Deliverable 1b: Analysis and Comparison of the Available Technologies for Electrification of HDVs

1 Introduction ... 3
2 Selected acronyms ... 4
3 Technological solutions for the electrification of HDVs ... 5
3.1 Hybrid electric powertrain (non-Plug-In) ... 5
3.2 Plug-in hybrid electric powertrain ... 5
3.3 Battery Electric Powertrain ... 5
3.4 Hydrogen Fuel Cell Electric Powertrain (FCEV) ... 5
3.5 Electric Road Systems (ERS) ... 6
4 Infrastructure specifications and requirements ... 7
4.1 HDEV electric recharging infrastructure ... 7
4.1.1 Charging use cases ... 7
4.1.2 Charging technologies ... 8
4.1.3 Recharging stations combined with Battery Energy Storage System ... 10
4.1.4 Logistic hub recharging station combined with local PV generation ... 12
4.2 HDEV Hydrogen refueling infrastructure ... 13
4.2.1 Requirement for HRS with on-site hydrogen production ... 15
5 HDEV market perspectives in the EU ... 17
5.1 Model Availability for Trucks ... 17
5.2 Model Availability for Buses ... 19
5.3 Prospects for HDV deployment ... 20
6 HDV total cost of ownership ... 23
6.1 Rigid Urban Trucks ... 24
6.2 Regional Delivery Trucks ... 25
6.3 Articulated Long-haul Trucks ... 25
6.4 Construction Trucks ... 27
6.5 Sensitivity analysis on non-ICE solutions ... 27
6.6 Other TCO evaluations from the literature ... 28
6.7 TCO for buses ... 28
7 Annex A: available models of electrified HDVs ... 29
8 Annex B: parameters for TCO analysis ... 31
9 Annex C: Other TCO analyses on HDVs ... 32
9.1 TNO analysis ... 32
9.1.1 Modelling parameters ... 33

9.1.2 Energy prices 34
9.1.3 TCO results 36
9.1.4 The main findings from the TNO report 38
9.1.5 Market-driven uptake scenario 38
9.2 ICCT analysis 41
9.2.1 Charging station infrastructure costs 42
9.2.2 Key findings 43
10 References 44

1 Introduction

This report provides an analysis of the available technologies for the electrification of Heavy-Duty Vehicles (HDVs). The analysis moves from the HDV vehicles categories described in Deliverable 1A; it will be recalled that 'electrification' means the use of either Battery Electric or Fuel-Cell Electric powertrains, abbreviated as Heavy-Duty Electric Vehicles (HDEVs).

The aim is to gather up-to-date information on the most mature technical solutions currently available for both the vehicles and the recharging/refueling infrastructure and to match these figures with the energy/mobility needs of today's HDVs, as analysed in Deliverable 1A. Following this analysis, it is possible to define the most important requirements of the possible recharging/refueling stations and to identify the most important economic parameters to use for a Total Cost of Ownership analysis.

The content is organised as follows:

Chapter 3 describes the current technological solutions for the electrification of HDVs.

Chapter 4 focuses on the recharging/refuelling infrastructures for HDEVs and their possible specific layouts.

Chapter 5 presents a market overview of the available main HDEV powertrain technologies, together with the prospects for HDEV deployment.

Finally, **Chapter 6** compares different powertrains concerning Total Cost of Ownership (TCO), separately for trucks and buses.

2 Selected acronyms

ACEA	European Automobile Manufacturers' Association
AFID	Alternative Fuels Infrastructure Directive
APS	Announced Pledges Scenario
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
E/P	Energy to Power ratio
ERS	Electric Road Systems
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GVW	Gross Vehicle Weight
HD	Heavy Duty
HDEV	Heavy-Duty Electric Vehicle
HDV	Heavy-Duty Vehicle
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
IEA	International Energy Agency
Q1	First quartile
Q3	Third Quartile
LDV	Light Duty Vehicles
LPT	Local Public Transport
MCS	Megawatt Charger
MD	Medium Duty
MOU	Memorandum of Understanding
NCS	Overnight Charger
PV	Photovoltaic
RD	Regional Delivery
RES	Renewable Energy Sources
RU	Rigid Urban
STEPS	Stated Policy Scenario
SOC	State Of Charge
TCO	Total Cost of Ownership
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TSO	Transmission System Operator
VECTO	Vehicle Energy Consumption Calculation Tool

3 Technological solutions for the electrification of HDVs

The following section provides a summary of the commercially available electrified powertrains. HDVs can be electrified at various levels and, depending on the size of the on-board storage, the capability of all electric operations and the recharging requirements are very different.

3.1 Hybrid electric powertrain (non-Plug-In)

- The vehicle is mainly driven by an Internal Combustion Engine (ICE). In the decarbonised scenario, the fuel is a carbon neutral biofuel or synthetic fuel. A small electric drive (5-20 kW [1]) supports the ICE during low efficiency operations, i.e. typically at low speed and intermittent stop&go;
- A small size low voltage battery (12–48V/2–5kWh [1]) provides the power to the electric motor;
- The micro-hybrid powertrain provides only stop-start functionality. The mild-hybrid allows limited electric operation at low speed, a temporary boost, limited accessory load during engine-off operations and limited brake regeneration;
- Only fuel refilling operations are requested. The small battery is charged by the ICE while driving;
- As discussed in Deliverable 1A, this solution is expected to be limited to agricultural and construction machineries for which direct electrification is unfeasible; and
- No impact on the electric grid.

3.2 Plug-in hybrid electric powertrain

- The vehicle powertrain consists of a battery powered electric motor in parallel or in series with the internal combustion motor;
- Hybrid powertrains support multiple vehicle architectures (series, parallel, or power split);
- The electric drive system can provide all or a substantial fraction of traction power for all electric operation (50–80 km [1]). A substantial portion of braking energy is recovered in the battery energy storage system;
- A battery is typically charged from the grid. However, recharge through the ICE is usually possible; and
- There is a limited impact on the electric grid due to marginal use of the electric energy and primary consumption of diesel fuel. Most of the charging comes from the internal ICE energy recovery system. Furthermore, limited grid flexibility services can be drawn from these types of vehicles.

3.3 Battery Electric Powertrain

- The vehicle is driven by an electric motor;
- The whole electrical power to supply the motor is provided by a large-sized battery (100–900 kWh [2]);
- A dedicated infrastructure is required to recharge the battery. Actual range from 7 kW to 375 kW, future infrastructure will reach up to 3.5 MW'
- Zero tailpipe emissions;
- Zero Well-To-Wheel emissions if electricity is generated from Renewable Energy Sources (RES); and
- Possible impact on electric grid.

3.4 Hydrogen Fuel Cell Electric Powertrain (FCEV)

- The vehicle is driven by an electric motor
- The electrical power to supply the motor is provided by a fuel cell which generates electric power from hydrogen and oxygen

- Hydrogen needs to be stored in gaseous form at high pressure (350 or 700 bar) to improve its energy density;
- A dedicated refueling infrastructure is required to handle high pressure hydrogen refilling;
- As no combustion is required to generate usable energy, FCEVs present zero tailpipe emissions;
- Zero Well-To-Wheel emissions if hydrogen is produced from RES; and
- Possible impact on the electric grid.

3.5 Electric Road Systems (ERS)

- The vehicle is driven by an electric motor;
- The electric power is transferred to the vehicle on motion via inductive coils, or through conductive connections between the vehicle and road, or via catenary (overhead) lines;
- The vehicles have a smaller onboard battery which can be charged while the vehicle is drawing power from the ERS and allows for electric autonomy when disconnected;
- A dedicated infrastructure is required to enable motion power supply. Technology harmonisation is essential to support interregional transport;
- Limited recharge needs during parking as the on-board battery storage is small;
- Zero tailpipe emissions;
- Zero Well-To-Wheel emissions if electricity is generated from RES;
- The likelihood of deployment of such infrastructures is low because their technological maturity is not ready for the market. Nowadays, there are only early-stage technologies tested in pilot projects with a very high infrastructure cost. However, if deployed, these infrastructures would have an impact on the electric grid.

4 Infrastructure specifications and requirements

With the diffusion of zero-emission HDVs, a contextual roll-out of a suitable recharging/refueling infrastructure is necessary. This infrastructure has to be designed considering the use modes of different kinds of HDVs, in particular considering their usual stop locations and durations.

Paragraphs 4.1 and 0 focuses on the electric recharging and hydrogen refueling solutions currently available for HDEV.

4.1 HDEV electric recharging infrastructure

After the definition of charging use cases, considering the combination of charging patterns and charging infrastructure access, the main available charging technologies are described.

4.1.1 Charging use cases

The distinction between different charging use cases is important as the charging use case differ in terms of required charging speed / power and flexibility potential.

Although duty cycles and mission profiles of HDVs can be very different, the most common charging locations could be defined considering the main charging patterns and infrastructure access (Table 1).

Table 1. Charging locations according to the charging pattern and the infrastructure access.

CHARGING PATTERN	INFRASTRUCTURE ACCESS	
	PRIVATE	PUBLIC
EN-ROUTE CHARGING	/	Along motorways
OPPORTUNITY CHARGING	Logistic hubs, terminals, depots	Urban nodes
OVERNIGHT CHARGING	Depots	Safe and secure parking areas

Each combination defines a possible charging use case, which is better described as follows:

- **Public en-route charging along motorways**: drivers usually stop at motorway service areas for short breaks (maximum 1 hour in case of lunch break). This amount of time could be exploited to recharge the HDV battery, which may be necessary to reach the destination in the case of long-haul applications;
- **Public opportunity charging at urban nodes**[1]**:** urban nodes represent multimodal transport hubs, which can serve not only road transport but also rail and inland shipping. Therefore, they are usually places where trucks/buses stop for loading/unloading goods or passengers.
  The average drivers' break at such locations is approximately 2 hours and it is possible to charge the vehicle battery and extend the driving range;
- **Private opportunity charging at logistic hubs, terminals or depots:** trucks and buses regularly stay at business areas/terminals to load and unload goods or passengers before recommencing their travel. Similarly to urban nodes, drivers stay in such places for a maximum period of 2 hours, which

[1] According to ERRIN-Polis, a urban node is defined as '*a functional area that encompasses one or more core cities, as well as the peri-urban and regional areas surrounding cities or polycentric city-systems, where the transport infrastructure of the trans-European transport network, such as ports including passenger terminals, airports, railway stations, logistic platforms and freight terminals, is interconnected between the different modal hubs and connected with the regional and local transport and traffic infrastructure*': https://www.polisnetwork.eu/wp-content/uploads/2020/12/2A_Urban-nodes-in-the-revised-TEN-T-regulation_final.pdf

can be exploited to recharge the battery and extend the driving range. Other categories such as cleaning vehicles or collection machines can also benefit from opportunity charging at private depots during the waste unloading time (maximum period of 2 hours);

- **Public overnight charging in secure and safe parking areas:** the European Commission has adopted specific standards for safe and secure parking areas [3], where drivers could spend their night in secure conditions and have access to all necessary facilities. Such places should be equipped with a recharging infrastructure and ensure complete battery charging during the night (in a timespan of approximately 8 hours); and
- **Private overnight charging in private depots:** trucks and buses return from a single or multiday travel and need to fully recharge their battery during the night (timespan of approximately 8 hours). The same pattern is also valid for other categories, such as collection machines or cleaning vehicles, which are fully recharged during the night in private depots.

Regarding work machines, which are not included in the list above, it will be recalled that their direct electrification is currently deemed unlikely for most of their applications. Work machines operating in urban areas may use a direct electricity connection with the local grid, but this is not expected to have any impact for the Transmission System Operator (TSO) grid.

4.1.2 Charging technologies

This paragraph reports the main technological solutions for recharging (Table 2), with a particular focus on the charging opportunities they can address.

Table 2. Available technological solutions for HDV recharging.

Charging technology	Suited HDV types	Examples of producers
Plug-in cable charging	All types	DAF [4]
Pantograph charging	Buses, demonstration projects for trucks	ABB [5], Siemens [6]
Inductive wireless charging (stationary)	Buses, demonstration projects for tractor-trailers	IPT Technology [7], Electreon [8]

Different recharging technologies are briefly reported below:

1. **Plug-in cable charging** for HDVs does not technologically differ from that for Light Duty Vehicles (LDVs) and usually refers to Combined Charging Systems, type 2 (as standardised by the [Alternative Fuels Infrastructure Directive] AFID for public charging points). However, because of HDV larger battery packs and the physical space required, they must have a dedicated recharging infrastructure. To recharge in a reasonable time, power levels must be higher than those required by cars and are dependent on the specific charging option: **Fast Chargers**[2] (50–150 kW) for overnight charging, **High**

[2] Common terminology for passenger cars, for which 50 kW is a high level of power delivered with respect to battery size. However, in the case of HDV, this is actually the technology used for the longer charging time.

Power Chargers (150 kW–1 MW) for opportunity charging and **Mega Chargers** (1–4 MW) for en-route charging (Table 3)[3].

Table 3. Available plug-in cable charging solutions.

Plug-in cable charger	Suited HDV types	Power level (kW)	Application	Examples of producers
Fast Charger[2]	All types	40 – 100 kW	Overnight charging	DAF [4]
High Power Charger (HPC)	All types	100 kW – 1 MW	Opportunity charging	DAF [4]
Mega Charging System (MCS)	Long-haul trucks	>1 MW	En-route charging	Projects under development (e.g. [9])

2. **Pantograph charging** [5, 6] is applied for electric buses and especially suited for short charging sessions during stops (Figure 1). Demonstration projects are also conducted for trucks [10]. Two options are available: in the case of **Off-board Top-down Pantograph**, vehicles are charged lowering a pantograph on collectors on the roof of vehicles, whereas with **On-board Bottom-up-Pantograph** the pantograph on top of vehicles is raised to an overhead line for recharging. Different power levels are used to provide opportunity charging (150/300/450/600 kW) or overnight charging (50–100–150 kW).

Figure 1. Example of bus pantograph recharging[4].

3. **Inductive wireless charging (stationary)** is based on high power inductive energy transfer between components integrated into streets and the receiving equipment installed beneath the vehicle (Figure 2). It is actually applied for buses in cities such as London, Madrid and Turin [7]. Some demonstration projects have also been conducted for trucks [11, 8].

[3] The mapping of charging technology to charging patterns may not be a 1-to-1 relationship as, in addition to Fast Chargers (50 – 150 kW), High Power Chargers (150 kW – 1 MW) could be used for overnight charging to increase the flexibility potential.

[4] https://new.abb.com/news/detail/47993/abbs-electric-bus-charger-hvc-300p-is-just-the-ticket-for-gottinger-verkehrsbetriebe

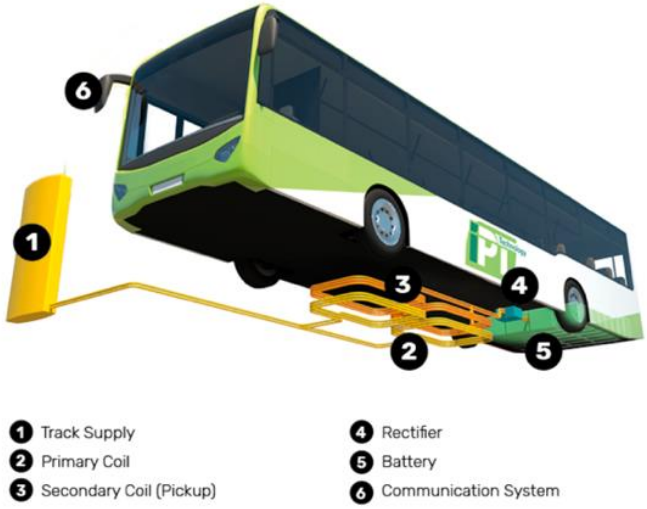


Figure 2. Inductive wireless recharging components[5].

