ENTSO-E Position Paper

Deployment of Heavy-Duty Electric Vehicles and their Impact on the Power System

October 2023

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ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The 39 member TSOs, representing 35 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E **brings together the unique expertise of TSOs for the benefit of European citizens** by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the **security of the interconnected power system in all time frames at pan-European level** and the **optimal functioning and development of the European interconnected electricity markets**, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first **climate-neutral continent by 2050** by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires **sector integration** and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources.

ENTSO-E acts to ensure that this energy system **keeps consumers at its centre** and is operated and developed with **climate objectives** and **social welfare** in mind.

ENTSO-E is committed to use its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in **solidarity** as a community of TSOs united by a shared **responsibility.**

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by **optimising social welfare** in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and **innovative responses to prepare for the future** and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with **transparency** and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its **legally mandated tasks**, ENTSO-E's key responsibilities include the following:

- Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;
- Assessment of the adequacy of the system in different timeframes;
- Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);
- Coordination of research, development and innovation activities of TSOs;
- Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the **implementation and monitoring** of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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Executive Summary

ENTSO-E considers electromobility a powerful resource for both the decarbonisation of the transport sector and for contributing to the provision of flexibility services to the power system; an optimal vehicle-grid integration will contribute to the overall efficient planning and operation of a "System of systems", with benefits for all involved actors (cfr. ENTSO-E's Vision: A Power System for a Carbon Neutral Europe)[1].

After passenger cars, Heavy-Duty Vehicles (HDVs) are the second most CO_2-emitting segment in the whole transport sector and, due to their business-oriented use cases, they are proving to be the fastest segment for approaching a decarbonisation strategy in a structural manner.

This Position Paper, focusing on Heavy-Duty Electric Vehicles (HDEVs) for road transport (buses and trucks) and their impact on the Power System, complements the findings and call for actions from the previous ENTSO-E Position Paper published in 2021 on "Electric Vehicle Integration into Power Grids"[2].

Our economy strongly relies on HDVs for passenger and freight transport, for construction and agricultural works, in addition to several specific needs requiring special-purpose vehicles. Buses & Trucks account for approximately 30 % of road vehicle emissions. Within the European Green Deal there is a clear strategy to also fully decarbonise HDVs (closely following the segment of passenger cars), either through emission-neutral fuels in today's Internal Combustion Engines (ICEs) or through electric engines fed by either batteries or hydrogen fuel cell. New EU legislation has been adopted, such as the Alternative Fuels Infrastructure Regulation (AFIR [1]) or proposed, such as the recent review of the CO_2 emission performance standards for HDVs [2].

From the various alternative fuels for HDV, latest projections show a consensus on battery-operated prevalence, due to the higher maturity of the supply chain. Fuel-cell HDV is still an uncertain technology but could be an option for long-haul road transport, however, the market uptake proportion between battery and fuel-cell HDV remains uncertain depending on technology readiness and on consumers' preference choice. Finally, ICEs HDV running on biofuels and synthetic biofuels are deemed applicable in specific use cases (hard-to-electrify applications) and shall be available in limited volumes, so they don't change the picture for the power system.

This is of particular relevance for Transmission System Operators (TSOs), both regarding grid planning (amount and profile of new load), grid operation (higher energy load and power peaks, higher variability) and energy system operation (flexibility from battery-operated vehicles as well as the impact of electrolysers required for fuel cell vehicles). The interface is the recharging infrastructure, and possibly small on-site electrolysers supplying some of the refuelling infrastructure, which needs to be coordinated both for its deployment (location, grid reinforcements) and for its operation (smart charging and Vehicle-to-Grid, V2G), through appropriate enablers: interoperable and digitalised chargers, market-driven charging processes management, tariff and business models for final users and for charging operators, and updated regulation and market rules.

This Paper addresses, from a TSO perspective, emerging technologies and trends for the uptake of Zero-Emission HDVs and their recharging/refuelling stations. It is based on a technical/economic analysis covering projections for vehicles and charging infrastructure uptake, consumers' operational requirements and economics, and regulation and market issues. The Paper identifies a taxonomy of charging use cases, their impact on the electric grids and on the broader power system, recommending actions to be taken in a coordinated manner by the various actors of a wide and cohesive ecosystem (vehicles and battery manufacturers, charging operators and energy aggregators operators, logistic operators, fleet managers, road and urban planners, regulators) under the fast evolution of European policy frameworks.

1 See **here**.
2 See **here**.

Key messages

1. HDVs are a large CO_2 emitting segment, and are approaching decarbonisation faster than expected, especially the battery electric (BE) operated type, due to their underlying business cases.

