissions from heavy-duty road-bound long-distance transports, i.e. long-haul transports. One is to reduce the number and efficient use of lorries e.g. through switching to rail transport, efficient driving, route optimisation, and increased degree of filling. A second is to use more fuel-efficient vehicles, and a third to use renewable fuels, including electricity (Government of Sweden, 2013; Ahlbäck and Johansson, 2015; Sweco, 2016). This report is about the third strategy, and, to some extent, the second.

Developing more fuel-efficient vehicles with conventional or new renewable fuels has been a priority for the automotive industry. The heavy-duty transport industry is no exception from this. Most efforts within development have been directed towards hybrid solutions where batteries are integrated with conventional drivetrains, fuel cells with hydrogen, and pure electrified vehicles. The hybrid solutions are now a commercially mature technology. The focus of this report, direct electrification and fuel cells, are technologies that still are under development. Electrification via batteries has until now not been a realistic alternative for heavy-duty long-haul transports, due to weight and space restrictions, but there are indications that this might change (Tesla, 2017). However, electrification via conduction, induction or fuel cells – the technologies studied in this report – are under a rapid development, not least in Sweden. These technologies demand changes in both the vehicles and the distribution infrastructure for the fuel (electricity or hydrogen), while this is not the case for some other solutions with renewable transportation fuels, e.g. hydrogenated vegetable oils (HVO). Thus, the shift to electrified long-haul transports is more of a technological transition than shifting to a fuel that can be distributed through established supply chains and used directly in conventional vehicles.

In chapter 2 in this report, an overview of the development for three technologies for electric road systems is presented: overhead catenary (OC), rail conductive (RC, and dynamic inductive (DI) systems. This is followed by an overview of fuel cell technologies for transportation in chapter 3. A gate-to-wheel energy cost comparison of the technologies is presented in chapter 4, followed by a brief concluding discussion in chapter 5.

1.1 AIM

The report provides an updated overview of the technical and economic development for long-haul road transports fuelled by electricity and hydrogen in a Swedish context. The primary focus is on direct conduction and fuel cells, since these are the technical pathways towards which most research, development and demonstration efforts are directed. Information has been gathered from scientific and grey literature, combined with interviews with vehicle manufacturers and electric road equipment and hydrogen suppliers, stakeholders with in-depth knowledge about long-haul road transports fuelled by electricity and hydrogen.

2 ELECTRIC ROAD SYSTEMS

Electric road systems (ERS) is a dynamic technology to transfer power from the road to vehicles in motion. This means that the required traction energy is not stored on board or that the support system, in this case usually a battery, is reduced compared to a pure battery electric lorry. Several technologies and pilot tests are currently being developed globally. The main competing technologies are power transfer from the road to the vehicle through conductors in the road (commonly rails), overhead catenary systems, and inductive solutions.

In Sweden, the Swedish Transport Administration has, together the Swedish Energy Agency and the public innovation founder Vinnova, performed a pre-commercial procurement in which two technologies intended for conductive electrification on highways were selected for further demonstration. The first is the *eHighway* by Siemens in a project on the highway E16 outside Sandviken, and the second is *Elways* in the project eRoadArlanda (Swedish Transport Administration, 2017). A description of the technologies follows in the sections below, together with cost estimates.

2.1 OVERHEAD CATENARY SYSTEM

The overhead conductive (overhead catenary, OC) solution uses a pantograph as a connector between the vehicle and electric overhead lines of the catenary system. For road systems, the pantograph must also be adaptive in order to connect and disconnect to the overhead catenary system during motion. Siemens, the major infrastructure stakeholder involved in OC, has developed and tested this technology in a system called eHighway.

2.1.1 The eHighway solution

When connected to the catenary system, the heavy-duty vehicle operates full electric reaching efficiencies as high as 85% from input from the grid to output from the motor (IEA, 2017a). This may be compared to conventional internal combustion engine (ICE) lorries in which tank to motor efficiencies reach up to 44% when driving on an uncongested road (VTT, 2013; Pettersson, 2017). The efficiency is then measured as from electricity or fuel in to power output from the engine or motor. When the electric lorry travels in non-electrified parts of the road, it should operate with a support system. According to Siemens, many alternatives and combinations for the support system exist: the vehicle could be equipped with on-board energy storage in form or batteries, have a conventional internal combustion engine, or use hydrogen in fuel cells as the support system. Possible applications for the eHighway system are open system as highways and long haul traffic corridors or closed traffic systems, such as shuttle transports and mine operations.

The eHighway is approved to be used in the Swedish highways by the Swedish Transportation Authority within the existing regulations (Åkerman, 2017). In Germany, the German Federal Environment Agency assessed the technology from a legal and safety point of view, to see whether the OC can be built on highways. After the assessment, Siemens got the approval to build three eHighway corridors in Germany (ibid.), as described in the next section.

The wayside equipment is similar to the one used in trolleybus lines in parts of the world. The basic system with the overhead wires is a standardized technology that has been used for 130 years. The contact line is made up with a specially designed two-pole contact-line system that can handle power flows in and out while the vehicle is running up to 90 km/h, in this way regenerative braking power from the lorries can be transmitted back to the overhead lines. This means that during braking, the electric motors act as generators and feed electricity back to the grid (Siemens, 2015).

The power is supplied by substations consisting of switching systems, inverters and transformers that convert the high voltage alternating current (AC) current into low voltage direct current (DC) with a potential range of 600V to 1500V (den Boer, et al., 2013). Direct current is used, otherwise the heavy-duty vehicle would have to carry transformers on-board, reducing space and payload. Masts, booms and isolators separated at a distance of 40-50 metres support the catenary (Svenska Elvägar AB, 2011). The catenary wires are at a standardized height of 5.15 metres. The catenary height changes if the lorry has to pass under a viaduct or a tunnel. If the viaduct is higher than 4.75 metres (98% of the viaducts in Germany and Sweden), the adaptive pantograph adapts to the height and the lorry does not interrupt the contact (Åkerman, 2017). Otherwise, if the viaduct is for example 4.50 metres high, the adaptive pantograph is lowered to a position so that the lorry may pass without electric contact, given that the lorry itself can pass under the viaduct (ibid.). Given the height of the catenary wires, it is also clear that this technology could not be adapted to cars or in general to vehicles with a height much less than four metres.

Apart from closed route systems like shuttle or mine transports, lorries that use the overhead technology at highways should be able to connect and disconnect to the overhead lines automatically. This may happen when the lorry enters/exits the highway or when it has to overtake a vehicle or change direction. For this reason, the pantograph cannot be of the same type as the one used at trolleybuses for which the route is fixed. The intelligent active pantograph should be able to detect when and where the overhead catenary lines are and it has to have a sensor that allows adjustments in the vertical and lateral position. This is also necessary because the vehicle could be slightly raised from the ground due to winter conditions or it may vary its path considerably while running.

In an interview with Siemens's representative (Åkerman, 2017), an overview of the pros and cons of this solution was presented. One of the main disadvantages is that only heavy-duty vehicles may use eHighway, but according to Siemens this may be an acceptable trade-off. For cars, there are many alternatives for renewable energy carriers available including batteries. Moreover, business models of ERS indicates that users should use the infrastructure a lot to justify the initial investment of equipping the vehicles with the devices in addition to the fees for using the ERS. According to Siemens, the cost of equipping cars with the pickup device for e.g. a ground bases ERS would not be competitive with other non-ERS solutions. On the other hand, lorries consume much more energy than cars, not only per km, but also totally because of the total driving distance per year. This means that for lorries, the savings in fuel may justify the extra costs of the ERS. However, implementing overhead-wired lorries requires substantial initial investments, both for the infrastructure and for the vehicle, as illustrated in section 2.1.3 about costs.

Another concern about overhead contact lines is the visual impact, including the aesthetic aspects. Firstly, it could be a safety problem because of distractions for the driver, but according to simulations performed by Siemens, drivers get used to it quickly (Åkerman, 2017). Secondly, eHighway is primarily planned to be installed in heavy freight corridors located in non-core urban areas, where thousands and thousands of lorries are already driving. According to Siemens, this means that the infrastructure not will ruin open urban spaces (ibid.).

2.1.2 Pilot projects and further developments

The first demonstration track for open systems such as highways has been in operation since 2010 on a private road outside Berlin (Siemens, 2015). Since then, many other pilot tests and projects have been developed and others are planned for the near future. Table 1 summarises the past and current eHighway developing projects for open-ended routes, while Table 2 summarises the closed routes applications under operation so far.

Table 1: Summary of the past and current Siemens eHighway pilot tests and operations all over the world (den Boer et al., 2013; Åkerman, 2017; Moultak et al., 2017).