An alternative practice is given by **battery swapping**, where batteries are charged before swapping and then used in the vehicles, saving time and limiting idle time. However, this option is currently scarcely applied because of the high number of extra batteries required. Applications are limited to some pilot programmes by various companies in China, for example CATL[6], Foton New Energy Vehicle[7], Geely[8], China Energy Investment Corporation[9] and Qiyuan Motive Power[10]. These trials include battery swapping for fleets from ten to low hundreds in heavy-duty short-distance operations such as urban and regional delivery. By early 2022, 159 new Chinese truck models have battery swapping capabilities.

4.1.3 Recharging stations combined with Battery Energy Storage System

A Battery Energy Storage Systems (BESS) can reduce the peak power demand to the grid and allow a reduction of the required grid connection power of charging stations.

The technical and economic opportunity of using BESS depends on several parameters and boundary conditions that shall be studied case by case as they may be country regulations, local grid conditions and market structures.

- For the design of batteries and grid connection, in addition to the business consideration, the economic consideration should be considered, which does not include grid fees but actual capacity-dependent grid expansion costs; and
- Integrated grid connection planning from a systemic perspective, considering other local generation and load as well as the provision of flexibility for the electricity system in total, could lead to different results.

Here a case study in Germany is presented [12], where the authors have analysed the possible peak power reduction using a combination of charging management systems and a BESS. Their simulation considered a service station at motorways equipped with both a Megawatt Charging Station (MCS) and an Overnight Charging Station (NCS). The simulated electricity demand profile is illustrated in Figure 3, for a charging

[5] https://ipt-technology.com/e-mobility/
[6] https://www.yicaiglobal.com/news/china-first-highway-heavy-duty-truck-battery-swap-service-starts-operating
[7] https://www.china5e.com/news/news-1095987-1.html
[8] https://www.carscoops.com/2022/03/geely-now-has-a-battery-swap-station-for-cement-trucks/
[9] http://www.techweb.com.cn/it/2022-03-28/2885341.shtml
[10] http://www.spicqyxdl.com/solution

station with a total grid capacity of approximately 9 MVA. This simulation refers to the situation in 2030 and considers a 20% share of battery electric long-haul trucks.

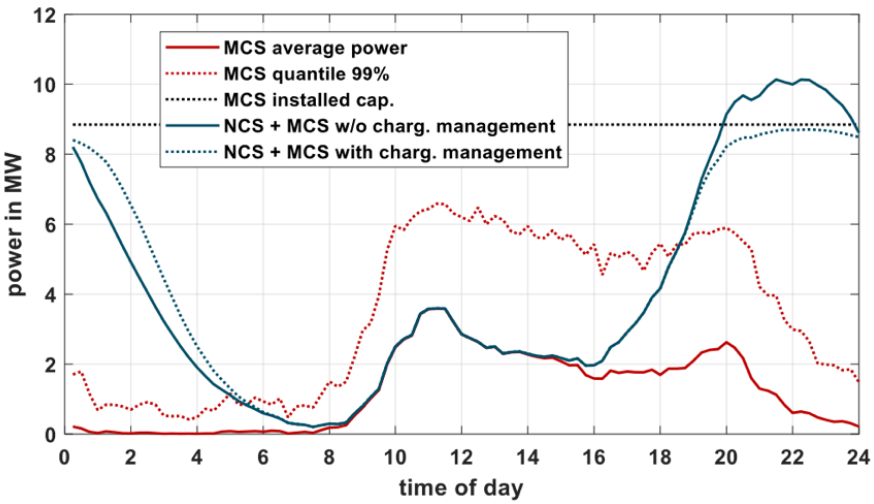


Figure 3. Average daily profile for power demand in the considered scenario (refers to 2030 with a 20% share of battery electric long-haul trucks), with a combination of Megawatt Charging Stations (MCS) and Overnight Charging Station (NCS) [12].

The load profile indicated by the dotted blue line is already almost flat between 7 PM and 2 AM: therefore, the BESS must shift all power between night and day and cannot recharge in-between. Authors found that above a grid capacity of 5.8 MVA, energy needs to be shifted between weekends and weekday, resulting in the requirement of even higher storage capacities.

The conclusions for this scenario (indicated by authors as Scenario 4, with a total grid capacity of 9 MVA) are reported in Figure 4: small storages below 1 MW are not beneficial whereas for systems in the range 1.1–3 MW, revenues are higher than costs as these systems allow a connection to the pre-existing MV-grid. Higher battery power levels would not be profitable as they would require **over-proportionally large battery capacities**. The considered scenario (indicated by authors as 'scenario 4') requires a total grid capacity of 9 MVA and considers the power demand indicated in Figure 3. The technical limit is linked to the maximum amount of energy which can be contained by a single container.

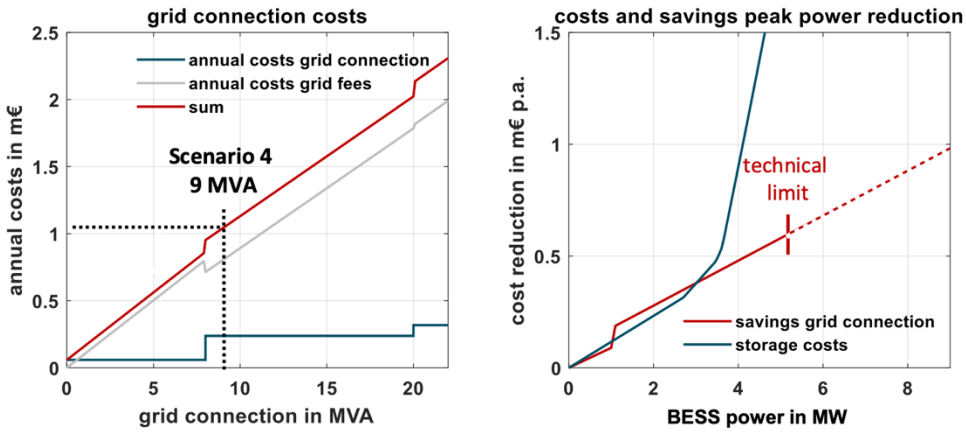


Figure 4. Annual grid connection costs subject to grid connection power (left); comparison of costs and revenues dependent on storage power (right) [12].

Results clearly depend on the considered scenario and grid fees (in this case they are based on tariffs of Westnetz, the largest German distribution grid operator).

Another aspect to consider is the energy to power ratio E/P, indicating the peak power demand duration: charging stations combining Mega Chargers and overnight chargers have long-lasting peak power demands and are not ideal for economic BESS operations whereas charging stations providing only Mega Chargers have a very different demand profile, with very short durations in peak power demands.

As presented in Figure 5 [12]**Error! Reference source not found.**, a storage system with an E/P ratio below 1h can be sufficient for a peak power reduction of almost 4 MVA, reducing the required investments and delaying the grid expansion measures.

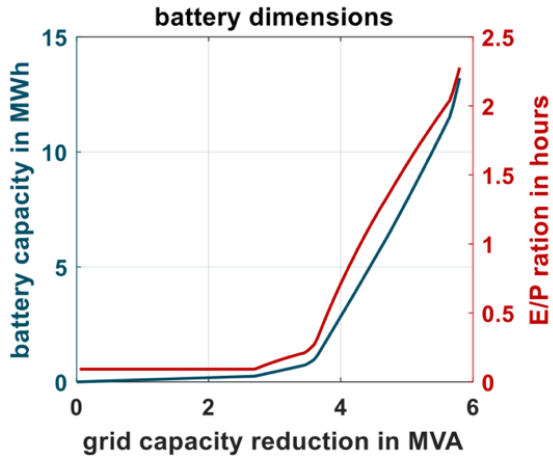


Figure 5. Required storage dimensions for MCS stations [12].

In conclusion, according to [12], the application of a **BESS in combination with MCS is a better option then in combination with both MCS and NCS**. In fact, in the first case, the battery does not compete with the cheaper charging management option and requires significantly smaller battery capacities.

Moreover, a BESS can potentially generate revenues from additional use-cases, as:

- Optimising the own consumption of locally generated renewable energy;
- Optimising electricity procurement costs;
- Increase of a renewable energy supply;
- Provision of ancillary services, as power-frequency control; and
- Backup supply in case of blackouts.

4.1.4 Logistic hub recharging station combined with local PV generation

Authors in [12] also report an analysis of the possible benefits from the combination of recharging at logistic hubs with local photovoltaic (PV) generation. Indeed, daytime opportunity charging is the use case for recharging at logistic hubs.

For their simulations, the authors considered the total recharging demand at two different sites (site 1 and site 2) in Germany, illustrated in Figure 6 below. The reference scenario is 2040, with a share of battery electric long-haul trucks of 80%. Here the results for two relevant cases are summarised:

- **PV plant on the rooftop of the logistic hub**: In this simulation, the limit to the size of the PV plant is given by the available rooftop surface area. The authors consider an average 40% share of the buildings of the total net area of the logistic hub and a ratio of PV module area to rooftop area of approximately 40% for the size of the PV installation, which leads to an annual PV generation of

approximately 10% of the total annual consumption. This low share of electricity guarantees that even in summer, the complete PV yield is immediately consumed on-site and no export needs to take place. This conclusion is valid for the charging profiles of both sites.

- **PV capacity matching grid connection for truck charging**: in this case, the size of the PV plant is maximised with respect to the grid connection capacity, which may lead, especially in summer months, to situations where the PV generation exceeds the charging demand. This situation can be seen in Figure 6, where the charging profile of site 2 does not correlate with the daily cycle of solar radiation. In this case, a share of the generation shall be fed into the grid. Such an oversized PV plant implies that additional space is available for the PV generation facility near the logistic hub; in many cases, **space limitations** will form the relevant restriction for this case.

In conclusion, authors report that adding PV generation alone is not beneficial towards reducing the grid connection capacity required by the recharging station. In fact, if PV panels are installed on a depot roof, they would not be sufficient to reduce grid connection capacity and to reduce peak load. Even in cases where the maximum load occurs during the day, in winter PV generation is not able to contribute to load coverage. Their conclusion is that deploying the existing synergies of on-site PV generation and truck charging at logistics hubs will be challenging due to institutional complexity and the difficulty to synchronise planning and implementation of infrastructure.

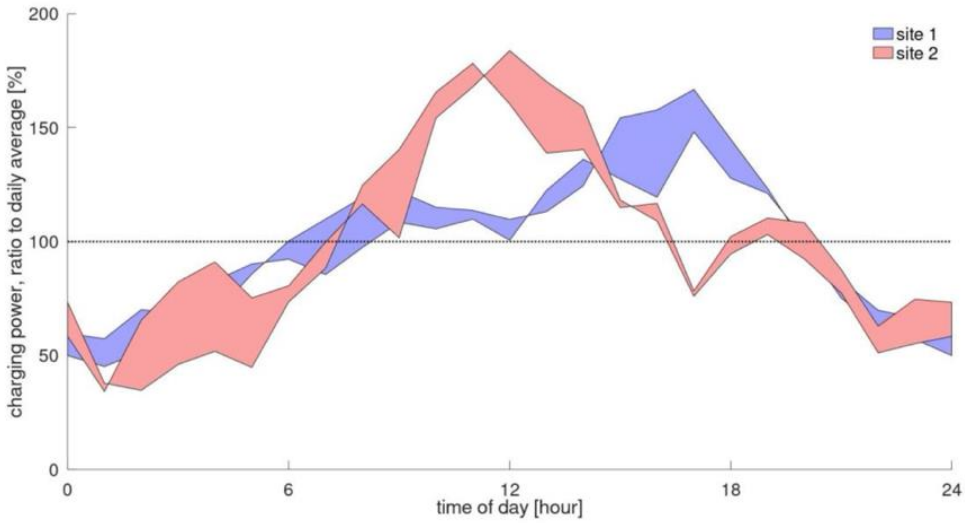


Figure 6. Estimated daily load profiles of battery charging for two prototypical charging stations at the logistics hubs with different traffic flow patterns and truck fleet composition [12].

4.2 HDEV Hydrogen refueling infrastructure

Hydrogen Refueling Stations (HRS) may be realised according to many different designs depending on how the hydrogen is produced, delivered, stored and dispensed. However, each station shall include, at a minimum:

- **Low-pressure Storage System:** where hydrogen is stored as a liquid or more commonly as pressured gas (40–200 bar) in tube trailers;
- **Compression system:** which draws hydrogen from the low-pressure storage and compresses it to replenish the high-pressure buffer storage system;

- **High-pressure buffer storage:** usually organised in a cascade system up to 950 bar, in case of 700 bar refueling, or 500 bar in case of 350 bar refueling;
- **Chiller**: hydrogen is cooled to subzero temperatures for fast and efficient filling to ensure the hydrogen can be dispensed safely avoiding overheating. Stations for some heavy-duty vehicles and material handling equipment may not use chillers as they are filled at lower pressure (350 bar); and
- **Fuel dispenser**: the hydrogen is dispensed via a nozzle controlled by a valve which regulates the flow rate of the gas to fill the vehicle to the required pressure.

The hydrogen dispensed by a hydrogen refueling station can be produced in two different ways. Hydrogen can be produced in a **central production unit** from a **Steam Methane Reforming** or **electrolysis** and then **delivered to the station**. The hydrogen is usually transported at the HRS in gaseous form. Nevertheless, there are HRS supplied with liquid subcooled hydrogen transported in vacuum-insulated cryo-tanks.

Another interesting option is to refuel HDV directly with liquid hydrogen. Subcooled liquid hydrogen has a significantly higher volumetric energy density compared to gaseous hydrogen. This propriety allows for high onboard storage capacities with limited space, enabling high driving ranges up to 1000 km/day without refueling. Currently, the technology is still in the R&D stage, with first prototypes close to validation.

Some of the major challenges are the lifetime of components exposed to cryogenic temperatures and the risk of boil-off losses. In addition, hydrogen losses increase in the event of long idle times or partial refueling under suboptimal conditions. Liquid hydrogen is thus more suited for HRS with high-demand placed along major traffic corridors. However, in comparison to gas hydrogen configuration, the liquid station footprint is expected to be significantly smaller, the liquid tanks will not need any carbon fiber cladding, and liquid hydrogen pumps require only a fraction of the power demand of a comparable gas compressor.

The liquid hydrogen technology is currently pushed by Daimler Truck from the vehicle side and Linde from the HRS side. Daimler Truck has announced a series production starting in 2027 and is working on the first prototypes of the GenH2 Truck using this technology. The refueling of liquid hydrogen into the insulated vehicle tank will be realized at approximately -247°C with pressures of up to 16 bar, resulting in an energy density of 2.2 kWh/l. To keep the boil-off to a minimum, the manufacturer idea is to increase the boiling point to higher temperatures so that greater heat input can be endured until phase transformation starts.

However, it is possible to **produce hydrogen on-site** with a **local electrolyser integrated in the refueling station.** This configuration avoids fuel transportation from the production site to the HRS, which can be costly and inefficient.

The economic feasibility of on-site hydrogen production via electrolysis can be limited by the **costs** associated with the electrolyser and the potential need for an electrical upgrade. The estimated cost of this type of HRS with a capacity of 120 kg/day is approximately $3.2 million. For comparison, one single Fuel Cell truck with long haul capabilities has a tank capacity of approximately 50 kgs of H2. Moreover, onsite electrolysis tends to have higher hydrogen production costs than central production due to limited production capacity.

Figure 7 shows the European Union (EU) average pump price for hydrogen produced onsite from renewable energy [13]. The renewable hydrogen production cost is expected to decline in the future due to technological improvements on the electrolysers (optimistic vs mid-level scenario, which differs on the expected technological advances for the electrolysers.). However, the levelised cost of HRS infrastructure is expected to decline mainly due to increased utilisation rates, assumed to be 50% in 2030 and 70% in 2050. Regardless of these cost reductions, the optimistic estimate of 6 euros per kg of hydrogen is still higher than the 2030 target of 1.8 euros per kg. Financial incentives are necessary to reach the EU cost reduction target.