- HDVs are an heterogenous sector (specialised machines), but the focus is on trucks for goods and buses for passengers, representing the vast majority of consumption.
- Trucks and buses, while representing only approximately 3 % of road vehicles, **account for almost 30 %** of road transport emissions and approximately 6 % of total EU greenhouse gas emissions in Europe.
- HDV owners are very **sensitive to the economics of the vehicle**, mainly to the upfront purchase cost, fuel cost, maintenance and lifetime; as well to the main performance indicators: payload and drive range; all these parameters are quite different across the fossil fuel and electrical/hydrogen versions.
- BE trucks for local and regional operations and especially buses are **commercially available and competitive** regarding Total Cost of Ownership (although this depends on fuel/electricity prices); therefore, they could represent an anchor load for faster commercial uptake by vehicle manufacturers and for charging operators (1 truck consumes the equivalent of 50 cars).
- **For long-haul trucks, the** battery-operated option still poses challenges to transport operators for the capillarity of recharging **infrastructure availability and payload limitations** (weight and space occupation of the battery pack).
- **Fuel-Cell** HDVs are at early stage, so they could **be a less appealing option for a fast decarbonisation target** (mandated and/or voluntary) by fleet managers/logistics operators; however, for long-haul operations, provided the refuelling infrastructure is in place, they present advantages for refuelling time, higher payload capability and extended driving range.

2. The recharging infrastructure for heavy duty electric vehicles is an additional driver for further developing the electricity grid

- **Taxonomy:** Charging stations, just as for cars, shall have both private access (depot, logistic hubs) and public access (roads, highways, parking areas, ports), whereas regarding the impact on the electric system/potential provision of grid services, they can be categorised as:

  - **Depot charging, at the own premises of the HDV operator, characterised by overnight/non-working hours charging**, expected to cover the majority (up to 80 %) of total charging demand; destination charging, in long stop-over locations depending on the HDV type of service, can be considered a sub-category.

  - **Opportunity charging** at urban nodes and logistic hubs will take place in limited time intervals which occur at loading/unloading operations or for mandatory drivers' resting hours.

  - **Charging stations along roads and highways** are needed for fast, unplanned charging and for long-haul missions; for HDVs, this will require an MW scale device (Hypercharger or Megawatt Charging System), with a target European standard expected before 2025 of max 1,250 V – 3,000 A.

- The deployment of the public recharging infrastructure for BE HDVs will require **thousands of new MWs in recharging stations** along all major European highways and roads. The AFIR requires a max distance of 60 km along the Trans-European Transport Network (TEN-T) by 2030. AFIR targets, also set for opportunity charging at urban nodes and overnight public charging points in parking areas, shall be a minimum mandated value, but commercial expectations from stakeholders' projections are higher.

- The presence of a **stationary battery in the charging station (or of battery swapping solutions)** would reduce its impact on the grid (lower connection power and peak demand) while providing benefits to the charging operator: lower grid tariff, arbitrage in the power purchase profile and sale of services to the grid. It would also substantially enlarge the potential for flexibility provision; therefore, it is a configuration that should be promoted (or at least analysed when designing the station).

- The deployment of the public hydrogen refuelling infrastructure for **Fuel Cell HDVs** will require hundreds of new stations along all major European highways and roads; these stations can be repurposed from the current fossil fuel refuelling ones, so special connections are not required to the electric grid. However, one option under consideration is to install **small electrolysers on-site**; this solution avoids the infrastructure and costs of hydrogen transport and could provide grid flexibility from the electrolyser operation, decoupling the electricity load profile from the hydrogen consumption profile in as much as local storage is present (H_2 tank and eventually also stationary battery).

3. Member States should involve grid operators in the planning of the recharging infrastructure

- In 2030, Battery HDEV consumption is expected to make up approximately 30 % of all electrified road transport, corresponding to approximately **1–2 % of the European final electricity consumption**.

- If unmanaged recharge is applied, the corresponding peak power demand could be up to 20 GW, concentrated during late evening and night hours, when most vehicles recharge at their depot/overnight location. This can be **efficiently smoothened through smart charging**, while increasing renewable energy source (RES) integration and offering opportunities for competitive grid services.

- HDEV charging shall have an important **impact on the local grids**; the advanced planning of network upgrades and reinforcement, coordinated with higher voltage levels, will become crucial as the permitting and construction of new substations and HV lines usually takes a long time, which is incompatible with the fast needs of transport electrification.

- MW scale charging stations are expected to require 15–35 MVA network connections, which usually occur directly at high voltage level but can also occur at MV level, depending on Member State specificities.

- **Member States should involve grid operators** in the planning of recharging and refuelling infrastructure. Thanks to a **coordinated planning**, driven by early engagement of fleet managers and relevant mobility and energy stakeholders, TSOs can use a system-aware proactive approach to **pre-identify suitable locations** along motorways where the high voltage grid connection may be available or may be easily extended.

- **Strong HV networks and nodes in the vicinity of logistics hubs** will become crucial to enable HDEV opportunity charging and destination charging.