Where	When	Details	Support system used
Berlin, Germany	2010	Test vehicles with 200 kW permanent magnet synchronous generator and motor, 300 kW diesel powerpack, power electronics, electric double-layer capacitors for energy storage.	ICE (Internal combustion engine)
Sweden	2013 2016-2019	Two km stretch of the E16 highway outside Gävle, part of the ongoing pre-commercial procurement of electric roads in Sweden. Testing operations on the E16 eHighway.	Hybrid system (ICE + small batteries with 2 km range or 10 km range)
Long Beach, Los Angeles, USA	2016, Testing for at least six months in 2017	eHighway to reduce emissions of port links on a distance of one mile including infrastructure in both directions near ports in L.A. and Long Beach; Cooperation with Volvo Trucks and local lorry converters; Contract with South Coast Air Quality Management District.	Three different types of lorries: ICE + small battery Gas ICE + small battery Pure electric (battery-only)
Germany	April 2012-December 2015 2017, 2018 (construction), 2019 (field trials)	ENUBA 2 project in Gross Dölln: a two km overhead catenary system on a road for heavy-duty vehicles and buses. Three field tests are announced: 1) close to Lübeck, negotiations are ongoing. It will cover six km in both directions, 2) close to Frankfurt, six km of ERS, and in the state of Baden-Württemberg, seven km of ERS.	

Table 2: Summary of the closed system under operation all over the world with internal combustion engines as the support system. Companies manufacturing trolley-mining lorries include Hitachi, Liebherr and Siemens (Siemens, 2014).

Where	Commissioning year	Details
Palabora Mining Company, South Africa	1981	Route Length: 8.0 km, voltage and substation power: 1 200V, 5.0 MVA, number of substations: seven, converted lorries: 80
Rössing Mine Company, Namibia	1986	Route Length: 8.5 km, voltage and substation power: 1 200 V, 3.0 MVA, number of substations: five, converted lorries: 30
Gécamines, Democratic Republic of Congo	1986-89	Route Length: 3.5 km, voltage and substation power: 1 200 V, 2.4 MVA, number of substations: four, converted lorries: 22
Barrick Goldstrike Mine, USA	1994	Route Length: 5.5 km, voltage and substation power: 1 500 V, 6.5 MVA, number of substations: seven, converted lorries: 11
Lumwana Mining Company, Zambia	2009	Route Length: 4.0 km, voltage and substation power: 2 400 V, 10.0 MVA, number of substations: five, converted lorries: 27

2.1.3 Cost analysis

Vehicle cost

The following analysis is made with the assumption that the overhead catenary (OC) long-haul lorry is equipped with batteries as a support system. Most part of the additional cost of the OC ERS vehicle, compared to the traditional ICE long haul lorry, is related to the pantograph and to the battery system. The cost of the batteries is assumed to decrease over time and this is reflected in Table 3 where the initial cost of €325/kWh for 2017 also indicates a higher cost of batteries to heavy-duty vehicles compared to batteries for personal cars. The reason the specific costs are normally higher for batteries to heavy-duty vehicles is that they have to last for a higher number of charging cycles than batteries to cars. According to IEA (2017b), current battery pack costs are close to €250/kWh, but the same organisation also assess that once batteries achieve commercial scale and high volume production, there will be the possibility to drastically reduce their cost, whereby the costs will fall to the range 90-150 USD/kWh (ibid.).

Contrary to the predicted development for battery costs, it should be noticed that the costs of internal combustion engines are likely to increase over time due to more demanding exhaust gas regulations, while the additional required system (ARS) that is necessary to manage the power flow in the vehicle, as well as the electric motor, is expected to cost less over time (den Boer et al., 2013).

The cost for the vehicle components in this report are generally adapted from den Boer et al. (2013) in which cost estimates for the years 2012, 2020 and 2030 are found. An assumed cost increase of 2% have been added to these cost estimates and the value for 2017 has been set by linear interpolation between the updated values for 2012 and 2020. The cost for the glider is assumed to be constant during the period. The term *glider* is used for all parts of the long-haul lorry that are not specified in the tables, e.g. chassis and cabin.

Table 3: Component cost specification for a 40 tonne long haul lorry. Adapted and updated from den Boer et al., (2013).

		2017	2020	2030
Internal Combustion Engine, ICE	€/kW	59	61	68
Battery system	€/kWh	325	245	164
Electric motor	€/kW	18	17	15
Additional required battery electric vehicle system (ARS are the power electronics including converters, battery management system, etc.), excluding the grid connection	€/kW	24	22	17

Table 4: Long haul internal combustion engine lorry, production cost. Adapted and updated from den Boer et al., (2013).

ICE Long haul vehicle production costs		2017	2020	2030
Total Vehicle Costs	€	82 975	83 925	86 475
Vehicle				
Glider	€	61 200	61 200	61 200
Drivetrain				
Power pack	€	20 500	21 450	24 000
Power	kW	350	350	350
Battery	€	255	255	255
Storage System				
Fuel Tank	€	1 020	1 020	1 020

Table 5: Long haul overhead conductive lorry, production cost. Adapted and updated from den Boer et al., (2013).

OC Long haul vehicle production costs		2017	2020	2030
Total Vehicle Costs	€	157 850	136 030	105 380
Vehicle				
Glider	€	61 200	61 200	61 200
ARS	€	8 280	7 680	6 070
Drivetrain				
Grid Connection (pantograph)	€	30 180	23 800	10 200
Electric Motor	€	6 340	6 070	5 360
Power	kW	350	350	350
Storage System				
Battery	€	51 850	37 280	22 550
Capacity	kWh	157	152	137

When comparing Tables 4 and 5, it should be noticed that the pantograph and the battery make up the major part of the cost of the long haul overhead conductive lorry. As can be seen in Table 5, the cost of the pantograph, electric motor, and ARS are in accordance to these estimates just above €20 000 in 2030 (den Boer et al., 2013).

The battery support system should cover a distance of 30 km. The decline of the battery capacity seen in the estimates is mainly due to projected future improvements in electricity consumption, i.e. efficiency improvements. Figure 1 shows the estimated difference between the ICE and the OC long haul lorry cost over time. Even if the OC lorry production cost decreases over time, it is not expected to have reached the production cost of the ICE lorry in 2030.

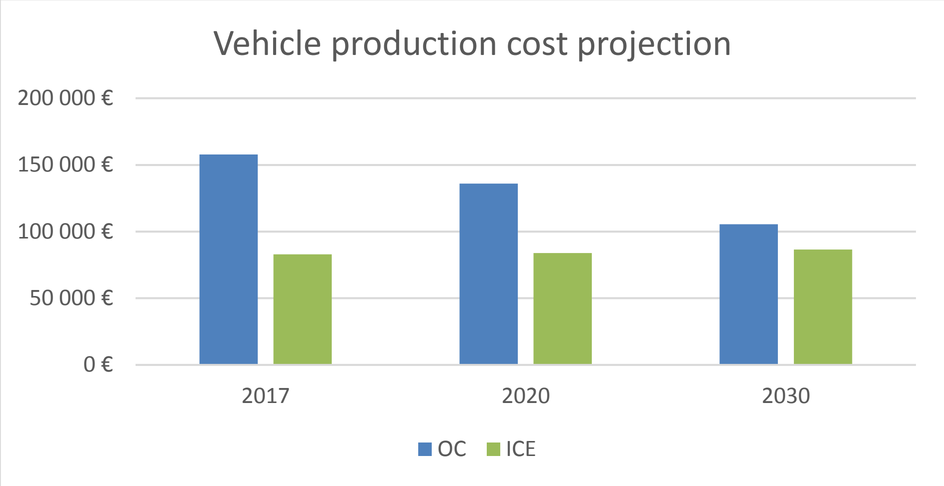

Figure 1: Comparison of the overall production cost of the OC and ICE long-haul lorries in 2017, 2020, 2030.

Infrastructure cost

As has been described for closed route applications in cities and mines, overhead catenary systems for on-road vehicles is not a new technology. Despite this, the wayside infrastructure has a considerable cost. Åkerman (2017) estimate a cost range from €2M to €3M/km for two lanes, while other sources provide estimates of costs from €1.0M/km (Ranch, 2010), €2.4M/km (Umwelt Bundesamt, 2016), to between €1.0M to €3.5M/km for two lanes (Couch, 2012). Table 6 summarises infrastructure costs from various sources.

Table 6: Overhead catenary solution infrastructure costs, two ways.