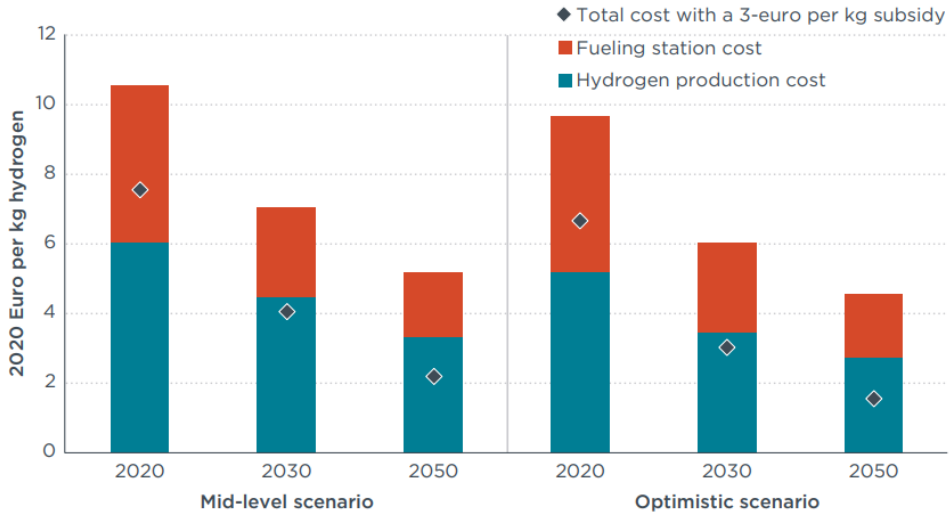


Figure 7. Average pump price for hydrogen produced onsite with local renewable energy [13].

Policy support is essential to make on-site hydrogen production economically viable, as observed by the authors of [13], if no CO_2 penalisations are added to the cost of diesel fuels. Beyond financial support for hydrogen production, robust regulations on the source of electricity are crucial to ensure the true climate benefit from renewable hydrogen.

4.2.1 Requirement for HRS with on-site hydrogen production

From the grid perspective, HRS with on-site production has the strongest impact. The combined load of the compressor and the electrolyser are likely to reach levels which influence the grid planning process. The major electric loads for on-site HRS configuration are represented by the electrolyser and the compressor. The required power to supply these two components can be calculated as:

$$Power_{Electrolyser} = \frac{Q_{H2} LHV_{H2}}{\eta_{electrolyser}} \quad (1)$$

$$Power_{Compressor} = \frac{Q_{H2} cp_{H2} T(\beta^{\theta} - 1)}{\eta_{compressor}} \quad (2)$$

Regarding the electrolyser power, Q_{H2} is the hydrogen flow rate (kg/h), LHV_{H2} is the lower heating value, $\eta_{electolyser}$ is set at 65% [14]. The compressor power depends on the hydrogen specific heat cp_{H2}; the compression ratio β, defined as the output hydrogen pressure (500 bar) out of the input pressure set by the electrolyser (30 bar); the compressor efficiency $\eta_{compressor}$, assumed at 50%; and the ambient temperature T and θ, which is the coefficient for diatomic gas.

Table 4 identifies the power requirement for a different HRS size, considering the power supply for the electrolyser and the compressor unit.

Table 4. Power requirement for different size of HRS with on-site hydrogen production (RSE elaboration).

HRS Size (kg/day)	Electrolyser Power supply (MW)	Compressor power supply (MW)	Total Power (MW)
500	3.0	0.1	3.1
1000	6.0	0.3	6.3
2000	12.1	0.6	12.7
3000	18.2	0.8	19.0

The main hypothesis introduced for this calculation is the electrolyser working hours, which influence the size of the electrolyser. Indeed, if the working time increases, the rated capacity of the electrolyser decreases. In this case, it is assumed that the electrolyser produce hydrogen and thus absorbs energy only when the electricity price is low, for about 10 h per day (3650 h/year); reducing electrolyser capacity implies the construction of a correspondent higher local hydrogen storage.

Fuel cell trucks and buses require high-capacity stations that produce 500 kg/day or more of hydrogen. An HRS capable of 500 kg of H2 per day would require a 3.1 MW connection to the grid. HRS with an on-site electrolyser capable of producing more than 2000 kg/day might require connection to high-voltage grids, which may serve approximately 40 FC trucks (full tank refill).

4.2.1.1 Comparison between Hydrogen refueling and fast charging infrastructure

The hydrogen refueling infrastructure has three main advantages compared to fast-charging infrastructure:

- Hydrogen infrastructure with a local electrolyser can act as a balancer to the grid in a geographically spread manner without requiring the use of smart charging solutions during the recharging/refueling operation. However, the use of on-site electrolysis as a balancer to the grid could be limited due to high costs or limited speed of load changes of the electrolyser; this should be investigated further. The hydrogen storage unit of the HRS represents a built-in energy storage that avoids the need of simultaneity between production and withdrawal. Hydrogen can be produced opportunistically from the electricity grid, especially when there is surplus or low-price electricity. In a charging station, the energy shift can be only partially achieved with the integration of a local battery energy storage, which adds costs to the basic station layout;
- As of 2022, hydrogen refueling takes one tenth to one fifteenth of the time that fast charging requires. This means that the HRS infrastructure, handling the same number of vehicles, requires approximately 10 to 15 times less space to fuel the same number of vehicles [15]. However, the upcoming Mega Charging system can reduce the charging time, almost equalising hydrogen refueling times; and
- One hydrogen refueling point can serve up to 10–15 times more vehicles in the same unit time compared to one fast charger. This makes the hydrogen refueling infrastructure more scalable (less costly to upgrade) with respect to an increasing FCEV fleet.

Table 5. Comparison of a hydrogen refueling station and fast charging station (RSE elaboration).

Hydrogen infrastructure	**Fast Charging station**
• Fast refueling in 10–15 min • Absence of simultaneity between production and withdrawal of hydrogen • Lack of existent and capillary network • High investment cost	• Longer recharge time > 45 min–1 h with actual technology. Upcoming MCS will handle the recharge in 15–30 min. • High instantaneous recharge power • Existing or Ongoing infrastructure development • Lower investment cost

5 HDEV market perspectives in the EU

In fact, most of the leading manufacturers have already started series production of battery-electric and fuel cell HDV and/or are in the final stages before series production. Indeed, in the last few years, HDEV have begun to circulate on European roads, and their absolute numbers are growing as well as the number of available models on the markets, covering increasing numbers of use cases of the transportation sector. This trend is expected to continue, with a debate on the speed of the transition. Figure 8 below summarises the yearly sales of HDEV regarding the total number of sales for the three main vehicle categories of the transport sector.

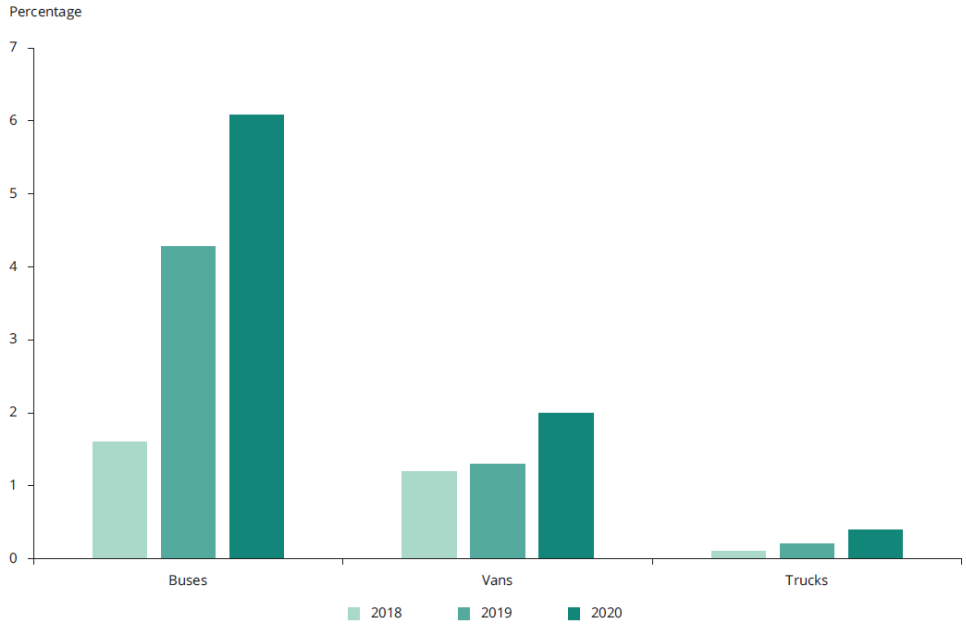


Figure 8. Share of electrically chargeable vans, buses and trucks in new vehicle sales in the EU-27, 2018–2020. Data from [16].

5.1 Model Availability for Trucks

Today, alternatively powered vehicles (battery electric, plug-in hybrid, hybrid and alternative fuels) together represent 3.4% of new truck sales in the EU. However, this market is expected to grow, driven by an increase in available models, policy support and rapidly improving technical and economic competitiveness [17].

In the EU frame, almost 40 battery-electric truck models are available today in various configurations that can be adapted to different mission profiles such as long-haul, regional distribution and construction [2]. More than 40% are HD trucks which present Gross Vehicle Weight (GVW) exceeding 12 tons. In addition, many of these trucks present up to 40 tons of GVW with regular payloads, which makes them suitable for transporting large quantities of goods over long distances. Table 9 in Annex A reports data related to some models of battery electric HDVs produced by the most important manufacturers.

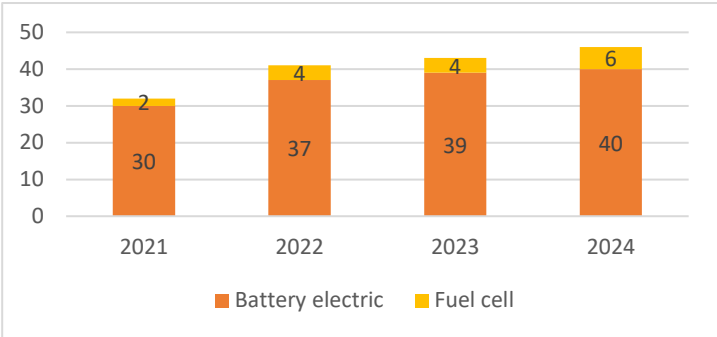


Figure 9. Available models for Battery electric and Fuel cell trucks [2].

Hydrogen-powered fuel-cell electric trucks are the second major zero-emission powertrain technology. Today, only 52 fuel-cell registered trucks are in operation in Europe [18]. Nevertheless, several manufacturers (Daimler, Nikola, Hyundai, MAN) have announced the start of series production of these vehicles from 2024 [19]. It is expected that hydrogen-powered trucks will become widely available within this decade.

Figure 10 represents the distribution of available ranges for the truck segments according to manufacturer's data [2]; models available in Europe through 2022 have been selected. Trucks exceeding 12 tons have median ranges of 270 km, which is not sufficient either for regional or long-haul application, unless introducing intermediate recharge which however could interfere with the truck operations. Some declared endurance ranges reaches 550 km for battery electric truck and 670 km for fuel cell trucks, which have the chance to be compatible with the truck operating profile.

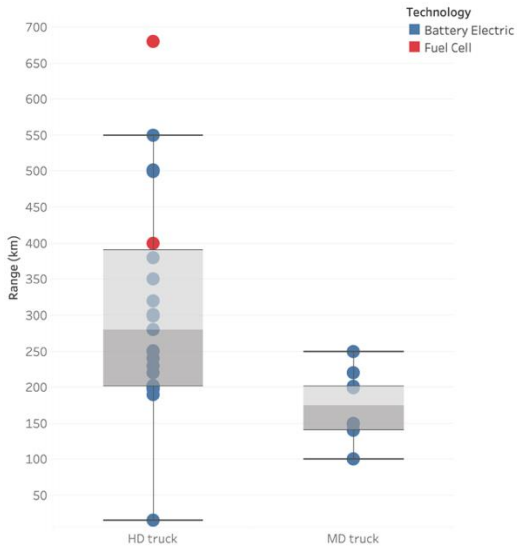
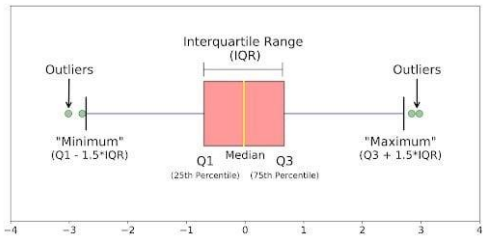


Figure 10. Boxplots[11] of ranges for non-ICE trucks, separated into HD trucks (>12 tons) and MD trucks (<12 tons) [2]. Models available in Europe through 2022 have been selected.

[11] A boxplot is a standardised method of displaying the distribution of data based on a five number summary ('minimum', first quartile [Q1], median, third quartile [Q3] and 'maximum'). Moreover, it indicates outliers and their values. These different components are shown below:



5.2 Model Availability for Buses

The availability of non-ICE bus models continues to expand across all leading global markets. This segment is the most-established zero-emission application, and according to the IEA is also becoming competitive on TCO [17]. In Europe, almost 50 models of electric buses are already available, most of them (>90%) dedicated to urban application, with batteries from 300 to 470 kWh (Annex A: available models of electrified HDV). Fewer models of fuel cell buses are available, although a significant increase has been registered in the last year.

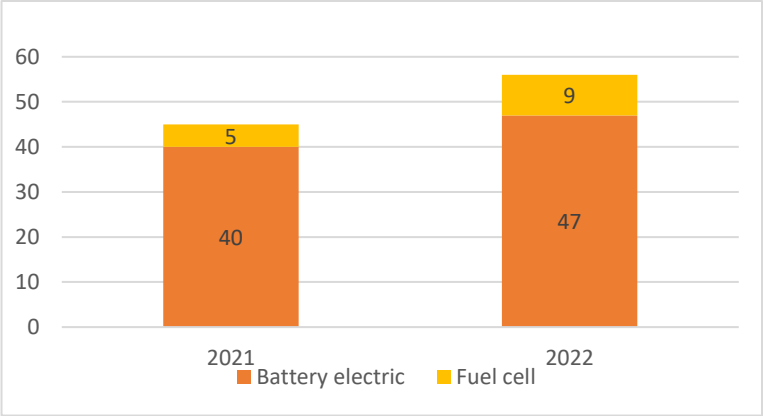


Figure 11. Available models for Battery electric and Fuel cell buses [2].

According to manufacturer data, zero-emission urban buses on the market in 2022 have a median range of 250 km, with several manufacturers reporting ranges greater than 300 km. Roughly half of the urban models have a manufacturer-reported range between 214 and 300 km, sufficient for most urban operations. Coach buses present a median range of approximately 390 km, with one battery electric model reaching 500 km of autonomy.

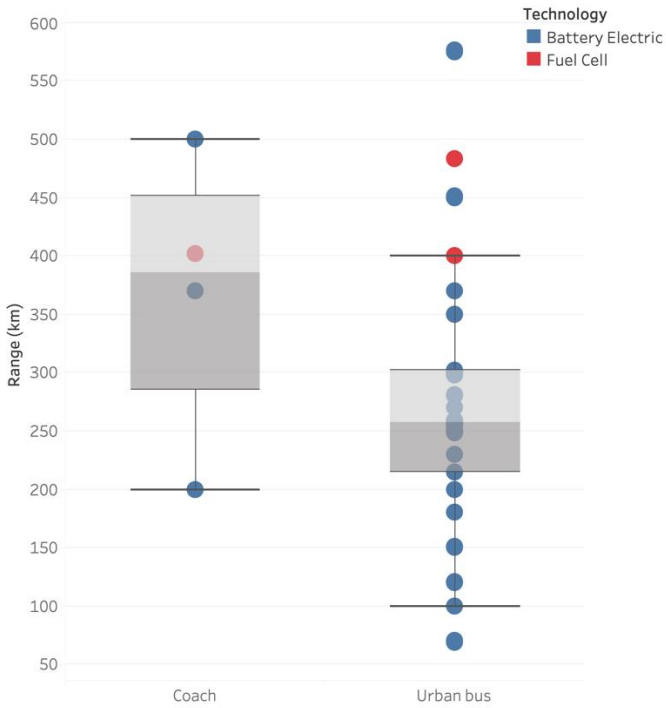


Figure 12. Boxplots of ranges for urban buses and coaches [2].

5.3 Prospects for HDV deployment

Today, the vast majority of HDVs run on diesel; however, electrification is gaining market. Registrations of new electrified (full battery electric vehicles [BEVs], fuel-cell electric vehicles, plug-in hybrids) buses and trucks significantly increased across EU in 2021. New electrified buses saw a strong growth of +78.7%, whereas trucks have begun to rise rapidly, reaching +26.6% in 2021.

Recent trends in sales, policy drivers and technology improvements drive the prospects of HDEV deployment. Projections of HDEV uptake for trucks and buses have been advanced by different agencies. This paragraph summarises the main prospects elaborated from **IEA, ACEA and McKinsey & Company** for the EU region. The IEA focuses the attention on battery electric and plug-in battery electric powertrains for both buses and trucks [17]. ACEA, in its position paper on recharging and refueling infrastructure for heavy-duty trucks, estimates future deployment both on the stock of battery electric and fuel cell vehicles and the required infrastructure [20]. A deep insight into the market uptake of battery and fuel cell electric trucks is provided by McKinsey & Company [21].

The IEA assesses the projected uptake of electric trucks and buses according to two scenarios: the Announced Pledges Scenario (APS) and the Stated Policy Scenario (STEPS). APS is based on existing climate-focused policy pledges and announcements. STEPS is based on current policy plans and does not take it for granted that governments will reach all announced goals.

Regarding trucks, the **IEA** expects that electric trucks could rise from 27,000 in 2025 to 130,000 in 2030 in the STEPS scenario. In the APS, electric truck stock could reach 54,000 units in 2025 and **340,000 units in 2030**. The share of electric truck sales could rise from 7% (STEPS) to **17%** (APS) of the **sales** by **2030**, reaching from 2% (STEPS) to **5%** (APS) of the total truck stock in the EU. In both scenarios, plug-in electric truck will reach lower levels, 4,600 in 2025 and 90,000 in 2030 according to the STEPS, and 23,000 in 2025 and 80,000 in 2030 according to the APS, addressing the full electrification as the most adopted solution.

Focusing on buses, the IEA foresees that the development of electric **buses** will accelerate in the next few years. From 180,000 (STEPS) to 200,000 (APS), electric buses are expected to circulate in Europe by 2025. The electric bus fleet will reach from 530,000 (STEPS) to **580,000 (APS) units in 2030**, representing from 11% (STEPS) to **25% (APS) of the stock by 2030**, with up to 55% (APS) of sale share. Even in this case, the number of plug-in hybrid buses will play a smaller role, with 6,800/12,000 units in 2035 and 24,000/33,000 in 2030.

In the period to 2030, the adoption of battery electric HDVs is expected to be most rapid for **city buses and urban and regional delivery** applications with short range routes (under 200 km/day). For these cases, buses and trucks will mainly recharge at their depot overnight or during breaks. As the electrification of intercity buses and long-haul trucks increases, public chargers, especially along highways, will be required.

Globally, the number of **bus depot** chargers increases from about 65,000 today to almost 600,000/750,000 in 2030, with a total capacity of over 50/70 GW, depending on the scenario [17]. In 2030, the number of **opportunity** chargers, along routes, for buses is **two orders of magnitude lower** than depot chargers, reaching **less than 3,500 chargers** in both scenarios. Regarding the power rate, depot bus chargers are assumed to have an average power rating between 50 kW and 100 kW, whereas opportunity chargers for buses are assumed to range between 150 kW and 500 kW.

The number of global **depot** chargers for **trucks** increases from approximately 7,000 today to over 260,000/390,000 in **2030**, depending on the scenario [17]. **Opportunity chargers** for trucks constitute only **approximately 5%** of truck chargers in 2030, yet up to 20% of truck charging capacity, reflecting the high-power rating required for the opportunity charging of trucks. Depot chargers for trucks have an assumed average power rating of approximately 100 kW, whereas opportunity chargers for trucks range from 150 kW to 1 megawatt (MW). Some industry actors are focusing the attention on the development of a 3.5 MW charger for HDEV, over ten times more than the fastest chargers currently installed for LDVs.

Other projections on HDEV are presented in **ACEA's** position paper on recharging and refueling infrastructure for heavy duty.

Regarding the deployment of battery electric technology, ACEA estimates that by 2025, approximately 10,000 medium-duty trucks (3.5 tons–16 tons GWV) and 30,000 c heavy-duty trucks (>16 tons GWV) will be in operation in Europe (EU27+UK). By 2030, the fleet will grow to approximately 70,000 medium duty and 200,000 heavy-duty trucks. It is interesting to note that these data are well **aligned with the IEA scenarios**.

To ensure the recharging infrastructure roll-out across Europe, ACEA identifies the target for each member state based on the share of new vehicle registrations and weighted according to national Gross Domestic Product (GDP) and average mileage. Accordingly, a target of 10,000–15,000 high-power public and destination charging points for HDVs should be set by 2025, and a target of 40,000–50,000 charging points by 2030. The large majority of these must be high-power (>500 kW) chargers. In addition, a target of at least 40,000 lower power (100 kW) public overnight chargers at truck parking areas along the highways should be set for 2030.

For fuel cell vehicles, **ACEA estimates that at least 60,000 hydrogen-powered trucks** will be in operation in EU by 2030, representing **1% of the actual truck fleet**. In total there is a need for approximately **300 public access hydrogen refueling stations suitable for HDVs by 2025,** and at least 1000 no later than 2030 [20][12]. ACEA also suggests that a hydrogen refueling station for trucks should have a minimum daily capacity of at least 6 tons of H2 with at least two dispensers per station.

More **promising** scenarios for battery electric and fuel cell trucks in Europe are formulated by McKinsey & Company — see Figure 13. In particular, it is expected that **battery electric and fuel cell** trucks will become the dominant powertrains in new vehicle sales, **covering 60% of new sales by 2030**. Projections to 2040 indicate that the sales share will reach 85%, making battery electric and fuel cell trucks 40% of the total vehicle fleet. The segmentation between the battery electric and fuel cell adoption is shown in Figure 13. Battery electric will play a major role in urban and delivery medium-trucks, which will share the market with the fuel cell technology in the long haul application with predictable operation. It is expected that fuel cell could cover most of the long haul segment with low predicable route and operation.

[12] This is a target proposed by the European Automobile Manufacturers' Association, drawn as the sum of the target identified for each nation in EU27+UK. Each nation target is based on the share of new vehicle registrations and weighted according to national Gross Domestic Product and average mileage (each compared to EU level).

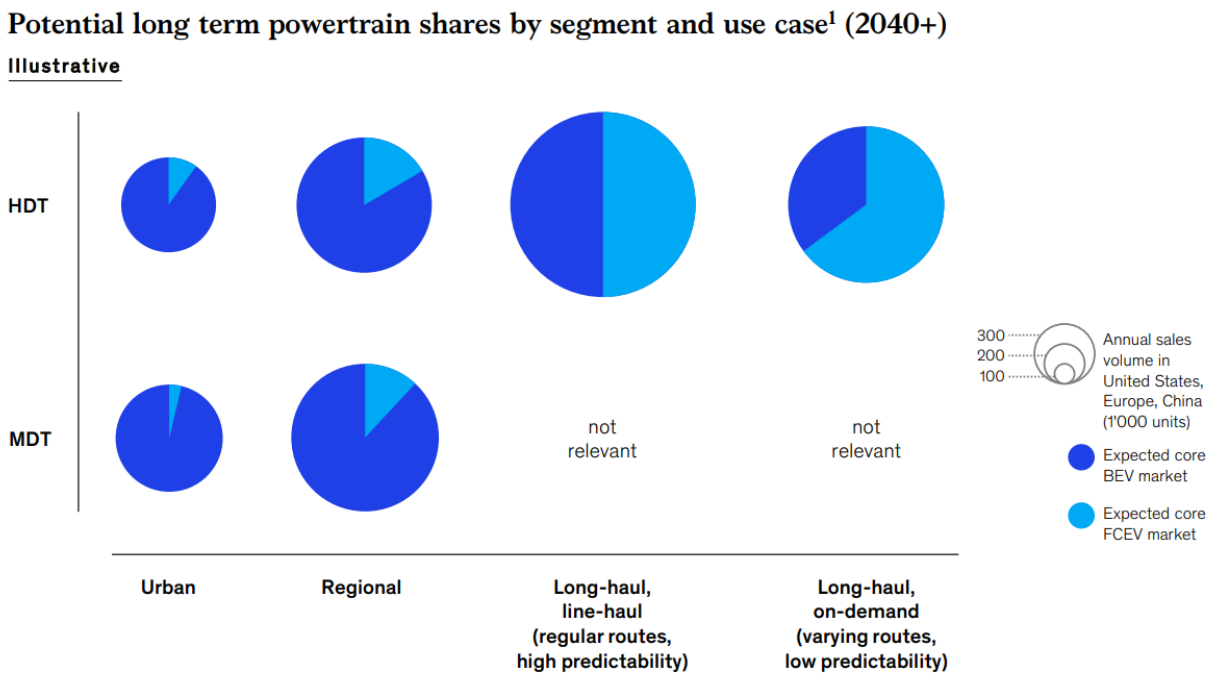


Figure 13. Battery electric and Fuel cell powertrain share according to McKinsey & Company [21]. Urban: Distribution use cases with daily mileages of 150 km or less; Regional: Distribution use cases with daily mileages of 250 km or less, returning to base at the end of the day; Line-haul: daily mileages of 500 km along predictable, regular routes; On-demand: daily mileages of 500-800 km, in ad-hoc settings with limited predictability.

It is worth mentioning the Memorandum of Understanding (MOU) on Zero-Emission Medium- and Heavy-Duty Vehicles, signed by 15 leading countries, including European ones. The MOU sets the commitment to enable 100% zero-emission new truck and bus sales by 2040, with an interim goal of 30% zero-emission vehicle sales by 2030 [17].

6 HDV total cost of ownership

Battery-electric and fuel cell vehicles can offer a viable pathway to decarbonising the HDV sector. However, understanding if alternative solutions to diesel powertrain will be successful and which of those will win depends on a variety of factors including technical and economic ones, including market penetration.

The heavy-duty road transport is a cost-sensitive sector and, in addition to their initial purchase price, the operational vehicle cost also plays a very important role making the TCO the key decision factor for transport operators. Furthermore, technical requirements such as vehicle range, charging and refueling times, as well as payload or possible constraints such as insufficient availability of charging/fueling infrastructure, are important criteria for the transition from conventional diesel vehicles to zero-emission HDVs[13].

According to vehicle segmentation adopted, the TCO analysis of four segments of vehicles (urban delivery, regional delivery, long haul and construction trucks) has been assessed.

The TCO considers the overall costs for the property and the use of vehicles during a five-year period and includes capital costs (purchase cost of the vehicle subtracting the discounted residual value) and operational costs (fuel and maintenance costs).

For this economic assessment, additional incomes (e.g. from grid and system services) reducing the TCO are not considered. These aspects are analysed in Deliverable 3.

The economic evaluation compares diesel vehicles with non-ICE technological solutions (only battery electric for urban and regional delivery, both battery electric and fuel cell powertrain for long haul and construction vehicles).

The following Table *6* reports the main general parameters used in TCO analysis:

Table 6. General TCO parameters used in TCO analysis [source [22]].

Parameter	Value
Timeframe	2020 – 2040
Operational days per year	265 days
Perspective	First owner period of 5 years
Discount rate (IRR)	5%
Residual value	35%
Maintenance costs	Included
Financial charge on vehicle cost	Excluded
Vehicle registration and circulation taxes	Excluded
VAT	Excluded
Road tolls	Excluded
Taxes: excise duty on diesel and unrecoverable taxes and levies on electricity	Included
Personnel costs	Excluded
Overheads	Excluded

Regarding taxes, it should be noted that:

[13] 'Zero-emission heavy-duty vehicle' means a heavy-duty vehicle without an ICE, or with an ICE that emits less than 1 g CO_2 /kWh as determined in accordance with Regulation (EC) No 595/2009 and its implementing measures, or which emits less than 1 g CO_2 /km as determined in accordance with Regulation (EC) No 715/2007 of the European Parliament and of the Council and its implementing measures.

- VAT has not been included as it is a recoverable tax; and
- Vehicle registration, circulation taxes and road tolls, as well as insurance costs, are assumed to be the same for the different type of vehicles and do not affect the TCO comparison.

The vehicle parameters such as fuels and energy consumption, fuels and electricity price, vehicles purchase costs, maintenance costs and annual mileages used in TCO analysis are summarised in Table 10 of Annex B.

Regarding the fuels and energy prices indicated in Annex B (Table 10), it must be noted that:

- Diesel price [€/litre] excludes VAT and includes excise duty and applicable fuel rebates;
- Electricity price [€/kWh] excludes VAT and recoverable taxes and levies and is composed by costs of electricity and costs of charging infrastructure (charging equipment and grid connection), with a distinction between depot and fast charging as indicated in Annex B;
- Hydrogen price [€/kg] includes infrastructure costs and excludes VAT, and duty does not apply.

Additional costs for emitting CO_2 that increase the energy costs for diesel vehicles and improves the relative cost competitiveness of non-ICE technological solutions are not considered in the analysis.

The following paragraphs present the results of TCO analysis performed by RSE on the basis of the General parameters as in Table *6* and Vehicle parameters as in Table 10 in Annex B.

6.1 Rigid Urban Trucks

The following Figure 14 shows the results of TCO analysis for rigid urban diesel and battery electric trucks in the timeframe 2020–2040.

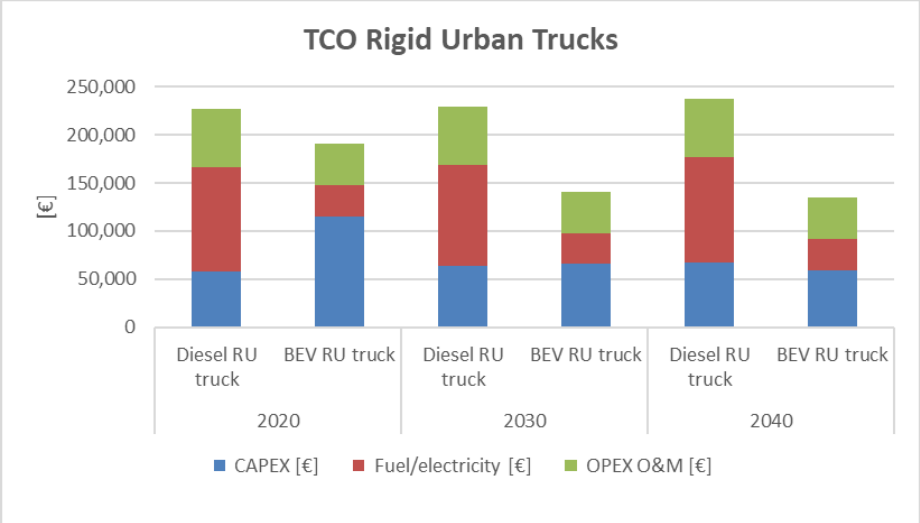


Figure 14. TCO for rigid urban (RU) trucks: comparison diesel vs battery electric (authors' elaboration).