Overhead pantograph solution infrastructure	Cost	Details	Reference
	€2-3M/km	An estimate from a supplier.	Åkerman (2017)
	€1-3.5/km	The upper cost includes security and control systems.	Couch (2012)
	1 M€/km	Cost of electrification of existing road, including protective equipment.	Ranch (2010)
	€2.4M/km	From a larger German study	Umwelt Bundesamt (2016)
Electricity infrastructure maintenance costs (O&M)	1.0% of the system annual cost per year		Couch (2012)
	From 1.0% to 2.5% of the initial catenary and electricity supply investment cost per year.		den Boer et al. (2013)

The maintenance cost is assumed to be 1.0% of the system annual cost (Couch, 2012) or between 1.0% and 2.5% of the initial catenary and electricity supply investment cost per year (den Boer et al., 2013).

2.2 RAIL CONDUCTIVE SYSTEM

Contrary to the overhead catenary system that resembles the trolleybus solution, the rail conductive (RC) solution is a technology for direct conductive electrification with no comparable application in use historically. The RC uses a conductive track installed in the ground to transfer power from the road to the vehicle, using a pick-up device that is linked to the vehicle via a robotic arm. The first application in use was the system Aesthetic Power Supply (APS) from Alstom for which operations started with tramways in Bordeaux in 2003 (Alstom, 2017). APS is now implemented for tramways in several cities (ibid.). Since then, several pilot tracks have been tested by different companies and organizations (e.g. Elways, Elonroad) as described in the following sections.

2.2.1 Elways solution

Elways rail conductive solution consists of transmitting power from a track in the road to the vehicle. Beside the conduction technology, one of the main advantages of this solution compared to other RC technologies is that it is suitable for both lorries and cars, as well as for other kinds of both light and heavy vehicles. This has been demonstrated in the Elways Arlanda test track (Asplund and Rehman, 2014). Power is fed to the vehicle via a movable arm. At the end of the arm, a magnet facilitates the contact between the rail and the two separate (redundant) contact devices and as long as the vehicle is above the track, the movable arm is automatically adjusted to keep the contact. When the direction of the vehicle is changed abruptly as during overtaking, the arm lifts up quickly. If the vehicle loses contact, it should be powered by a support system such as batteries until it reaches the rail again (ibid.; Asplund 2017). According to the inventor Gunnar Asplund, the Elways rail conductive system has an efficiency between 85% and 96%, calculated from electricity input from the grid to the output from the electric motor including losses in the transformers, alteration switches, rails and vehicle contacts (ibid.). This value depends on the voltage used on the grid and on the quality of electric components.

The Elways track system consists of two contact devices. Should one of them lose its contact (e.g. due to a jump), contact will usually be kept by the other. The potential of the system is 800V and each section of 50 metres of the rail may deliver up to 250A. For safety reasons, the current is only available on each section when a vehicle is passing with some overlap between the sections, all monitored through sensors. The rail consists of two 0,1 m deep narrow channels, “trenches”, which are electrified at the bottom only. The contact device is designed so that electrified bottom should not be reachable with a finger. If the control system measures low resistance due to e.g. salt water in winter time, the current is not switched on to that section. However, the rails can stand against intensive rains and melting snow though a drain between every section of 50 metres. Also, the sections may be heated to melt snow and ice (Asplund, 2017). Although Elways has not released any details about the working principle and the final design of the pick-up device yet, some information is available (Asplund and Rehman, 2014; Viktoria Swedish ICT, 2014a).

Volvo has developed two prototype electric pickup devices for the Elways RC system; the first has electric motors that handle the vertical and lateral adjustments (i.e. rotationally), while the second handles lateral adjustments through linear movements and the vertical adjustments with a pneumatic system that use compressed air from the lorry. According to Asplund (2017), a maximum of two long-haul heavy-duty lorries may pass over one section at the same time, but only at limited uphill elevation due to power transmission limits. The system is thus dependent on the support systems in the heavy vehicles when the elevations is more pronounced. In order to electrify the railroad, high voltage cables should follow the RC system, and then transformers should decrease the voltage and transmit power to the active sections through fast switches located alongside the road. The high voltage cables are necessary in order to avoid too many in-feeds from the electric grid (Asplund and Rehman, 2014).

The conductive pick-up device may last up to 10 000 km if the system is kept reasonably clean according to Asplund (2017). The pick-up device is designed so that it should be easy to replace, i.e. not involving a workshop. The track itself instead should last for 20 years with medium traffic, periodic cleaning and basic maintenance, but if the traffic intensity is high, the rail may have to be replaced more often.

Elways tested their solution in 2012 on a 200-metre test track, close to the Arlanda airport in Sweden (Asplund, 2017). In October 2017, tests started on a 2 000-metre track on a public road next to the previous test track. A lorry from DAF was selected for the tests of the Elways RC system and this test is part of a procurement of electric roads in Sweden that was mentioned above. The results from the 200-metre test track show that with specially developed cleaning systems (not yet publicly demonstrated), it is possible to operate this RC solution even under severe winter conditions (Asplund and Rehman, 2014).

2.2.2 Pilot projects and further developments

As mentioned earlier, several stakeholders have developed different RC solutions, but only Elways has tested their technology on a public road so far. The company Elonroad has tested their components and is going to test the solution outside Lund, while Alstom has tested their entire APS (Aesthetic Power Supply) system after having adapted it to lorries, but not on public roads, see Table 7. Commercial operations will require integration between various stakeholders and large initial investments (Tongur and Sundelin, 2016). See a cost discussion below.

Table 7: Overview of the current test pilot tracks for RC technology.

Organizations	Location	Year	Description	Reference
Alstom, Volvo, Lund University and the Swedish Energy Agency	Hällered, Sweden	2012	435 m test track (275 m electrified) with two embedded power lines, operating with DC voltage at standardized level of 750V DC. The site is specifically for electrical road tests without disturbing other traffic. Vehicles can speed up to 80-100 km/h when entering the electrified track.	(Moultak et al., 2017; Fabric, 2017a)
Elways, NCC, KTH University, Swedish Energy Agency, & Arlandastad Holding AB	Arlanda, Sweden	2012-2017	A 200 m test track was built in May 2012. In October 2014 an additional 150 m track was built. The first 200 m were replaced by a new version in August 2016. An additional 50-metre rail was installed in March 2017. Demonstration is in progress in October 2017 on a 2000 m test track on a public road in Arlanda.	(Asplund, 2017; Moultak et al., 2017; Connolly, 2016)
Elonroad and Lund University	Lund, Sweden	2017	Demonstrated in lab. 200 m pilot test under development. This solution provides a rail on top of the road, not embedded in it. This solution should be suitable for all types of vehicles.	(Moultak et al., 2017; Connolly, 2016)

2.2.3 Cost analysis

Vehicle cost

In Table 8, an overview of the production costs of a long-haul RC lorry is presented. Comparing Table 8 with the OC costs seen previously, the difference is mainly due to the different cost of the grid connection device. According to Connolly (2016), the conductive pick-up device for buses and lorries could vary in the range €5 000-10 000. The cost suggested in Viktoria Swedish ICT (2014a) is around €5 000[1] in 2013 and given this, the cost of €8 280 for 2017 may be considered conservative.

Table 8: Long haul rail conductive lorry production cost. Adapted from den Boer et al. (2013).

RC Long haul lorry production costs		2017	2020	2030
Total Vehicle Costs	€	135 870	119 380	100 280
Vehicle				
Glider	€	61 200	61 200	61 200
ARS	€	8 280	7 680	6 070
Drivetrain				
Grid Connection (pick-up device)	€	8 200	7 150	5 100
Electric Motor	€	6 340	6 070	5 360
Power	kW	350	350	350
Storage System				
Battery	€	51 850	37 280	22 550
Capacity	kWh	157	152	137

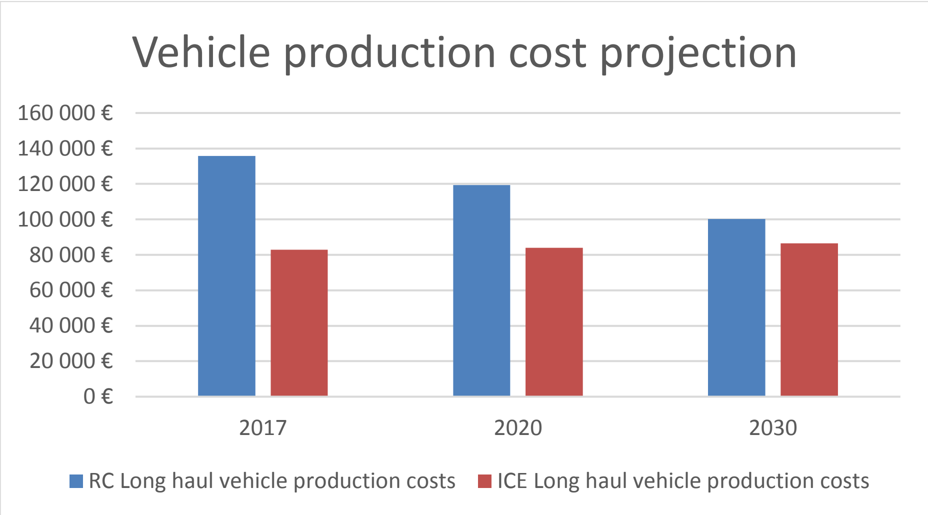

Figure 2: Comparison of the overall production cost of the RC and ICE long-haul lorries in 2017, 2020, 2030. See Table 4 for details about the estimates of the ICE lorry costs.