For the daily energy need of urban trucks, an overnight recharge at the depot has been assumed.

Analysing Figure 14, it appears that already in 2020, despite the higher upfront purchase cost of BEVs, the lower operational costs make the TCO of BEV lower than that of the diesel equivalent. The economic advantage of BEV trucks will increase in 2030 and in 2040 due to expected technology improvements and cost reductions of vehicle components such as batteries in addition to the future development of diesel and electricity prices [22].

Already now, rigid urban BEV trucks are the most cost-effective option.

6.2 Regional Delivery Trucks

The following Figure 15 shows the results of TCO analysis for regional delivery diesel and battery electric trucks in the timeframe 2020–2040.

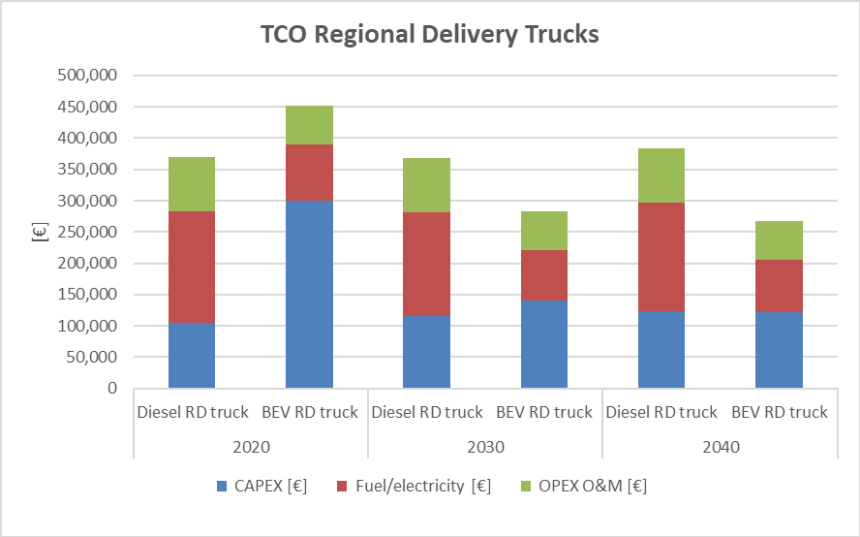


Figure 15. TCO for regional delivery (RD) trucks: comparison diesel vs battery electric (authors' elaboration).

For regional delivery BEV trucks, the daily energy required is obtained by a combination of 90% of the total energy needs recharged during overnight at the depot and the remaining 10% at fast charger during the 45 minutes of rest break.

Figure 15 clearly shows that in 2020, the lower operating costs of the battery electric truck cannot compensate for the higher initial purchase price and the TCO of diesel trucks is more cost-effective than that for BEVs. However, the expected important technology improvements, higher in the years between 2020–2030 than those in the period 2030–2040, will bring from 2030 onwards the TCO of BEV vehicles to become cost-effective than diesel counterparts.

6.3 Articulated Long-haul Trucks

The following Figure 16 shows the results of TCO analysis for articulated long-haul trucks, comparing diesel, battery electric and fuel cell vehicles in the timeframe 2020–2040. In this economic analysis, FCEV trucks have also been introduced and assessed as many studies such as [22] and [23] foresee a future uptake of FCEVs in the long-haul segment, in particular for higher daily mileage.

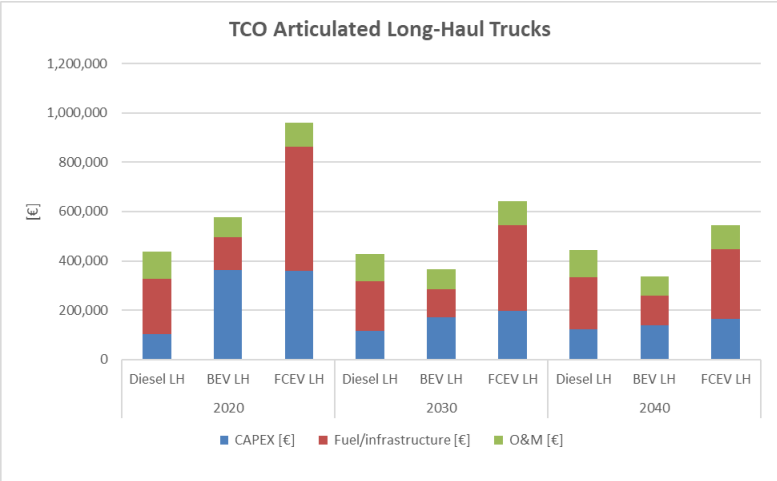


Figure 16. TCO for Articulated Long-haul trucks: comparison between diesel, battery electric and fuel cell vehicles (authors' elaboration).

For long-haul trucks, the daily energy required is obtained by a combination of 80% of an overnight charging at the depot and 20% at a fast charger during the 45 minutes of rest break [23].

Figure 16 clearly shows that in 2020, diesel trucks were the most cost-competitive option, whereas FCEV trucks had a significantly higher TCO even compared with BEVs. However, the expected important technology improvements, from 2030 onwards, will make the TCO of BEV vehicles more cost-effective than their diesel counterpart, whereas FCEVs will remain the less competitive option.

Another way to present the TCO analysis is to assess if TCO parity between different type of trucks will be reached and when. Analysing Figure 17, it clearly appears that battery electric long-haul trucks will reach TCO parity with diesel before 2030, whereas only after 2040 do FCEV trucks reach TCO parity with diesel but have a higher TCO if compared to BEV trucks.

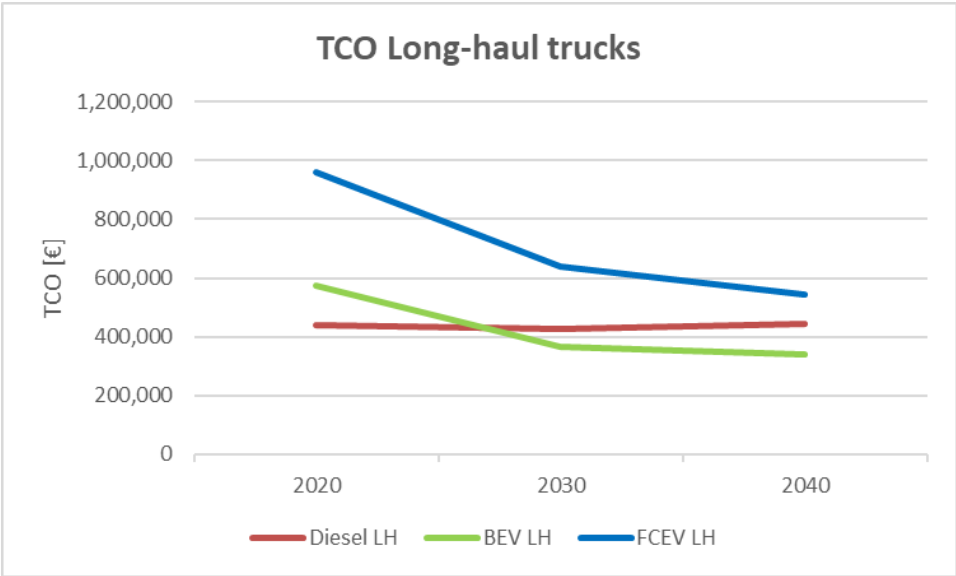


Figure 17. TCO long-haul trucks over the years (authors' elaboration).

6.4 Construction Trucks

The following Figure 18 shows the results of TCO analysis for regional delivery diesel, battery electric and fuel cell trucks in the timeframe 2020–2040.

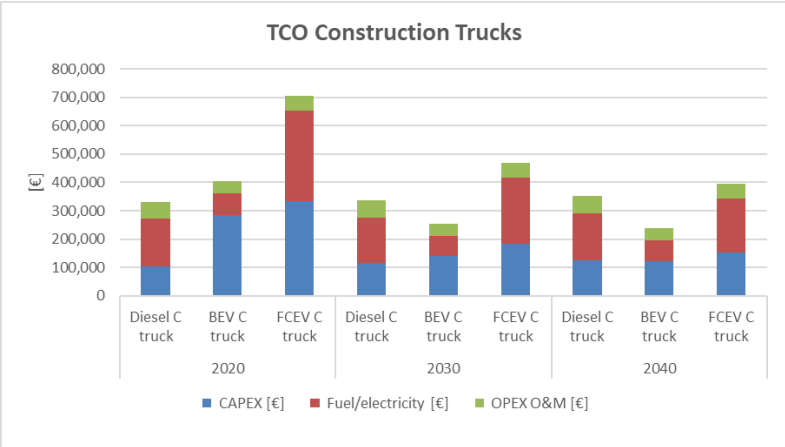


Figure 18. TCO for Construction trucks: comparison diesel, battery electric and fuel cell (authors' elaboration).

Figure 18 shows that in 2020, diesel trucks are the most cost-effective option, whereas the TCO of FCEV trucks is higher than that of BEVs' TCO. The technology improvements from 2030 onwards will make the TCO of BEV vehicles more cost-effective than the diesel equivalent whereas FCEVs will remain the less competitive option.

6.5 Sensitivity analysis on non-ICE solutions

As electricity and hydrogen prices are highly uncertain and have a significant impact on operational costs, a sensitivity analysis varying these two parameters was performed.

The Scenario analysed concerns 2040, when the difference between the TCO of battery electric long-haul trucks and FCEV long-haul trucks is at a minimum value, as shown in Figure 16.

Table 7 presents the results of the sensitivity analysis done by RSE, whereas Figure 19 shows an Excel graphic representation.

Table 7. Scenario 2040 – Difference in TCO between BEV and FCEV LH trucks.

		Hydrogen price [€/kg]					
		4	**6**	**7.5**	**9**	**11.5**	**13**
Electricity price [€/kWh]	**0.16**	-90 789 €	-166 257 €	-222 858 €	-279 460 €	-373 795 €	-430 396 €
	0.19	-73 270 €	-148 739 €	-205 340 €	-261 941 €	-356 277 €	-412 878 €
	0.25	-34 479 €	-109 948 €	-166 549 €	-223 150 €	-317 486 €	-374 087 €
	0.50	121 935 €	46 467 €	-10 135 €	-66 736 €	-161 071 €	-217 673 €
	0.70	247 067 €	171 598 €	114 997 €	58 395 €	-35 940 €	-92 541 €
	0.90	372 198 €	296 730 €	240 128 €	183 527 €	89 191 €	32 590 €

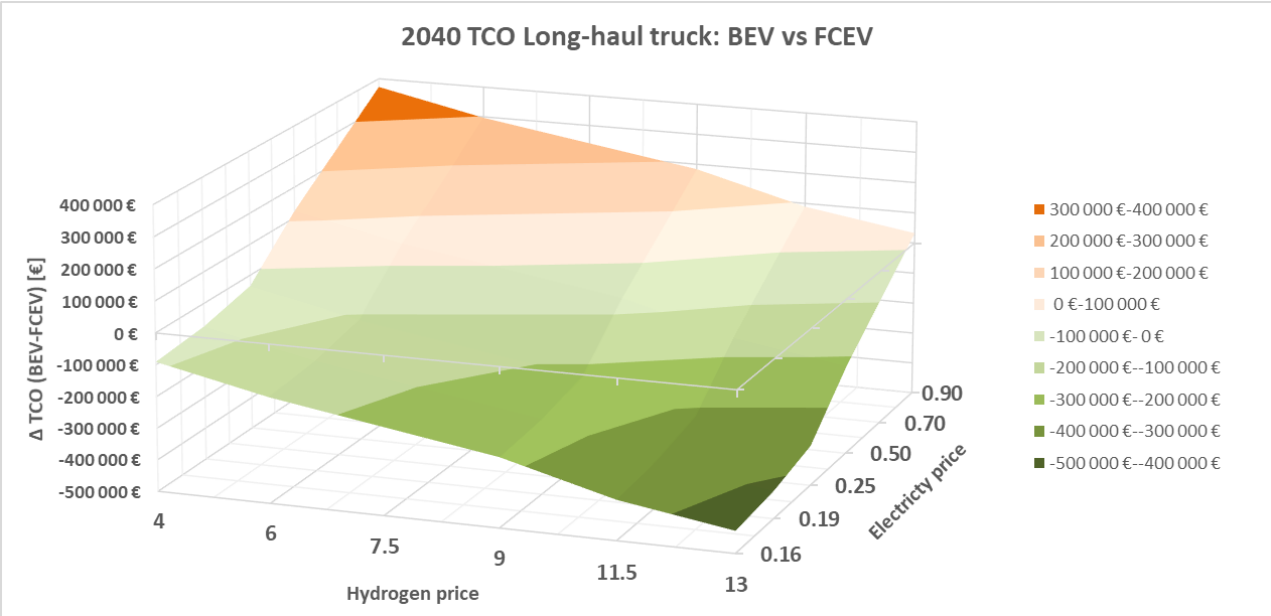


Figure 19. 2040 Scenario – Difference in TCO BEV – FCEV LH trucks varying electricity and hydrogen prices (authors' elaboration). Green areas identify the regions where battery electric trucks are more convenient than fuel cell trucks, whereas orange regions indicate where fuel cell trucks are more convenient. For an average electricity price below 0.5 €/kWh, it is difficult to identify any economic convenience of fuel cell trucks.

The zero line (when colors turn from light green to light orange) represents the combination of electricity prices and hydrogen prices for which there is a parity between a BEV or FCEV truck. Below the zero line, the BEV is cheaper (green area) than the FCEV truck. Above the zero line (orange area), the use of the FCEV truck is more convenient. The different graduations of colors, in the green and orange areas, indicate the higher or lower convenience of the electric long haul truck compared to the hydrogen equivalent. Each band of color represents one hundred thousand euros.

The price dynamics will have to be carefully evaluated to understand how the economic convenience between the two zero-emission technological solutions will develop.

6.6 Other TCO evaluations from the literature

Annex C shows the main results of two recent studies on the TCO of HDVs, confirming the results of the analysis.

The studies considered are the following:

- TNO 2022 R11862 – Techno-economic uptake potential of zero-emission trucks in Europe; and
- ICCT 2021 – TCO for Tractor-Trailers in Europe: battery electric versus diesel

6.7 TCO for buses

The following Table 8 presents the TCO for Local Public Transport (LPT) buses of various solutions, with particular reference to the electric one [24].
The TCO results are based on overall ownership costs evaluated in the case studies of Italian city of Bolzano, Torino, Milano and Bergamo. In the absence of accurate data for battery cost, the estimation related to the cost of purchase, maintenance (10 years for Turin, 5 for Milan, 11 for Bergamo) and battery replacement was considered, whereas the charging infrastructure costs have been excluded.

Table 8. Overall ownership costs for LPT [24].

		Purchase cost	Maint. cost	Battery replace	Fuel cost	**Owns. Cost**
		[€]	*[€]*	*[€]*	*[€]*	*[€]*
Electric	BZ	428,172	111,228	142,500	177,333	859,233
	TO	420,000	77,600	55,000	177,333	729,933
	MI	406,120	111,228	142,500	177,333	837,181
	BG	410,750	111,228	142,500	177,333	841,811
Diesel	BZ	220,000	205,192	-	358,631	783,823
	TO	227,000	234,000	-	358,631	819,631
	MI	250,000	205,192	-	358,631	813,823
Hybrid	BZ	230,000	243,295	-	330,536	803,831
CNG	TO	247,000	175,500	-	388,232	810,732
LNG	BZ	250,000	175,500	-	295,218	720,718
H_2	BZ	650,000	610,428	-	732,514	$1.99 \cdot 10^6$

For the battery electric solution, a purchase price of just over € 400,000, an average consumption in urban areas of 1.4 kWh/km and a 'mileage' cost of 0.23 €/km can be assumed as average data. These values make it fairly competitive with other solutions, whereas – from a pure economic perspective – diesel vehicles are still the best solution for LPT. Apart from air quality limits, new regulatory rules, such as the electricity charges reduction for LPT companies, may represent a possible driver for the electrification of buses.

7 Annex A: available models of electrified HDVs

Table 9. Available models of battery electric HDVs.

Type	Manufacturer	GVW(t)	Payload(t)	Battery(kWh)	Range(km)	Rech. power DC (kW)	Rech. power AC (kW)	Consumption (kWh/100km)
Collection vehicle	Mercedes Benz[14]	27	17.8	336	125	160	22	242
	Mercedes Benz[15]	27	/	508	190	150	44	220
	Volvo[16]	27	/	265	120	150	/	199
	Mean	27	17.8	301	123	155	22	250
Light Heavy	Mitsubishi[17]	7.5	4.2	86	100	50	7	77
	BYD	7.5	3.3	126	200	120	/	57
	Orten[18]	3.5	1.2	87	150	/	22	52

[14] https://www.mercedes-benz-trucks.com/it_IT/models/eeconic.html
[15] https://www.volvotruckcenter.it/vtc/it-it/trucks/electric-trucks.html?gclid=CjwKCAiA68ebBhB-EiwALVC-Nqe2l9rVob3CzqyG0uL1XgWZ8botSq3J7Pu8GcmLkj8ymON2iEKRihoCX0gQAvD_BwE
[16] https://www.volvotruckcenter.it/vtc/it-it/trucks/electric-trucks.html?gclid=CjwKCAiA68ebBhB-EiwALVC-Nqe2l9rVob3CzqyG0uL1XgWZ8botSq3J7Pu8GcmLkj8ymON2iEKRihoCX0gQAvD_BwE
[17] https://www.fuso-trucks.it/content/eu/italy/it/modelli/ecanter.html
[18] https://www.electric-trucks.de/images/files/Datenblaetter_Englisch/ORTEN_ET_35_M.pdf

Duty vehicle	Orten[19]	7.5	2.3	116	150	/	22	70
	Quantron[20]	4.5	1.6	81	185	60	6.6	39
Medium HDV	Orten[21]	11.8	4.2	217	200	/	22	98
HDV	DAF[22]	19	11.7	282	280	150	/	91
	DAF[23]	29	/	350	250	250	/	126
	Mercedes Benz[24]	19	10.6	336	330	160	/	92
	Mercedes Benz[25]	27	16	448	400	160	/	101
	Scania[26]	40	/	624	250	375	/	160
	Quantron[27]	27	/	392	250	350	/	101
Bus	Bluebus[28]	20	/	441	320	160	/	124
	BYD[29]	19.5	/	422	450	/	/	84
	Ecitaro mercedes[30]	/	/	292	200	/	/	131
	Volvo 7900 e[31]	/	/	470	/	300	/	/

[19] https://www.electric-trucks.de/images/files/Datenblaetter_Englisch/ORTEN_E_75_AT.pdf
[20] https://www.quantron.net/wp-content/uploads/2022/10/Q-Light-QARGO4EV_Infobrochure_EN.pdf
[21] https://www.electric-trucks.de/images/files/Datenblaetter_Englisch/ORTEN_E_120_LF.pdf
[22] https://www.daf.com/en/about-daf/sustainability/alternative-fuels-and-drivelines/battery-electric-vehicles/daf-lf-electric
[23] https://www.daf.com/en/about-daf/sustainability/alternative-fuels-and-drivelines/battery-electric-vehicles/daf-cf-electric
[24] https://www.mercedes-benz-trucks.com/en_GB/emobility/world/our-offer/eactros-and-services.html
[25] https://www.mercedes-benz-trucks.com/en_GB/emobility/world/our-offer/eactros-and-services.html
[26] https://www.scania.com/group/en/home/products-and-services/trucks/battery-electric-truck.html
[27] https://www.quantron.net/wp-content/uploads/2022/10/Q-Heavy-QHM-QHB-Infobrochure-EN.pdf
[28] https://www.bluebus.fr/sites/bluebus/files/medias/images/PDF/bluebus_12_m_-_fiche_technique_1.pdf
[29] https://www.bydeurope.com/pdp-bus-model-12
[30] https://www.mercedes-benz-bus.com/it_IT/models/ecitaro/facts/technical-data.html
[31] https://www.volvobuses.com/it/city-and-intercity/buses/volvo-7900-electric/specifications.html

8 Annex B: parameters for TCO analysis

Table 10. Vehicle parameters assumed for TCO analysis (source [22]).

Parameter					Type of vehicles											
					R_U			A_RD			A_LH			A_C		
					2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Vehicle cost	[€]	D			79,000 €	87,000 €	92,000 €	144,000 €	159,000 €	170,000 €	144,000 €	159,000 €	170,000 €	144,000 €	159,000 €	170,000 €
		BEV			159,000 €	91,000 €	81,000 €	413,000 €	193,000 €	167,000 €	498,000 €	236,000 €	193,000 €	393,000 €	192,000 €	166,000 €
		FCEV									494,000 €	274,000 €	226,000 €	459,000 €	252,000 €	208,000 €
Mileage	[km]				75,753			108,164			140,575			75,753		
Efficiency	[l/100km]	D			30.8	26.9	26.9	35.2	29.6	29.6	33.7	27.5	27.5	47.1	40.9	40.9
	[kWh/100km]	BEV			61.9	56.1	55	116.9	99.2	97.2	130.6	105.6	102.8	141.4	126.1	123.1
	[kg/100km]	FCEV									7.4	6.3	6.2	8.7	7.9	7.8
Fuel/electricity cost	[€/litre]	D			1.08	1.2	1.25	1.08	1.2	1.25	1.08	1.2	1.25	1.08	1.2	1.25
	[€/kWh]	BEV	Depot	electricity depot charging (incl.	0.16	0.17	0.18	0.16	0.17	0.18	0.16	0.17	0.18	0.16	0.17	0.18
				infr. equip.+ grid connection	0.047			0.047			0.047			0.047		
			Fast charger	electricity fast charging (incl. Infrastructure)				0.20	0.21	0.22	0.20	0.21	0.22	0.20	0.21	0.22
				infr. equip.+ grid connection				0.073	0.096	0.055	0.073	0.096	0.055	0.073	0.096	0.055
			electricity: % depot + % fast charger					0.164	0.174	0.184	0.168	0.178	0.188	0.164	0.174	0.184
	[€/kg]	FCEV									11.2	9.0	7.5	11.2	9.00	7.5
Maintenance cost	[€/100km]	D			18.5			18.5			18.5			18.5		
		BEV			13.24			13.24			13.24			13.24		
		FCEV			15.87			15.87			15.87			15.87		

9 Annex C: Other TCO analyses on HDVs

The TCO of a vehicle considers the overall costs for the property and the use of a vehicle during a certain period and includes capital costs (purchase cost of the vehicle minus discounted residual value) and operational costs (fuel and maintenance costs).

For the purpose of this economic assessment, additional incomes (e.g. from grid and system services) which can reduce the TCO are not considered. These aspects are addressed in Deliverable 3.

The following considerations are based on the information taken from two documents on TCO assessment:

- TNO 2022 R11862 – Techno-economic uptake potential of zero-emission trucks in Europe [22]; and
- ICCT 2021 – TCO for Tractor-Trailers in Europe: battery electric versus diesel [23].

The TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek) document gives the economic (TCO) assessment of zero-emission trucks for the European Union and United Kingdom in the timeframe 2030–2040 for four different vehicle segments, i.e. rigid trucks for urban delivery and three different articulated tractor-trailers for regional delivery, long haul and construction. For the same segments, the market uptake potential of the non-ICE vehicles has also been assessed from 2020 till 2040.

The ICCT document has evaluated the TCO of long-haul trucks, that is the highest emitting road freight segment, and represents a significant challenge in the electrification of trucks, comparing the battery electric solution with its diesel counterpart. The evaluation covers the timeframe 2020–2030.

9.1 TNO analysis

TNO has realised a techno-economic evaluation on the potential uptake of zero-emission powertrains (battery-electric and fuel cell) compared to diesel powertrain. The assessment with timeframe 2020–2040, analyses four segments (Table 11) with use cases aligned to 'four vehicle groups' as classified in VECTO (Vehicle Energy Consumption Calculation Tool).

Table 11. Vehicle types and characteristics for TCO analyses (source [22]).

Vehicle type **Duty Cycle**		**Rigid** **Urban delivery**	**Articulated** **Regional delivery**	**Articulated** **Long haul**	**Articulated** **Construction**
GVW		**16 tons**	**40 tons**	**40 tons**	**40 tons**
Reference payload		6 000 kg	12 900 kg	19 300 kg	19 300 kg
Diesel truck [l/100km]	**2020**	30.8	35.2	33.7	47.1
	2030	26.9	29.6	27.5	40.9
	2040	26.9	29.6	27.5	40.9
BEV large- Truck [kWh/100km]	**2020**	61.9	116.9	130.6	141.1
	2030	56.1	99.2	105.6	126.1
	2040	55.9	97.2	102.8	123.1
FCEV Truck [kg/100km]	**2020**			7.4	8.7
	2030			6.3	7.9
	2040			6.2	7.8
BEV large truck configuration		200 km	400 km	800 km	300 km
Nominal battery	**2020**	155 kWh	569 kWh	1 243 kWh	520 kWh
	2030	139 kWh	465 kWh	966 kWh	457 kWh
	2040	140 kWh	459 kWh	946 kWh	441 kWh
FCEV Truck		n.a.	n.a.	800 km	300 km

The transition from ICEVs to non-ICE vehicles in the TNO analysis is considered feasible when TCO parity with diesel equivalents is reached (affordability) without any operational limitations such as range constraints, time or payload losses (applicability) and without other barriers such as the availability of vehicles, the roll-out of charging and refuelling infrastructure.

Affordability, assessed through TCO, permits the identification of the most cost-effective drivetrain technology regarding capital and operating costs.

Applicability refers to the ability of the vehicle with a given range to perform a given transport operation.

Consequently, the techno-economic uptake potential of BEVs and FCEVs in a certain year corresponds to the share of the new registrations for which the BEV or the FCEV is the most cost-effective option and where the applicability of these options is ensured.

9.1.1 Modelling parameters

The following Table 12 contains the parameters used in TCO evaluation.

Table 12. General TCO modelling parameters [source [22]].

Parameter	Value
Timeframe	2020 – 2040
Operational days per year	265 days
Perspective	First use period of 5 years
TCO Method	Net Present Value (NPV) with discounted cash flows
Discount rate (IRR)	9.5%
Residual value	37.5% fixed rate + 'x' variable rate
Maintenance costs	included
Cost of capital	excluded
Vehicle registration and circulation taxes	excluded
VAT	excluded
Taxes: excise duty on diesel and unrecoverable taxes and levies on electricity	included
Personnel costs	excluded
Overheads	excluded
CO2 pricing, purchase subsidies, CO2 based tolling	included only in specific policy scenarios, not in the central scenario

- Vehicle prices has been assumed to be the same across Europe and vehicle costs have been calculated based on components costs taken from the literature;
- Batteries do not have to be replaced during the first use period (5 years); and
- To evaluate the residual value, a fixed depreciation rate of 37.5% plus a variable depreciation rate based on the mileage of the truck has been considered. The assumption is that the residual value is zero at 1.49 km of mileage of truck calculated as a daily mileage of 1150 km for 5 years.

The following Figure 20 shows the pre-tax prices of the vehicles in the timeframe 2020–2040, including the markup factor.

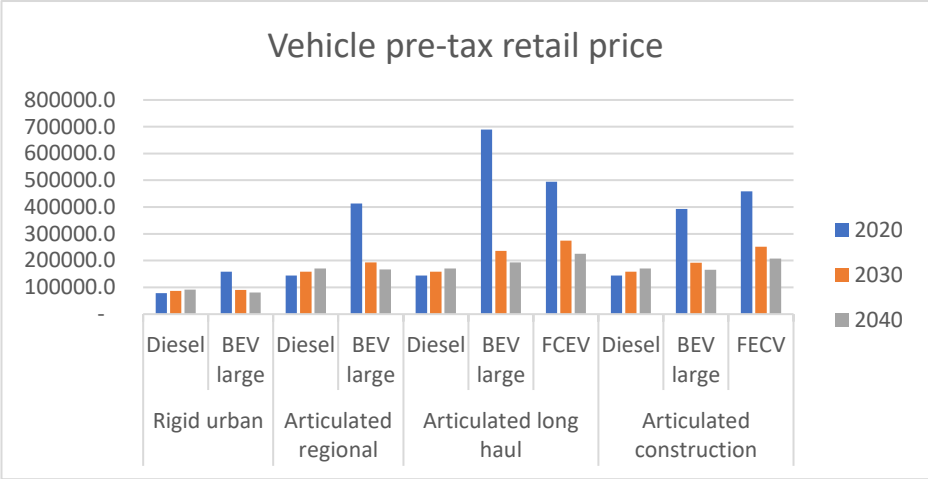


Figure 20. Pre-tax retail price including mark-up factor and trailer [€] (source [22]).

The mark-up factor is deeply influenced by market maturity and accounts for indirect costs such as:

- Assembly costs;
- Research and development costs;
- Marketing costs;
- Distribution costs; and
- Profit, both for manufacturer and retailer.

Whereas the market for diesel trucks is mature and the risk of the technology is low, for zero-emission drivetrains the market is still developing, and the technology risk is higher.
TNO has evaluated that for diesel trucks, the mark-up factor is 19% in 2020, whereas for zero-emission emission drivetrains, the mark-up factor for 2020 is expected to be significantly higher due to lower production volumes. A value of 40% has been assumed for 2020.
In the next few decades, the production of diesel trucks is expected to decrease whereas zero-emission should increase. In 2040 it has been assumed that the mark-up for diesel and for zero-emission powertrain will be the same and equal at 25%.

9.1.2 Energy prices

9.1.2.1 Diesel

Figure 21 gives the oil price projections up to 2050 and is taken from the TNO document [22]. The oil price projections from 2030 onwards were taken from the IEA World Energy Outlook 2021 [25] and includes two scenarios:

1. 'Stated policies', which include not only existing policies and measures but also those under development; and
2. 'Announced pledges' that fully implement the national targets to 2030 from 2050.

Between 2023 and 2030, a linear interpolation was used.

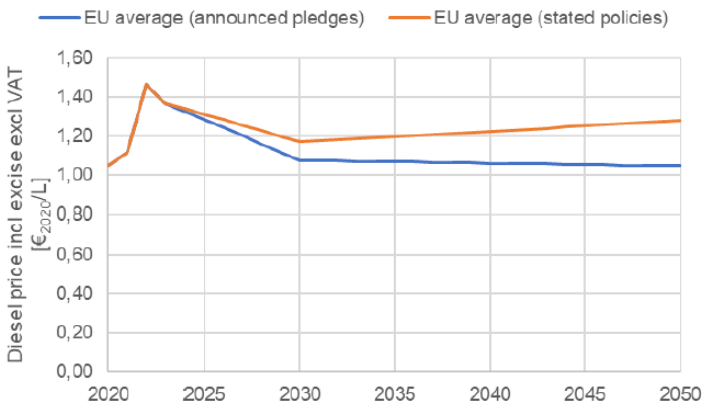


Figure 21. Oil price projections (source [22]).

9.1.2.2 Electricity

The electricity price presented in the TNO report considers 3 elements:

- production cost;
- distribution cost; and
- cost of charging infrastructure, considering 2 options of depot charging (Figure 22) and fast charging (Figure 23). It is assumed that electric trucks will be able to fully charge the battery at the depot during overnight. In the case of more demanding days, with longer distances, higher payload or more uphill driving, is assumed that trucks will be charged at a fast-charging station during the legally required 45 minutes rest break.