[1] The cost includes two electrical motors or a combination of an electrical motor and a pneumatic activator with corresponding controls (around 1 500 €), mechanical design and components, springs, joints, belts (around 1 500 €), and power converter cost (around 2 000 €).

Infrastructure cost

RC solutions have the potential to reduce both light and heavy vehicles' use of batteries, their size and weight, and to increase the vehicle driving range on electricity. Unfortunately, the initial investments required to build RC infrastructure are high and have a high level of uncertainty for the future, due to a lack of standardization of both the vehicles and the infrastructure. Because of the high investment costs, a suggested approach has been to implement these systems in high-freight corridors initially, for example in roads that connect shipping ports to cities (Moultak et al., 2017). Table 9 presents an overview of the infrastructure and maintenance costs provided by three main RC manufacturers.

Table 9: Rail conductive solution infrastructure costs.

Rail conductive solution infrastructure	Cost	Details	Reference
	0.75 M€/km – 1.5 M€/km	Elonroad solution: one way including full installation, electric grid costs	(Connolly, 2016)
	0.5 M€/km – 1 M€/km	Elways solution: one-way, the lower limit value refers to a very commercial phase with around 1000 km of electric roads. The upper limit refers to the first commercial operation for a 100 km road.	(Asplund 2017)
	0.8 M€/km – 2 M€/km	Alstom solution: one-way, no installation costs included. The lower value refers to the average case, the upper to the maximum load case. See reference for details.	(Viktoria Swedish ICT, 2014a)
Energy infrastructure maintenance costs (O&M)	Elonroad solution: 1% of the initial investment per year		(Connolly, 2016)
	Elways solution: cleaning the rails from dirt, water and snow about 6€/km per day.		(Asplund, 2017)
	Alstom solution: around 1-2 % of the total investment per year, medium/low voltage components will be designed to be maintenance free and only require periodic check-ups, maybe once every 6 years followed by the needed reinvestments.		(Viktoria Swedish ICT, 2014a)

2.3 DYNAMIC INDUCTIVE SYSTEM

In a dynamic inductive (DI) charging system, the power is transferred to the vehicle from the road through an electromagnetic field while the vehicle is moving, i.e. without the physical contact used in the overhead catenary (OC) or rail conductive (RC) systems. The delivering system, i.e. a primary coil embedded approximately 25 mm under the road surface, and connected to the power grid, is constantly powered to send the power needed to the receiving system, the pick-up device in the vehicle where the magnetic field is converted to electric power in a secondary coil. In this way, the vehicle recharges while driving. Thereby, it lacks the range limitations that come with conductive charging, and it does not need a heavy space-demanding battery to carry all of the electricity needed for the transportation.

2.3.1 Primove solution

Primove is a leading company in dynamic inductive technology. It has developed both stationary and dynamic technologies able to transfer up to 200 kW power for lorries and buses (Viktoria Swedish ICT, 2014b). The inductive charging road is divided into 20-metre segments that only are activated when a Primove-equipped vehicle passes over it with a speed exceeding 50 km/h. To avoid problems with the magnetic field on non-Primove vehicles, the system detects other vehicles that are to close and the segment will not be activated (ibid.). Segments could be located all along the road or grouped into clusters. Travelling over distances without segments/clusters are made possible through an on-board battery.

In one case for which modelling with the Primove system has been carried out, the vehicle is equipped with an ICE to supply power during extensive acceleration, climbing, or when the battery is out-of-use (Viktoria Swedish ICT, 2014b). However, in our cost analysis, the long-haul lorry is equipped with a battery instead of an ICE. In this way, the cost comparison with the other ERS technologies could be made in accordance with the same initial assumptions.

The infrastructure is composed of substations with transformers and rectifiers that turns the power from a 20-kV medium voltage grid to 750 V_{DC}. The DC power is then distributed to wayside power converters that transform it to 20 kHz AC current again to supply the coils in the segments (Viktoria Swedish ICT, 2014b). There are possibilities implement inductive charging all along the road or to have the inductive charging over parts of the road. In the latter case, the power per metre of the road should be higher to allow for charging of the battery capacity that should be used in non-electrified parts of the road (ibid.).

Primove has tested their technology in a 300-metre track made up of the 20-metre segments. Due to track length limitations, the maximum speed achieved has been 70 km/h. During tests at different speeds – 20 km/h, 35 km/h and 70 km/h – it has been reported that the power transfer could be above 150 kW, and even up to 200 kW (Viktoria Swedish ICT, 2014b). To enable efficient transfer of the power, the vehicles should follow a path, but the tests revealed that lateral misalignments between 100 and 150 mm have minimal impacts on the efficiency. However, the efficiency of the system is more sensitive to the air gap. The efficiency for transferring 185 kW at 85 mm distance between the road and the pick-up device in the test was 89%, measured from the wayside inverter to the vehicle’s onboard converter (Viktoria Swedish ICT, 2014b). The global efficiency of the system, i.e. from the grid to the output from the motor, also depends on factors such as the material used for cables. The total power requirement per km was estimated to 470 kW (both directions) with normal traffic intensity on a highway near Borås, considering that 2 out of 13 vehicles are long-haul lorries. The average number of lorries in each direction was during the studied period over ten months in 2012 around one thousand per weekday (ibid.).

The Primove vehicle is equipped with a control system that use sensors to adjust a lifter for the pick-up device. When the vehicle enters an inductive section of the road, the lifter changes the pick-up position in order to reach the optimal voltage, and when the vehicle exits from the electrified track, the pickup lifter retracts the pick-up device to protect it.

Although the inductive system has the advantage of not utilising a visible infrastructure, there are also disadvantages with this solution. Firstly, the cost of the infrastructure is very high compared to the conductive solutions, see section 2.3.3 below. According to den Boer et al. (2013), the solution is best suited for an implementation on parts of roads instead of all along and initially for those vehicles that follow a fixed route, e.g. delivery lorries. However, the inductive system is in the long run adapted to be used for many types of vehicles as is the rail conductive solution. The system efficiencies are generally lower than for the conductive solutions.

2.3.2 Pilot projects and further development

Compared to the two conductive systems discussed previously, the inductive technology for long-haul lorries is further away from commercialisation. According Tongur and Sundelin (2016) and den Boer et al. (2013), most of the inductive systems have the potential to provide power for long-haul lorries, but they are in a developing phase with few testing tracks for these kind of vehicles. The current pilot test tracks are summarised in Table 10.

Table 10: Overview of the current pilot test tracks for DI technology.

Organizations	Location	Year	Description	Reference
INTIS	Lathen, Germany	2014	25-metre modular test track. The maximum transferred power is 200 kW.	Intis, 2017
Korea Advance Institute of Science and Technol-ogy	Seoul, South Korea	Since 2009	80% efficiency with one cm air gap (possible since the route was a fixed 400-metre route in an amusement park).	den Boer et al. (2013)
DARPA – Path program	Berkeley, California, USA	2017	Pilot project for buses that use a dynamic in-ductive technology.	den Boer et al. (2013)
Viktoria Swedish ICT, Volvo GTT, Scania CV, Bombardier (Primove), Vattenfall, The Swedish Transport Administration, Svenska Elvägar AB, Lund University, KTH, Chalmers	Belgium, Germany and Sweden	2014	Feasibility study to estimate the cost and technical details, tested on an 80-metre road in Mannheim, Germany.	(Viktoria Swe-dish ICT, 2014b; Tongur and Sundelin, 2016)
Electric Highways, High-ways England	England	2015	Feasibility study, running 18-month off-road trials.	(Highways England, 2015)
EU FABRIC Project, SAET, Fiat, Qualcomm, Renault	Italy, France	2016	Italy: test track near the A32 motorway Torino – Bardonecchia, two lanes equipped with the inductive technology, more than 50 kW of electric power supply. France: pilot test located in Satory, near Ver-sailles, made up of three tracks with different topographies.	(Fabric, 2017b)
EU project, ENDESA, CIRCE	Spain	2016	Inductive pilot test for buses in Malaga. Eight 80 cm 50 kW coils distributed along a 100-metre road.	(Tongur and Sundelin, 2016)

2.3.3 Cost analysis

Vehicle cost

The inductive long-haul lorry production cost is comparable to the rail conductive one and the cost estimates provided here give that OC solution costs around 15% more than the inductive one, 12% more in the year 2020, and around 2% in 2030, see also Tables 5 and 11. As previously pointed out, this is mainly due to the pantograph cost, but given the uncertainties, the costs seem to be com-parable.

Table 11: Dynamic inductive long-haul lorry production cost. Adapted and updated from den Boer et al. (2013).

DI Long haul vehicle production costs		2017	2020	2030
Total Vehicle Costs	€	136 690	120 950	103 210
Vehicle				
Glider	€	61 200	61 200	61 200
ARS	€	8 300	7 700	6 100
Drivetrain				
Grid Connection	€	9 000	8 700	8 000
Electric Motor	€	6 340	6 070	5 360
Power	kW	350	350	350
Storage System				
Battery	€	51 850	37 280	22 550
Capacity	kWh	157	152	137

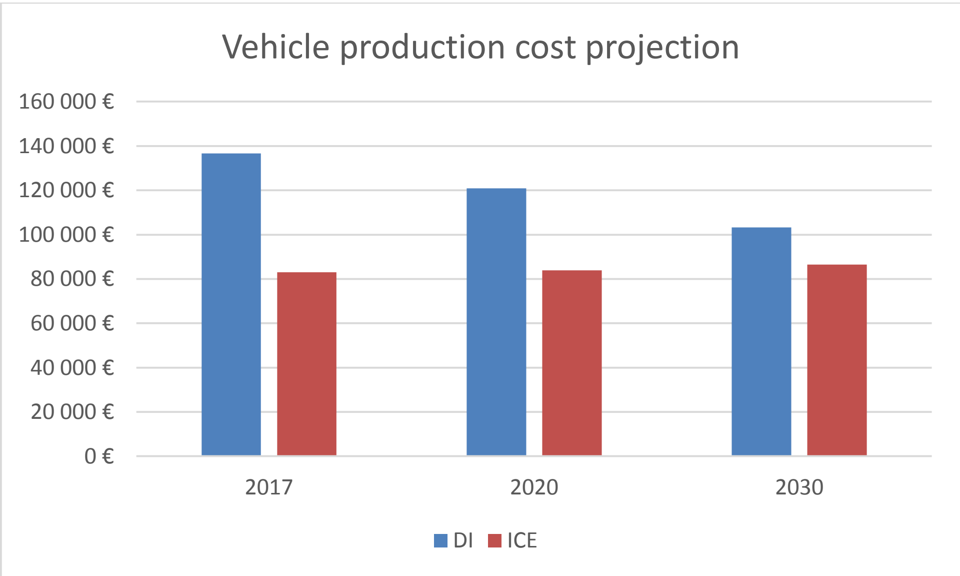

Figure 3: Comparison of the overall production cost of the DI and ICE long haul lorries in 2017, 2020, 2030. See Table 4 for the ICE lorry costs.

Infrastructure cost

Although the OC system according to the estimates presented previously has a higher vehicle production cost than the DI system, the costs of the infrastructure are not in favour of the DI system. The power transfer components are placed under the road so, compared to the OC, the infrastructure involves not only an addition of electric components for the inductive power transmission but also an invasive modification of the existing road. However, according to den Boer et al. (2013), only 50% of the road would have to be electrified and the maintenance costs would be very low since there is no direct contact involved in the power transmission.

Table 12 Dynamic inductive system infrastructure costs.

Inductive infrastructure cost estimates	**Costs**	**Sources**
Primove technology from Bombardier	1.6 M€/km, one way	(Connolly, 2016)
	2.8 M€/km, one way (today) 1.5 M€/km, one way (commercial scale)	(Viktoria Swedish ICT, 2014b)
Highways England	2.6M€/km, one way	(Highways England, 2015)
Energy infrastructure annual maintenance costs	1% of initial investment cost per year	(Highways England, 2015; Connolly, 2016; Viktoria Swedish ICT, 2014b)

3 FUEL CELL LORRIES

Fuel cell lorries – here also called fuel cell hybrid electric vehicle (FCHEV) – are vehicles equipped with a fuel cell and one or several batteries. The fuel cell uses hydrogen stored in a tank to produce electricity. In the sections below, details regarding storage, fuel cells efficiency and refuelling infrastructure are discussed.

3.1 TECHNOLOGY ASSESSMENT

3.1.1 Performance

Polymer-electrolyte membrane fuel cells (PEMFC), also called proton-exchange membrane fuel cells, are the type of fuels cells used in FCHEV vehicles. They offer low operating temperatures (from 60°C to 120°C), short start-up time, and an efficiency from 50% to 60% (lower heating value, LHV) over a large load span (Feroldi and Basualdo, 2012; DOE, 2006), measured as hydrogen input to electricity output.

In a fuel cell vehicle, the battery system is essential in order to cover peak power that may occur for example in acceleration or in uphill roads. The battery will also enable energy to be recovered during breaking, as for many solutions involving propulsion with electricity. The power delivered from the battery may be higher than the power that is possible to deliver from the fuel cell. One factor of importance for the competiveness of the FCHEV vehicles are the power and there are claims that it is necessary that the sum of the power from the fuel cell and the battery should at least be equal to the power from the comparable internal combustion engine for the FCHEV to be competitive (den Boer et al., 2013).

3.1.2 Refuelling

The refuelling time for hydrogen in fuel cell cars is 3-5 minutes for 5 kg hydrogen, i.e. comparable to the refuelling time of vehicles that use conventional fuels (IEA, 2017a). The refuelling time for fuel cell buses varies between 7 and 10 minutes for 35 kg hydrogen (den Boer et al., 2013). It should be noticed that this interval could vary in relation to both the pressure of the vehicle storage and the pressure-capacity of the station. The storage of hydrogen in vehicles has not yet been standardized and the used options today are compressed at 350 bar for buses and lorries and 700 bar for cars (Sjödahl, 2017). The refuelling time naturally depends on the amount of hydrogen that should be filled and also on the pressure. Hydrogen has negative Joule-Thomson coefficient at room temperature and will thus get warmer when expanded. When refuelling at 700 bar this effect is so pronounced that cooling is necessary to keep the refuelling time comparable to refuelling of conventional fuels (Aronsson, 2017), which adds to the costs of refuelling stations.

The capacity of the station in terms of the amount of delivered hydrogen per day is one factor that decides whether the hydrogen should be produced at the refuelling station or not. The capacity has also implications whether compressed or liquefied hydrogen is the most financially viable option. However, state of the stored hydrogen is naturally defined by the vehicles as well. An indication of when liquefied and off-site production could be more financially viable for refuelling stations than on-site production of compressed hydrogen is above 500 kg of hydrogen per day (IEA, 2017a).

3.1.3 On-board storage

Fuel cell vehicles have reached a commercial status, but the volumes are still so modest that is questionable to present the states of storage for hydrogen in the vehicles in use as standardized. Nevertheless, the tendency is that cars use compressed hydrogen at 700 bar while heavier vehicles use 350 bar (Aronsson, 2017). Other but less developed alternatives are on-board storage of liquefied or cryo-compressed hydrogen (DOE, 2008). In the latter case, the fuelling is as liquefied hydrogen but the pressure in the on board storage is allowed to increase because of the unavoidable heat in-leakage to the tank. The venting of the boil-off necessary to keep the pressure of liquefied hydrogen constant is thereby reduced. Other options like physical adsorption and chemical absorption are promising considering the volumetric capacities but have too complex load and unload cycles to be realistic alternatives currently (den Boer et al., 2013).

Measurements that are used to compare different storage options are the volumetric and gravimetric capacities, commonly expressed as kg/m^3 and % (kg H_2/kg tank) respectively. Compressed hydrogen at 350 bar have volumetric and gravimetric storage capacities of approximately 16 kg/m^3 and 3.5%, whereas the corresponding figures for compressed at 700 bar and liquefied hydrogen are approximately 23 kg/m^3 and 5.4% and 40 kg/m^3 and 6% respectively (den Boer et al., 2013). Other ranges of values are found in DOE (2008). Despite the advantage in volumetric capacity for liquid hydrogen, the most obvious disadvantages for this solution are the energy needed for liquefaction and the previously mentioned need for venting of the boil-off when stored. Between 30% and 35% of the lower heating value of the hydrogen is commonly used in a liquefaction process (DOE, 2007). The corresponding energy losses due to compression energy to 440 bar and 880 bar, i.e. the pressures need to supply hydrogen to 350 bar and 700 bar, are approximately 7% and 10%[2] (DOE, 2009). The boil-off would be less of a problem for long haul lorries than for cars because of the operation patterns where long haul lorries commonly are running considerably more hours per year than cars.