The 2020 electricity prices have been based on the 10-year average prices per member state and for the EU+UK average, obtained from Eurostat.

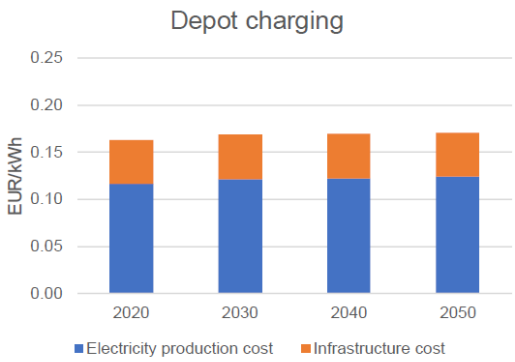


Figure 22. Average end user electricity price at depot charging infrastructure (source [22]). Costs include the recharging equipment and connection costs that are assumed to be 0.047 €/kWh.

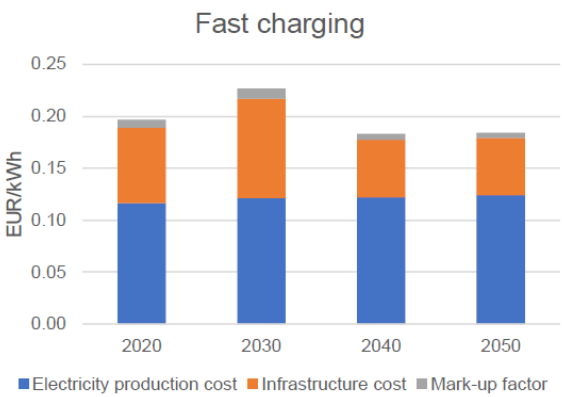


Figure 23. Average end user electricity price at fast charging infrastructure (source [22]). The costs for fast charging equipment and grid connection have been evaluated in 0.073 €/kWh in 2020, 0.096 €/kWh in 2030 and 0.055 €/kWh from 2040 onwards.

9.1.2.3 Hydrogen

The main assumption is that only renewable hydrogen is used. The average hydrogen price considered is shown in Figure 24.

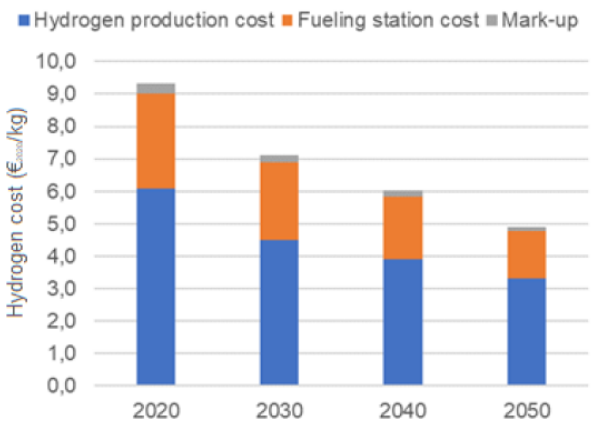


Figure 24. Average end user renewable hydrogen price based on local production (source [22]).

9.1.2.4 Maintenance costs

The maintenance costs are indicated in the following table.

Table 13. Maintenance costs, based on (source [23]).

Drivetrain	Cost [€/100km]
Diesel	18.50
BEV	13.24
FCEV	15.87

9.1.3 TCO results

The following figures show the TCOs, expressed in euros per kilometer based on 2020 EU average energy prices [26] for the four segments analysed. Modeling parameters are reported in Table 12 .

The TCO for higher mileage result in a lower average cost per kilometer because initial investment costs are distributed over a longer distance.

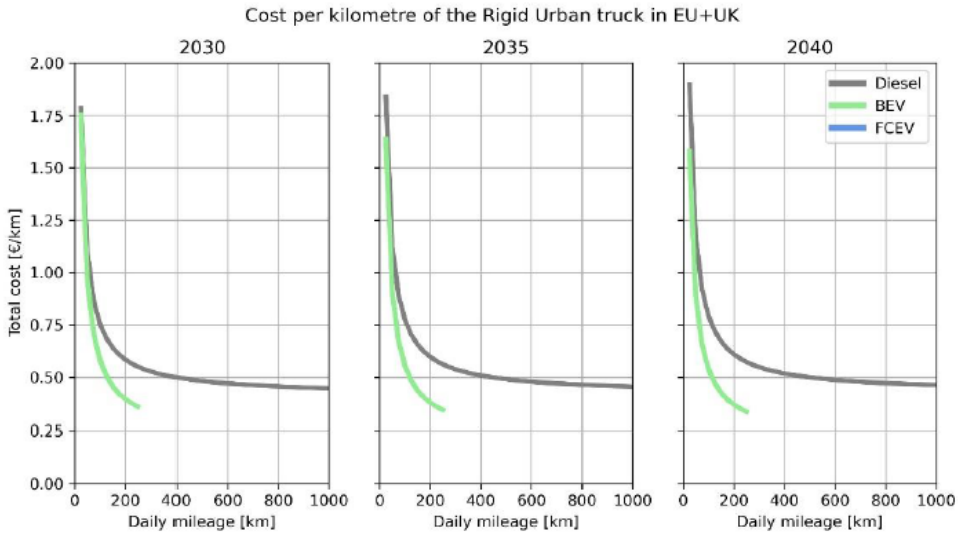


Figure 25. TCO per kilometer of rigid urban delivery trucks (source [22]*).*

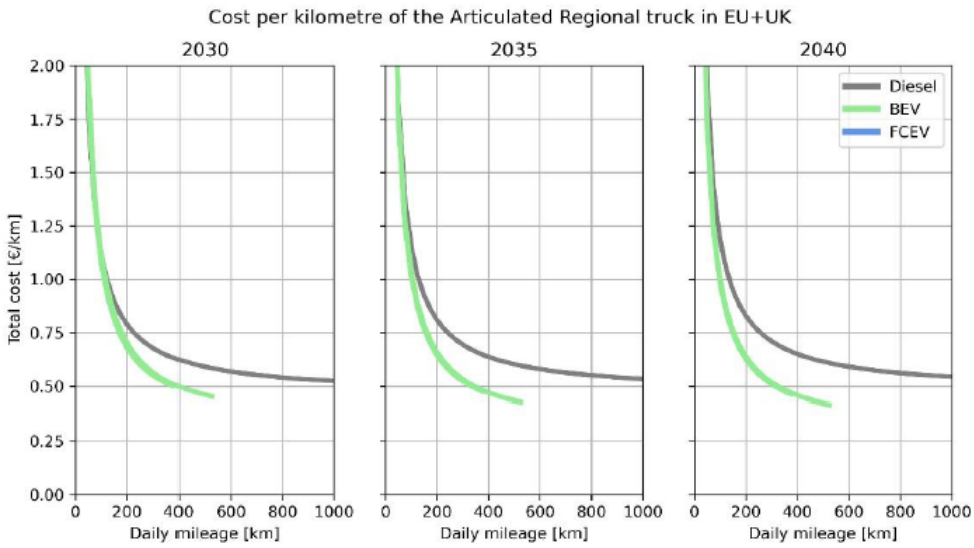


Figure 26. TCO per kilometer of articulated regional trucks (source [22]*).*

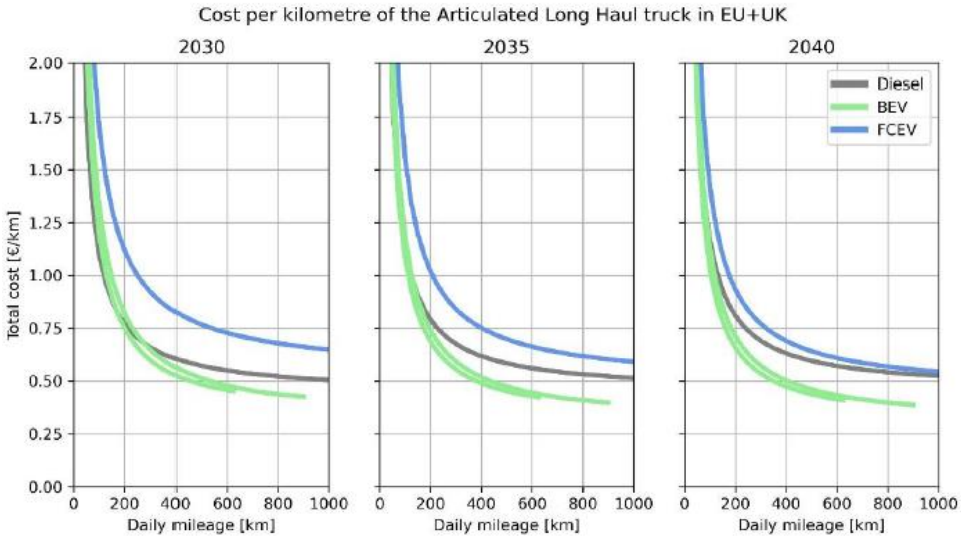


Figure 27. TCO per kilometer of articulated long-haul trucks (source [22]*).*

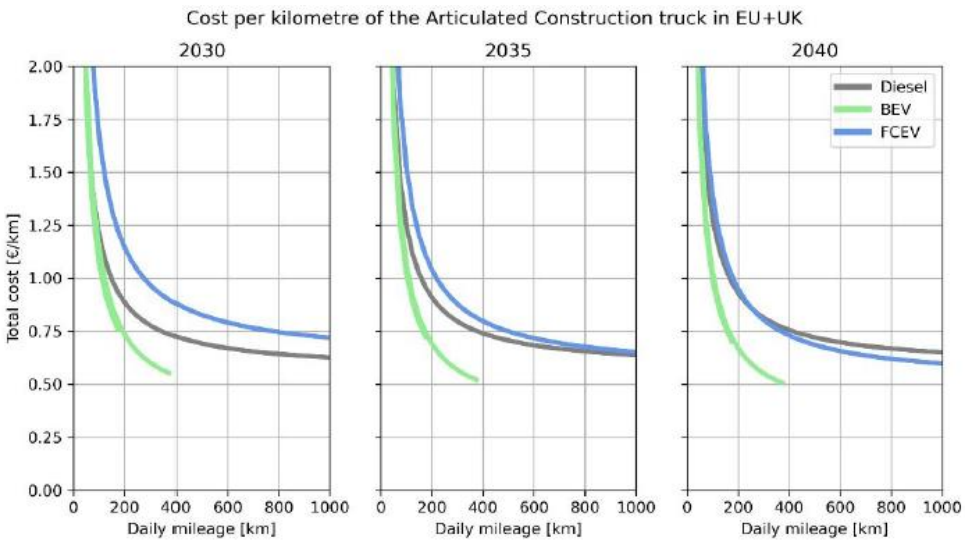


Figure 28. TCO per kilometer of articulated construction trucks (source [22]).

9.1.4 The main findings from the TNO report

- From 2030 onwards, BEV trucks are expected to be the most cost-effective option in all the segments evaluated. However, due to range limitations, battery electric vehicles can potentially not be used for longer trips, which makes them unsuitable for replacing trucks with high average daily mileages or large distances on certain days;
- FCEVs can be a zero-emission alternative for diesel trucks that drive very large distances at least part of the time. However, it is expected that these will not be cost-competitive with BEV trucks;
- The TCO of FCEV long haul articulated trucks is higher in all the timeframes considered except in 2040 when FCEV long haul articulated trucks only become cost competitive for very high mileages (>1000 km/day). Such distances can only be achieved by two drivers in one vehicle; and
- FCEV articulated construction trucks in 2030 are significantly higher than the TCO of diesel equivalent trucks. In 2035, the TCO are getting closer even though FCEV is still more expensive, except for extremely high mileages for the construction trucks (>1000 km/day on average). Towards 2040, the TCO of the FCEV articulated construction truck becomes cost competitive but only at average daily mileages beyond 300 km.

9.1.5 Market-driven uptake scenario

In document [22], TNO analysed the potential share of non-ICE vehicles that could replace diesel vehicles in the new sales based on the TCO results. Figures 29 to 32 show the uptake potential of the four different BEV segments, analysed as Rigid Urban, Articulated Regional, Articulated Long-haul and Articulated Construction. Notably, the difference between articulated regional delivery and the articulated long-haul truck lies only in the duty cycle, the battery capacities and the payload as their vehicle configurations are the same. The different duty cycles translate into a difference in energy consumption and therefore vehicle configuration and energy cost.

The main findings are summarised as follows:

- For the Rigid Urban trucks, the maximum non-ICE vehicles uptake potential of 100% is achieved by 2030;
- For articulated regional delivery trucks, 80% of the sales of battery electric trucks would be cost competitive and applicable just before 2025, increasing to 100% by 2030. There is no potential

uptake for FCEVs due to the higher TCO than that of BEVs, and the range of BEVs is sufficient to be deployed;

- For articulated long-haul delivery trucks, 80% of the sales battery electric trucks would be cost competitive and applicable in 2026, increasing to 100% by 2030. The TCO of FCEVs is higher than the TCO of diesel and they do not therefore become cost competitive compared to equivalent diesel vehicles in the long-haul segment, with the exception of Finland where hydrogen prices are expected to be relatively low; and
- For the articulated construction segment, the techno-economic non-ICE vehicle uptake potential of 100% is reached by 2033. Similarly, as for the long-haul truck, BEVs are the most cost competitive drivetrain type and have sufficient range (based on an overnight charge plus 45 minutes of fast charging per day) to cover the demanded distance. As BEVs have a lower TCO than FCEVs and BEVs have sufficient range to cover the deployment of construction trucks, there is no uptake potential for FCEVs under these conditions.

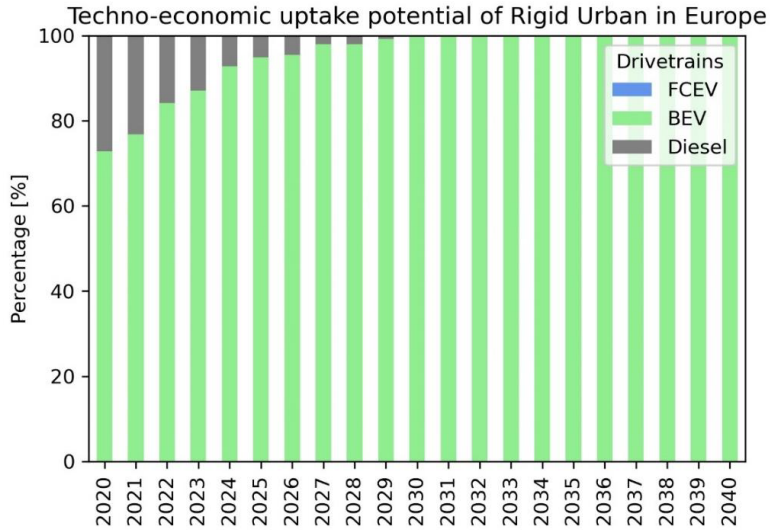


Figure 29. Aggregated techno-economic zero-emission powertrain uptake potential for rigid urban delivery trucks in the EU+UK (source [1]).

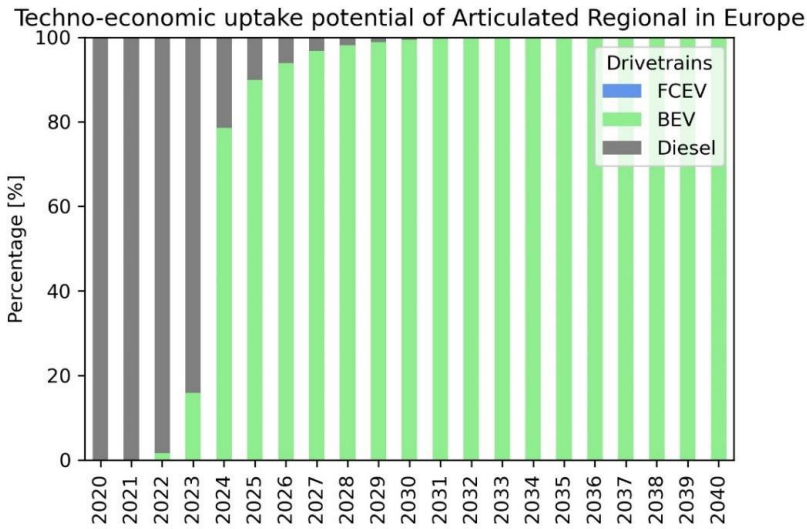


Figure 30. Aggregated techno-economic zero-emission powertrain uptake potential for rigid Articulated Regional in the EU+UK (source [1]).