Presently, 700 bar compressed hydrogen represents the state-of-art for vehicles storage of hydrogen. It enables higher gravimetric and volumetric capacities compared to the 350 bar technology and the high energy penalty for liquefied hydrogen is avoided as well as the need for venting of the boil-off.

3.1.4 Pilot projects and further developments

The market for hydrogen in transportation is still small, with only 500 vehicles (mostly cars and buses) in operation around the world (IEA, 2017). Despite this, some automotive companies and other institutions demonstrate interest in hydrogen vehicles and are developing pilot projects all around the world, as presented in Tables 13 and 14. Among the examples are the State of California that provide funds in order to reach the goal of 100 hydrogen refuelling stations by 2020, Germany that plans to have 400 refuelling stations by 2023, and China and South Korea that together are planning to build a network for hydrogen including 830 refuelling stations by 2025 (IEA, 2017a).

[2] The energy penalty in the 700 bar case also includes energy for the precooling necessary before refuelling.

Table 13: Overview of hydrogen-fuelled heavy-duty lorries developed and planned for the future. Adapted and updated from Moultak et al. (2017).

Organization	Location	Time frame	Description	Source
Environmental Defense Fund, US DOE, (H-GAC), Gas Technology Institute, US Hybrid, Richardson Trucking, University of Texas	Port of Houston, Texas	2015	Three-year demonstration project of three zero-emission heavy-duty Class 8 lorries powered by hydrogen fuel cells in an electric hybrid power system with a 320kW electric motor. The project received $3.4M in federal funding and partners are expected to invest $3.0M.	(DOE, 2017)
Hydrogenics, Siemens, Total Transportation Services (TTSI)	Alameda Corridor, Port of Los Angeles & Long Beach, California	2015	Two projects: 1. "Advanced Fuel Cell Vehicle Technology Demonstration for Drayage Truck": Integration of Hydrogenics fuel cell drive system into a Class 8 drayage lorry. Technical support from Siemens. 2. "New Flyer Advanced Fuel Cell Vehicle Technology Demonstration for Bus". New Flyer (leading manufacturer of heavy-duty buses) will integrate Hydrogenics' fuel cell drive system into its 40-foot battery transit bus platform for a 12-month demonstration.	(Hydrogenics, 2015)
SCAQMD, CTE, TransPower, U.S. Hybrid, Hydrogenics USA	Port of Los Angeles & Long Beach, California	June 2015-September 2018	Development and demonstration of six battery electric lorries with hydrogen fuel cell range extenders for drayage applications.	(Impullitti, 2015)
Scania and Asko	Norway	2016	Three-axle distribution lorries with a gross weight of 27 tonnes, where the internal combustion engine in the powertrain is replaced by an electric motor powered by electricity from hydrogen-fuelled fuel cells. Three lorries will form part of the research project, with an option for one vehicle more.	(Scania, 2016)
Toyota	Ports of LA & Long Beach, California	Summer 2017	Hydrogen fuel cell system designed for heavy-duty lorry use. The zero-emission "proof-of-concept" lorry will take part in a feasibility study examining the potential of the fuel cell technology in heavy-duty applications.	(Toyota, 2017)
Nikola Motor Company	Company based in Salt Lake City, USA	In production by 2020	The Nikola One lorry utilises a fully electric drivetrain powered by high-density lithium batteries. Energy will be supplied by a hydrogen fuel cell giving the Nikola One a range of 1 300-1 900 km. The drivetrain may deliver over 735 kW and 2 700 Nm of torque.	(Nikola Motor Company, 2016; 2017)

Table 14: Overview of light to medium weight fuel-cell lorries and vans developed and planned for the future. Adapted and updated from Moultak et al. (2017).

Organization	Location	Time frame	Description	Source
Hytruck	Netherlands	2012	Fuel cell lorry based upon a conventional chassis of the Mitsubishi Canter 7.5-tonne lorry. It has a 16 kW nominal power PEM fuel cell stack, with a 350 bar pressure tank containing 5.8 kg of hydrogen. In addition, it has a 25 kW nominal and 50 kW peak lithium-ion battery power, electric in-line motors (30 kW/wheel) and a daily operational range of 400 km.	(Den Boer et al., 2013; Hytruck, 2012)
CTE, UPS, University of Texas, EVI, Hydrogenics USA, Valance Technology	California	2014	The project will equip 17 delivery vans with a fuel cell hybrid technology and test them at distribution facilities in California.	(CTE, 2015)
Renault Trucks and French Post Office	France	2015	Maxity Electric lorry with fuel cells that has a range of approx. 100 km by battery plus an additional 100 km from the fuel cells. The fuel cells are capable of delivering a maximum power of 20 kW.	(Renault Trucks Deliver, 2015)
FedEx, US Department of Energy, Plug Power, Workhorse Group	Memphis, Tennessee & California	May 2016-October 2019	Twenty hydrogen fuel cell battery electric parcel delivery lorries operating one shift (10 hours) 260 days annually for approximately 1.92 years (around 5 000 hours/lorry). The project received $3.0M in funding from the DOE and $3.367M from partners.	(Griffin, 2016)

3.1.5 Cost analysis

Vehicle cost

Tables 15 and 16, respectively, examine the components cost and production cost of a long-haul fuel cell lorry for the years 2017, 2020, 2030, considering a 700-bar hydrogen 88 kg storage system and a battery capacity of 5 kWh. The range with the 88 kg hydrogen is assumed to be 1 000 km (den Boer et al., 2013). The projected cost reduction for fuel cells in Table 15 is even more distinct than for the previously discussed projected cost reduction for battery systems, electric motors, and additional required systems (ARS). den Boer et al. (2013) have, in turn, been using information from various sources in the estimated cost development, e.g. Özdemir (2012). Also, the main reason the estimated reduction in specific costs of the fuel cells is, as for the other components, the increased production. However, in addition to this, other types of innovations and a reduction in the specific use of platinum are mentioned. For fuel cells, the quantities produced are presently very modest and the same is also true for the hydrogen storage systems for which a cost reduction over time was also assumed, albeit not so noticeable as for the fuel cells (den Boer et al. 2013).

Table 15: Cost specification of a 40-tonnes long-haul lorry with fuel cells components. Adapted and updated from den Boer et al. (2013).

Year		2017	2020	2030
Battery system	€/kWh	325	245	164
Electric motor	€/kW	18	17	15
Fuel cell system	€/kW	494	194	82
Hydrogen storage (700 bar)	€/kWh	21	18	10
Additional required FCHEV system (ARS are the power electronic, battery management system, etc.)	€/kW	17	16	13

Table 16: Long haul fuel cell lorry production cost. Adapted and updated from den Boer et al. (2013).

FCHEV Long haul vehicle production costs		2017	2020	2030
Total Vehicle Costs	€	281 940	179 420	121 500
Vehicle				
Glider	€	61 200	61 200	61 200
ARS	€	6 100	5 700	4 650
Drivetrain				
Fuel cell system	€	148 200	58 150	24 500
Power[a]	kW	350	350	350
Electric Motor	€	6 340	6 070	5 360
Power				
Storage System				
Battery	€	1 600	1 200	800
Capacity	kWh	5	5	5
Hydrogen storage	€	58 500	47 100	25 000
Capacity	kWh	2 734	2 622	2 533

[a] The maximum power delivered from the drivetrain is 350 kW, of which 300 kW may be delivered from the fuel cell system and 50 kW from the batteries.

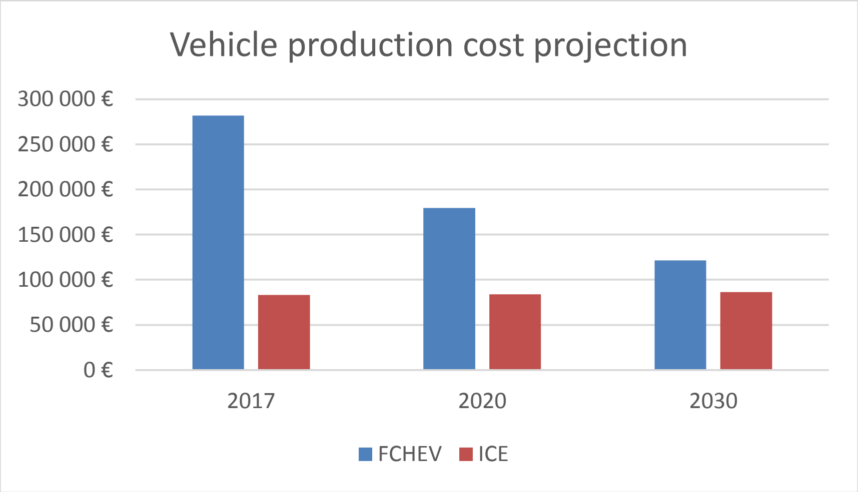

Figure 4: Comparison of the overall production cost of the FCHEV and ICE long haul lorries in 2017, 2020, 2030. See Table 4 for the ICE lorry costs.

Infrastructure cost

Hydrogen infrastructure costs are difficult to estimate since the market for transportation hydrogen as well as the equipment used to distribute the hydrogen is under development. There are also several possibilities for production and distribution available as well as several on-board storage possibilities that affect the infrastructure.

The cost of the infrastructure has roughly been estimated to 5% of the total cost of ownership of a car, or between €1 000 and €2 000/vehicle (den Boer et al. 2013). With this estimate, it is clear that the cost of the infrastructure highly influences the final cost of the vehicle. In Table 17, the estimated costs are for a refuelling station for fuelling of a 700-bar on-board storage, with or without on-site production, i.e. with or without an electrolyser. The 1 000 kg/day capacity would also enable refuelling of long-haul lorries, where we earlier have used the assessment of 88 kg of hydrogen for a 1 000 km range.

The costs of a hydrogen refuelling station at 700 bar in Table 17 includes dispensers, compressors and on-site storage. The estimates for on-site hydrogen production are with an additional 40% in investments on the first estimate in accordance with estimates that the electrolyser will add 30-40% to the total investment (Wallmark et al., 2014). One possible strategy during the build-up phase would be to initially focus on relatively small stations and then to shift to larger ones in order to prioritise coverage instead of capacity (ibid.). It should be mentioned that the analysis for refuelling stations in Wallmark et al. (2014) uses a car that consumes 0.35 kWh/km as the point of departure. This is a considerably low specific hydrogen consumption, with corresponding lower needs for hydrogen storage, than the long-haul lorry with an approximate hydrogen consumption of 2.2 kWh/km used in the cost estimates in this report.

The estimates presented could be compared to an estimate from Sjödahl (2017) that the cost of a 700-bar pressure hydrogen fuelling station with a consumption rate of 35 kg/h in average (and with a maximum filling rate increase of 50%) should be around €1.2-1.4 M excluding costs of ground preparations (and VAT).

Table 17: Estimates costs of hydrogen fuelling stations in million €. Adaption of data from Hydrogenics (2015) and Wallmark et al. (2014).

Year		2017	2017 (with electrolysis)	2020	2020 (with electrolysis)	2030	2030 (with electrolysis)
200 kg/ day	M€	1.5	2.1	1.3	1.8	1	1.4
1 000 kg/ day		3	4.2	2.5	3.5	2	2.8

4 GATE-TO-WHEEL ENERGY COST COMPARISON

The following analysis tries to compare the energy cost per km of three different cases of long-haul lorries: overhead catenary, fuel cell hybrid, and conventional ICE. With gate, we here mean power from the grids to the substation for the electric road system, power to the fuel electrolyser for hydrogen production, or diesel to the tank for the internal combustion engine. In all cases, we use the power output from the motor or engine necessary to keep a long-haul lorry at a speed of 85 km/h as the basis for the calculations.

The analysis is made with costs inputs based on electricity and diesel prices without taxes representing low, medium and high cases. We assume that hydrogen is produced via electrolysis. The basic thought behind this comparison without taxes is that all kinds of transport solution will be taxed when they reach a certain scale and that the specific taxed per distance in the long run probably will be comparable for different kind of solutions. Thus, the costs without taxes are more comparable than the costs with taxes.

The calculations are performed for the fuel fell case, the overhead conductive case and the conventional internal combustion engine case. Considering the energy cost estimates, the only difference between the overhead conductive, the rail conductive, and the inductive cases are the efficiencies. The information previously presented indicates that the rail conductive and the overhead conductive have similar efficiencies while the inductive have slightly lower efficiencies from grid to wheel.

4.1 ELECTRICITY COST OF THE OVERHEAD CATENARY CASE

Three different electricity prices are considered: €0.02, €0.04, and €0.06/kWh. The lower and higher of these are meant to reflect extremes in the spot prices for electricity in Sweden during the last decade. The yearly averages between 2001 and 2016 have all been within this price range even if there are periods when the monthly averages actually are lower than €0.02/kWh, e.g. during the summer of 2015 (Nord Pool Spot, 2017). Except for taxes and in Sweden also – possibly – the green certificates, the electricity price for a consumer also includes some kind of distribution fee. We have chosen not to make an estimate of a distribution fee for connection of the OC system to the grid, since there are many unknowns about the connections that all will affect the distribution fee.

The following calculations may also represent the rail conductive given the information provided about the efficiencies in that case. Calculations for the inductive case would be similar but with slightly lower efficiencies in the transmission of power.

Table 18: Assumption data as input for the OC case.

OC		
Electricity price	0.02	€/KWh
	0.04	€/KWh
	0.06	€/KWh
Substation to wheel efficiency[a]	0.85	
Power output from the electric motor	100	kW

[a] The substation to wheel efficiency is according to Siemens (2015) 80-85%, the higher value is chosen since the calculations are based on the 100 kW output from the motor at 85 km/h for a long-haul lorry (Pettersson, 2017), not the power needed at the wheels. This will give 1.176 kWh motor work per km.

Table 19: Evaluation of the cost per km in the OC case.

Cost/km, OC case		
Electricity input to the substation per km	1.38	kWh/km
Electricity cost per km for the three different electricity prices	0.028	€/km
	0.055	€/km
	0.083	€/km

4.2 ELECTRICITY COST OF THE FUEL CELL HYBRID ELECTRIC VEHICLE CASE

The same three electricity prices as in the OC case are applied as inputs for the estimates.

Table 20: Assumption data as input for the FCHEV case.

FCHEV		
Electricity price, three cases considered	0.02	€/kWh
	0.04	€/kWh
	0.06	€/kWh
Electrolyser efficiency[a]	0.67	
Energy (electricity) for compression and precooling[b]	3.2	kWh/kg (H_2)
LHV H_2[c]	33.3	kWh/kg
Fuel cell consumption (hydrogen, LHV)[d]	2.2	kWh/km

[a] DOE has been using this value as an example in efficiency calculation for hydrogen electrolysis (NREL, 2009).

[b] This value corresponds to 3.0 kWh /kg H_2 for compression energy from 20 bar to 880 bar (pressure from electrolyser to refuelling pressure for 700 bar) and 0.2 kWh/kg H_2 for as suggested by the HDSAM model used by DOE (DOE, 2009). The values are also close to the values from existing DOE validation refuelling sites.

[c] LHV from DOE (2009). The energy penalty for the compression and precooling thus corresponds to 9.6% of the LHV value of hydrogen, i.e. the efficiency compression and precooling of the hydrogen is (1-0.096) = 90.4%.

[d] Estimated from a need of 100 kW power from the motor at 85 km/h for a long-haul lorry (Pettersson, 2017). This will give 1.176 kWh motor work per km and with an estimated fuel cell efficiency of 54% (LHV), and approximately 2.2 kWh hydrogen/km. The range with this hydrogen consumption would then be 1 330 km given the LHV for the hydrogen and the previously mentioned 88 kg hydrogen tank, i.e. more than the 1 000 km assumed in the study from Delft (den Boer et al., 2013).

Table 21: Evaluation of the cost per km in the FCHEV case. The calculated cost of electricity per kg hydrogen is also added as a comparison.

Cost per km, FCHEV case		
2.2 kWh hydrogen/km, with an electrolyser efficiency of 67%	3.25	kWh_e/km
Adding the energy penalty for compression and precooling, efficiency=90.4%	3.60	kWh_e/km
Electricity cost per km for the three different electricity prices	0.072	€/km
	0.144	€/km
	0.216	€/km
Electricity cost per kg hydrogen in the three cases with given figures[a]	1.10	€/kg
	2.20	€/kg
	3.30	€/kg

[a] The costs of electricity for the different cases reveal that the calculated energy costs are low when only using the energy costs and not considering any capital costs.

4.3 FUEL COSTS OF THE INTERNAL COMBUSTION ENGINE CASE

The inputs in form of diesel costs chosen for the ICE have been selected by a method that has tried to get a cost that could be comparable to the spot price of electricity used as the input in the previous calculations. The price for oil products like diesel fuel is partly set by the price for crude oil and thus it would be valuable to have some kind of relation between the product price including the gross margin for diesel fuel and the crude oil price in order to reflect the volatility of the oil market. However, there are factors that disturb this picture: one is the influence of renewable blend-in fuels that have a higher production costs than conventional diesel but that also are differently taxed in Sweden. This means that the retrievable production price including gross margin increases even at a stable crude oil price, since the share of renewable blend-in fuels like fatty acid methyl esters (FAME) and hydrogenated vegetable oils (HVO) are increasing in the country.