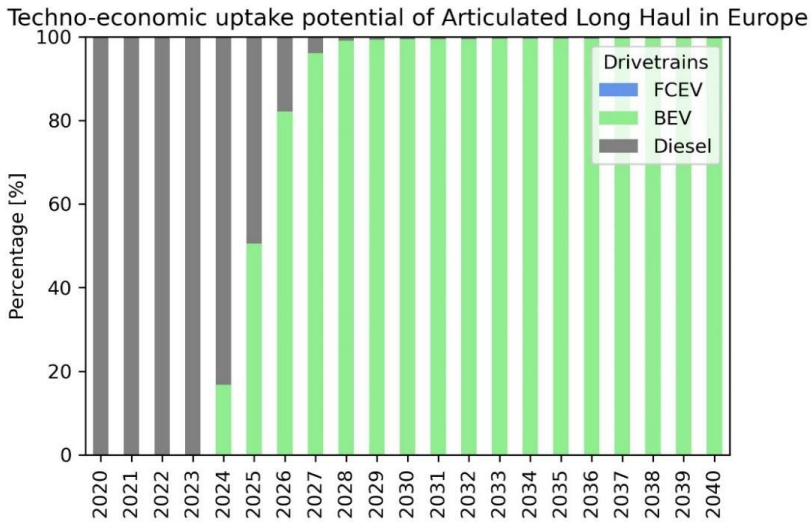


Figure 31. Aggregated techno-economic zero-emission powertrain uptake potential for articulated Long-haul in the EU+UK (source [1]).

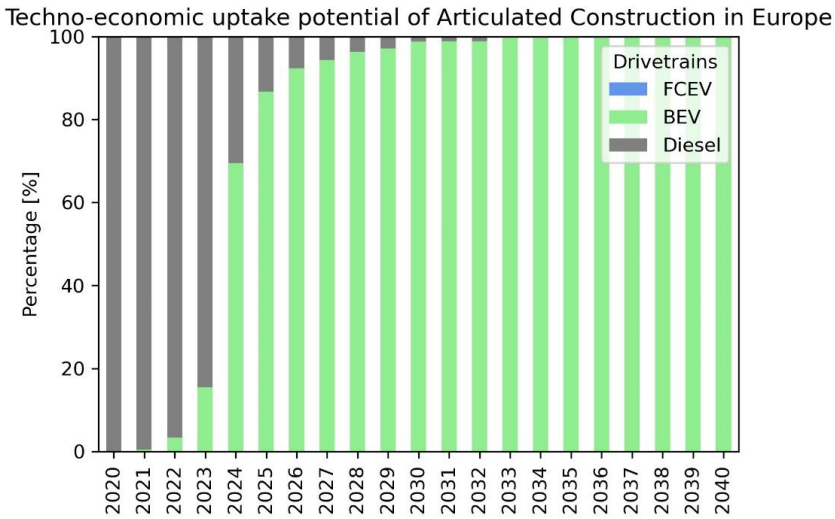


Figure 32. Aggregated techno-economic zero-emission powertrain uptake potential for articulated Long-haul in the EU+UK (source [1]).

9.1.5.1 Payload penalty

The payload penalty is defined as a reduction of payload compared to the maximum payload due to weight restrictions.

According to TNO documents, BEV trucks with urban, regional and construction duty cycles suffer no penalties on the maximum payloads, even in the year 2020. Whereas for the long-haul BEV truck, despite the additional weight allowance for zero-emission trucks permitted by the directive (EU) 2019/1242, the large batteries required in the early years in combination with the relatively low energy density of batteries (see Table 14) results in a temporary penalty on the maximum.

Table 14. Assumed battery-pack energy densities (source [1] and [2]).

Battery-pack energy density [Wh/kg]	2020	2025	2030	2035	2040
Weighted average	184	232	280	328	376

The long-haul BEV with the large battery has a penalty of 3200 kg on the maximum payload in 2020 which reduces to zero by 2030. The mass of the FCEV drivetrain for the long-haul truck is sufficiently low not to result in any payload penalty, partly due to the increased weight allowance of zero-emission trucks.

9.2 ICCT analysis

The study by ICCT compares the TCO of battery-electric tractor-trailers to the diesel counterparts between 2020 and 2030. The segment analysed is tractor-trailers, covering a daily distance of at least 500 km with a return-home route. This use case is the highest emitting road freight segment and represents a significant challenge in the electrification of trucks. The main parameters used for the TCO analysis are shown in Table 15 .

Table 15. TCO parameters used in the study (source [23]).

Parameter	First-ownership perspective
Analysis period	5 years
Residual value	Considered
Discount rate	9.5%
Taxes	Only nonrecoverable taxes considered
VAT	Excluded
Road tolls	Included
CO_2 external cost	Excluded

Table 16 summarises the technical specifications and the main parameters of the battery electric and diesel trucks uses in the TCO analysis.

Table 16. Technical specifications and main parameters of battery-electric and diesel in the TCO analysis (source [23]).

	Parameters	Diesel tractor-trailer		Battery-electric tractor-trailer	
	Gross vehicle weight	40 tonnes		42 tonnes	
	Maximum payload	25.4–27.3 tonnes		22.5–27.3 tonnes	
	Axle configuration	4×2		4×2	
	Powertrain rated power	350 kW		350 kW	
	Transmission	12 speed		2 speed	
	Range single charge	—		~500 km	
	Year	**2020**	**2030**	**2020**	**2030**
	Fuel/energy consumption (estimated)	30.7 l/100 km	23.2 l/100 km	1.38 kWh/km	0.99 kWh/km
	Battery capacity	n.a.	n.a.	930 kWh	675 kWh
Fixed costs:	**Vehicle purchase (VAT excluded)**	€ 133,000	€ 145,000	€ 470,000	€ 185,000
	Residual value (after 5 years)	30%	30%	30%	30%
	Residual value of battery (after 5 years)	n.a.	n.a.	15%	15%
	Registration (one time fee) and ownership taxes (annual): country dependent	€ 0 - 1.500 + €/year 550 - 1.350			
	Vignette (fixed annual road-use charge): country dependent	€/year 1.000 - 1.250			
Operational costs:	**Distance-based road tolls: country dependent**	€/km 0 - 0.320			
	Maintenance costs	€/100km 18.50		€/100km 13.24	
	Diesel prices (included Excise duty refund): country dependent - average	€/ liter 0.897			
	Energy prices included charging infrastructure - average			€/kWh 0.394	€/kWh 0.152

The capacity of the battery-electric truck required to meet the requirements of daily mileage at a minimum range of 500 km without charging the battery at the reference payload is shown in the following Figure 33.

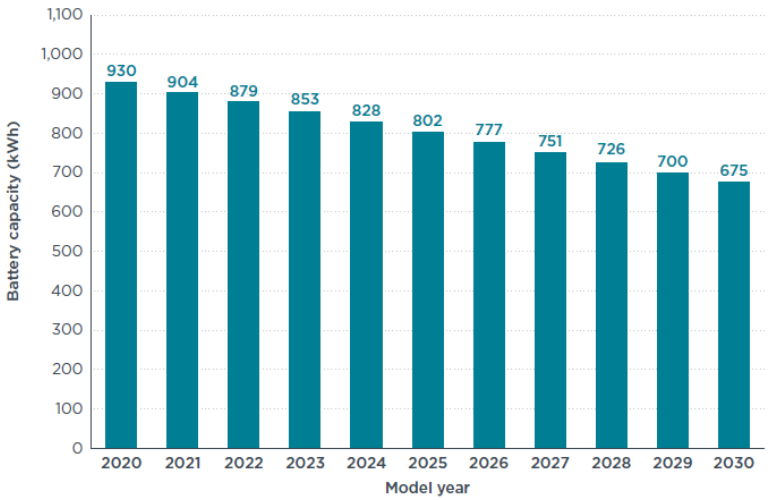


Figure 33. Battery capacity required for a minimum of 500 km without charging [23].

9.2.1 Charging station infrastructure costs

The charging infrastructure costs consist of capital expenditure (Capex) and operating expenses (Opex). These costs are charged as a fee in addition to the electricity price and the sum determines the final energy price for consumers.

ICCT has assumed that the truck leaves the depot fully battery charged. It travels for 4.5 hours, followed by a rest period of 45 minutes, during which the truck charges at 350 kW of power. After the midway charging, it travels until the depot is reached. Here it charges overnight with 100 kW power.

The daily necessary energy is composed as follows:

- 20% charged at 350 kW; and
- 80% charged at 100 kW (overnight at the depots)

9.2.2 Key findings

The following figures show the TCO results without any policy interventions. BEV trucks can achieve TCO parity with diesel tractor-trailers during this decade for all the considered countries. The Netherlands will reach TCO parity by 2024 and Germany by 2029.

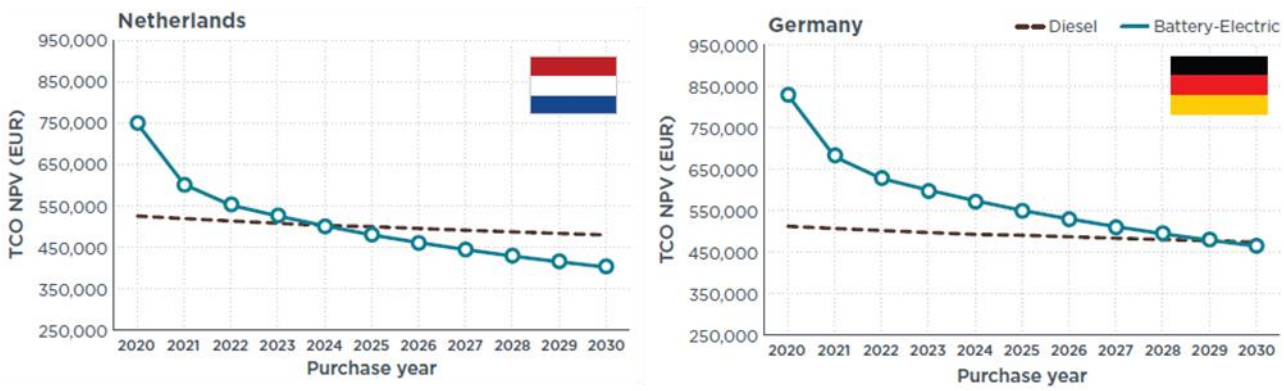


Figure 34. TCOs of BEVs versus diesel trucks considering fixed diesel fuel and electricity prices for the 2020–2030 time frame (source [23]).

The following summarises the TCO parity for each of the countries analysed without incentives and with current adopted policy (different country by country).

Table 17. TCO parity without incentives and with current adopted policies [23].

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity with adopted policies	2022	2021	2027	2022	2025	2026	2026

Without policy intervention, the country with the lowest TCO parity time is the Netherland (parity by 2024 due to low energy costs and high diesel fuel prices). Germany, Italy and Poland are expected to achieve TCO parity in the second half of the decade.

The current adopted policies are:

- Purchase premiums: applies for all countries;
- Infrastructure incentives: applies for Germany, France, Spain, and Poland;
- Exemption or reduction in road tolls: applies for Germany; and
- ETS for transport – applies for Germany

Under current adopted policies that are different for each country, TCO parity could be achieved in 3–4 years.

10 References

[1] U.S. Department of Energy, 'Medium- and Heavy-Duty Vehicle Electrification - An Assessment of Technology and Knowledge Gaps,' 2019.

[2] CALSTART, 'Global commertial vehicle - Drive to Zero,' [Online]. Available: https://globaldrivetozero.org/.

[3] European Commission, 'Protecting lorry drivers and their cargo: European Commission adopts EU standards for safe and secure parking areas,' 2022. [Online]. Available: https://transport.ec.europa.eu/news/european-commission-adopts-eu-standards-safe-and-secure-parking-areas-2022-04-07_en.

[4] DAF, 'DAF introduces charging stations for electric vehicles,' [Online]. Available: https://www.daf.com/en/news-and-media/news-articles/global/2021/q2/29-04-2021-daf-introduces-charging-stations-for-electric-vehicles.

[5] ABB, 'Electric bus pantograph up,' [Online]. Available: https://new.abb.com/ev-charging/pantograph-up.

[6] Siemens, ‘Fast Charging Systems for eBuses,’ [Online]. Available: https://new.siemens.com/my/en/markets/transportation-logistics/electromobility/ebus-charging.html.

[7] IPT Technology, ‘IPT Charge Bus,’ [Online]. Available: https://ipt-technology.com/product-ipt-charge-bus-100kw/.

[8] Electreon, ‘Wirelessly charge electric vehicles,’ [Online]. Available: https://electreon.com/.

[9] Charin, ‘Mega Charging System (MCS),’ [Online]. Available: https://www.charin.global/technology/mcs/.

[10] M.G.H. Gustavsson; M. Lindgren; H. Helms; M. Mottschall, Real-world experiences of ERS. Best practices from demonstration projects in Sweden and Germany, Swedish-German research collaboration on Electric Road Systems, 2020.

[11] A. H. Van Grinsven et al., Research for TRAN Committee – Alternative fuels infrastructure for heavy-duty vehicles, Brussels: European Parliament, Policy Department for Structural and Cohesion Policies, 2021.

[12] K. Burges; S. Kippelt, ‘Grid-related challenges of high-power and megawatt charging stations fot battery-electric long-haul trucks,’ RE-xpertise, 2021.

[13] ICCT, ‘ Cost Of Renewable Hydrogen Produced Onsite At Hydrogen Refueling Stations In Europe,’ 2022.

[14] IRENA, ‘Green hydrogen cost reduction: Scaling up electrolysers,’ 2020.

[15] Fuel Cells and Hydrogen 2 Joint Undertaking, ‘Hydrogen Roadmap Europe,’ 2019.

[16] European Environment Agency, ‘Decarbonising road transport — the role of vehicles, fuels and transport demand,’ Brussels, 2021.

[17] International Energy agency, ‘Global EV Outlook 2022,’ 2022.

[18] European Alternative Fuels Observatory, ‘Vehicles and fleet in the European Union,’ [Online]. Available: https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/vehicles-and-fleet.

[19] ACEA, ‘Review of CO2 emission standards regulation for heavy-duty vehicles,’ 2022.

[20] ACEA, ‘ACEA Position Paper: Heavy-duty vehicles: Charging and refuelling infrastructure,’ 2021.

[21] McKinsey & Company, ‘Preparing the world for zero emission trucks,’ 2022.

[22] TNO, ‘Techno-economic uptake potential of zero-emission trucks in Europe,’ 2022.

[23] ICCT, ‘Total cost of ownership for tracktor-trailers in Europe: Battery Electric versus Diesel,’ 2021.

[24] C. Carlini; D. Moneta, ‘Preliminary Economic Assessment for Electric Buses Adoption in the Italian Framework,’ *AEIT International Annual Conference (AEIT),* 2019.

[25] IEA, ‘World Energy Outlook,’ 2021.

[26] European Commission, ‘Energy statistics,’ [Online]. Available: https://ec.europa.eu/eurostat/web/energy/data/database.

[27] H2 Mobility, ‘Overview Hydrogen Refuelling For Heavy Duty Vehicles,’ 2021.