The price for crude oil has changed rather dramatically during the last decade and in Table 22, average annual figures for product costs, fuel taxes, value added tax (VAT) and bulk retail price for diesel fuels in Sweden are listed for the years 2007 to 2016 together with the annual average price for Brent crude oil. The main crude oil used for Swedish oil products are Brent and Russian crude oils. The latter – often represented by a blend called Ural, the main blend for Russian crude oil – follows the price of Brent, but at a discount due to the higher sulphur content. Thus, it is not so important what grade of crude oil that is chosen in order to see how the relationship between the product cost and the crude oil price.

Table 22: The production costs including gross margin for diesel fuel in Sweden between 2007 and 2016, including other factors that affect the retail bulk price.

Year	Production cost (SEK/l)	Gross margin (SEK/l)	Fuel taxes (SEK/l)	VAT (SEK/l)	Bulk retail price (SEK(l)	Brent oil price (USD/bbl)
2007	3.68	0.63	3.72	2.01	10.04	72.52
2008	4.98	0.85	4.16	2.50	12.50	96.99
2009	3.34	0.81	4.34	2.12	10.62	61.51
2010	4.08	0.79	4.34	2.30	11.50	79.47
2011	5.08	0.87	4.54	2.62	13.11	111.27
2012	5.44	0.95	4.67	2.76	13.82	111.63
2013	5.13	0.81	4.63	2.64	13.20	108.56
2014	4.90	0.83	4.62	2.59	12.93	99.03
2015	3.67	0.91	4.88	2.37	11.83	52.35
2016	3.03	1.08	5.38	2.37	11.86	43.55

All data in the table (except from the average Brent prices) are average annual figures based on monthly averages retrieved from SPBI, prices and taxes (SPBI, 2017). The average Brent prices have been retrieved from Statista, The Statistics Portal (Statista, 2017). The bulk retail price is the price for a larger customer that buys the diesel oil directly from a fuel tanker.

From the information in Table 22, three different values for the production cost and gross margins have been selected as input for the following calculations, €0.40, €0.55 and €0.70/litre. The lower and the upper values are thus representing extremes for the annual averages (and somewhat more than that) during the past decade.

Table 23: Input data for the ICE case.

ICE		
Production cost and gross margins for diesel	0.40	€/l
	0.55	€/l
	0.70	€/l
Power output from the electric motor[a]	100	kW
Efficiency (LHV) from tank to output from engine[b]	0.44	
LHV for diesel[c]	36.3	MJ/l

[a] The power output from the engine is 100 kW at 85 km/h for a long-haul lorry (Pettersson, 2017). This will give 1.176 kWh engine work per km.
[b] VTT (2013) also verified by Pettersson (2017). The efficiency will give 2.672 kWh diesel fuel per km.
[c] A value for diesel environmental class 1 (MK1) from Preem (2017), the largest diesel producer in Sweden. The value corresponds to 10.08 kWh/l.

Table 24: Evaluation of the cost per km in the ICE case.

Cost/km, ICE case		
Diesel input/km, (2.672 kWh/km)/(10.08 kWh/l)	0.265	l/km
Diesel cost per km for the three different inputs for production costs and gross margin	0.106	€/km
	0.146	€/km
	0.186	€/km

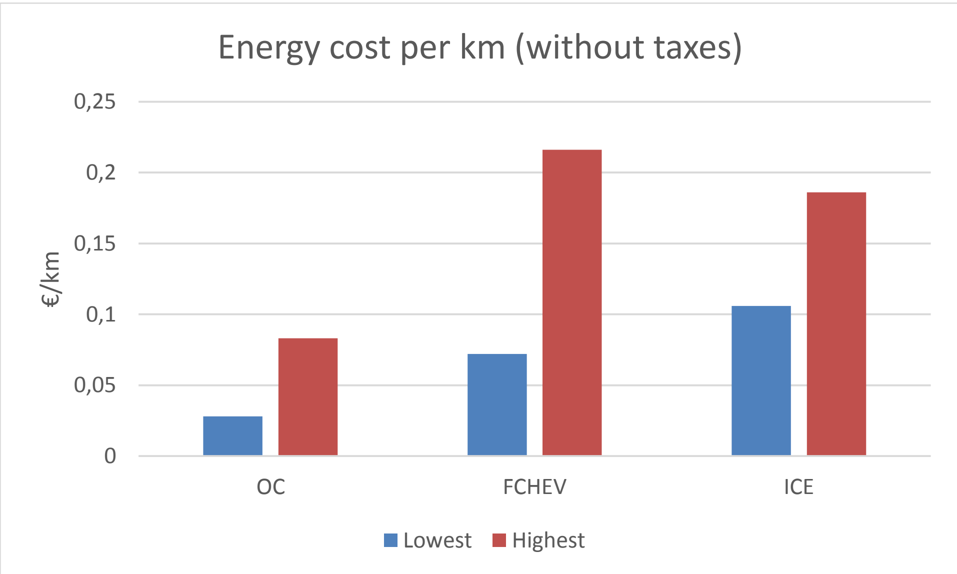

Figure 5: Graphic comparing the energy costs of OC, FCHEV and ICE lorries.

The estimated energy costs in the different scenarios reveal that without the taxes, it is not entirely certain that the variable costs of the new technologies are lower than the conventional solutions, since the FCHEV actually have the highest energy costs at the relatively high electricity price, €0.06/kWh. It should be noticed that the 'extreme' values for both electricity and diesel (without taxes) are not unrealistic. The energy costs are – as expected – by far the lowest for the conductive electric road solution at the lowest electricity price. However, for the electric road system we also have to build up an infrastructure that is much more expensive than the necessary infrastructure for the other new technology – FCHEV – that utilise hydrogen.

5 CONCLUDING DISCUSSION

In this report, three vehicle propulsion technologies for long distance heavy-duty transport (also known as long-haulage) have been examined. The tree systems are electric road systems (ERS), fuel cell hybrid electric vehicles (FCHEV), and the conventional internal combustion engine (ICE) fuelled with diesel.

Three different types of electric road systems defined by the way of transferring the electricity to the vehicle have been studied: overhead conductive, rail conductive and dynamic inductive. The overhead conductive system can only be used by heavy-duty vehicles while the other two systems are possible for both heavy duty vehicles and smaller vehicles such as passenger cars.

The total costs of the system are composed of vehicle costs, infrastructure costs and energy costs. No taxes were included in the cost calculations, which is especially important to consider for the energy costs. For example, during times of low crude oil prices, the cost of diesel fuel can increase to almost three-fold when including Swedish carbon emission and energy taxes as well as value added tax (VAT). The taxes on electricity may be just as high or close to zero depending on the use in Sweden, and the future level of these taxes are difficult to assess for the use for commercial road transports. Nevertheless, the main reason we have excluded taxes from the comparison is that it is unlikely that the taxes per kilometre for any kind of road transport solution in the end and at a developed stage will depart significantly from other solutions. Otherwise, the fiscal impact of a shift to either of the propulsion systems that utilise electricity would be too high. Even if the CO_2 taxes not will be applied on the electric road solution, the extensive new infrastructure needed in these cases will have to be financed somehow, perhaps via a fee that for the individual heavy-duty lorry is comparable to the CO_2 tax for conventional diesel.

In the beginning of the considered time period (2017 to 2030), vehicles costs of fuel cell vehicles, but also of electric road vehicles, were found to be a lot higher than those of diesel engine vehicles. However, this cost difference decreases considerably toward the end of the period in accordance with the cost projections in the sources used for the cost estimates.

The infrastructure costs of electric road systems are somewhere in the range of €1.0-3.5 million/km (using sources for overhead catenary systems with both directions included). If, for example, we assume an electrification of the 1 260 km road triangle connecting Stockholm, Malmö and Gothenburg, the cost would be in the range of €1.3-4.4 billion.

The infrastructure costs of hydrogen consist of the hydrogen fuelling stations. The hydrogen is assumed to be produced locally at the fuelling station by electrolysis of water. The cost of a 1 000 kg/day hydrogen filling station, including electrolyser, is assumed to be in the range of €2.8 million in the year 2030.

Not surprisingly, the energy costs are the lowest for the electric road system with the lowest of the three considered electricity prices (€0.02/kWh). The energy cost of hydrogen (only the electricity cost is considered as the capital cost of the electrolyser is included in the infrastructure cost) is only lower than all the corresponding diesel costs at the lowest of the electricity prices. Somewhat unexpectedly is that at the highest electricity prices, the estimated energy costs are actually the highest for the fuel cell long-haul lorry.

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