- Connection requirements and technical specifications are crucial for the predictability of investments and timely infrastructure implementation. Therefore, it is key to ensure **non-discriminatory connection requirements** for all stationary installations connected to the electricity network, as part of the standard categorisation in the Network Codes, in addition to harmonised requirements for onboard (movable) converters.

- For depot charging, the additional demand may exceed the available capacity of the local grid, especially in urban areas, and required network upgrades may face restrictions. **Coordinated planning**, driven by the early engagement of fleet managers, road operators, local municipalities, Charging Point Operators and grid utilities is essential to anticipate public acceptance and potential land use issues, and to establish a feasible and timely power-delivery schedule.

4. HDEV have the potential for flexibility of services, provided that the relevant framework is swiftly developed and implemented

- Buses and Trucks have in general more **predictable routes and time schedules** than private cars, so in principle they are more prone to planned charging.

- Depot charging during night/out of service hours has the **potential for the provision** of flexibility services, whereas opportunity charging and highway charging during short time intervals offers limited room for flexibility services.

- The feasibility to perform grid services from HDEV recharging depends ultimately on the technical abilities of both the charging device and of the vehicle's Battery Management System to adjust the load profile according to system signals. Therefore, **it will always be the choice of the driver** to decide a smart charge, depending on several objective and subjective conditions. TSOs are encouraged to **investigate the real technical limits** of demand response and load balancing, also depending on HDEV penetration rate.

- To enable the utilisation of HDEVs for flexibility services, a **clear regulatory framework, incentives and attractive business models** are necessary, comprising data and information exchange and digitalisation for cross-sector integration, and enabling their participation in the electricity markets on a peer level with other flexibility mechanisms.

- Further research and demonstrations are required to understand the **charging patterns and the cost-opportunity** for transport operators and Mobility Service Providers to **participate in the market of flexibility services**. TSOs, in collaboration with fleet operators, can play a crucial role, for example, by introducing **pilot projects and regulatory sandboxes** to gather experience on grid impacts and reactions to time-varying tariffs and to eventually assess the real flexibility potential.

Useful definitions

Heavy-Duty Vehicles (HDVs): all land vehicles with a mass greater than 3.5 t used for the transportation of people and goods, or to perform agricultural or other energy intensive mechanical duties.

Zero-Emission HDVs (ZE-HDVs): HDVs where all the energy for moving or performing mechanical jobs is given by an electric engine, which can be powered by either a Battery Electric pack **(BE-HDV)** or a hydrogen Fuel Cell **(FC-HDV)**. They are defined Zero-Emission HDV for the lack of the Internal Combustion Engine (ICE) and tailpipe emissions.

Plug-in hybrid HDVs: electric HDVs constituted by a conventional combustion engine combined with an electric propulsion system, which can be recharged from an external electric power source.

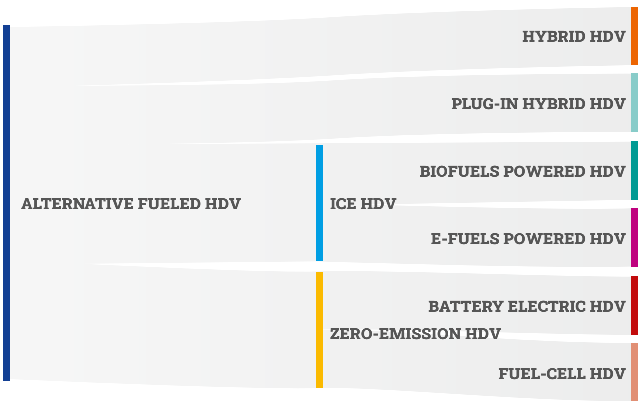


Figure 1: Alternative fuelled HDV infographic

Hybrid HDVs: HDVs mainly driven by an Internal Combustion Engine (ICE), whereby a small electric drive supports the ICE for temporary boost, limited brake regeneration and stop-start functionality.

Alternative fuelled HDVs: HDVs using fuels or power sources which serve as a substitute for fossil oil sources in the energy supply for transport and which have the potential to contribute to its decarbonisation and enhance the environmental performance of the transport sector (Figure 1 and Figure 2), including:

(a) Alternative fuels for zero-emission vehicles: electricity, hydrogen, ammonia (if produced with no Carbon Dioxide-CO_2 emissions).

(b) Renewable fuels: biofuels and E-fuels produced from renewable energy.

(c) Alternative fossil fuels: they will be used only for a transitional phase and are therefore out of the scope of this document.

Biofuels: liquid fuel produced from biomass.

Electro fuels (E-fuels): fuel manufactured using capture carbon dioxide or carbon monoxide, together with hydrogen obtained from non-CO_2 emitting electricity sources such as wind, solar and nuclear power.

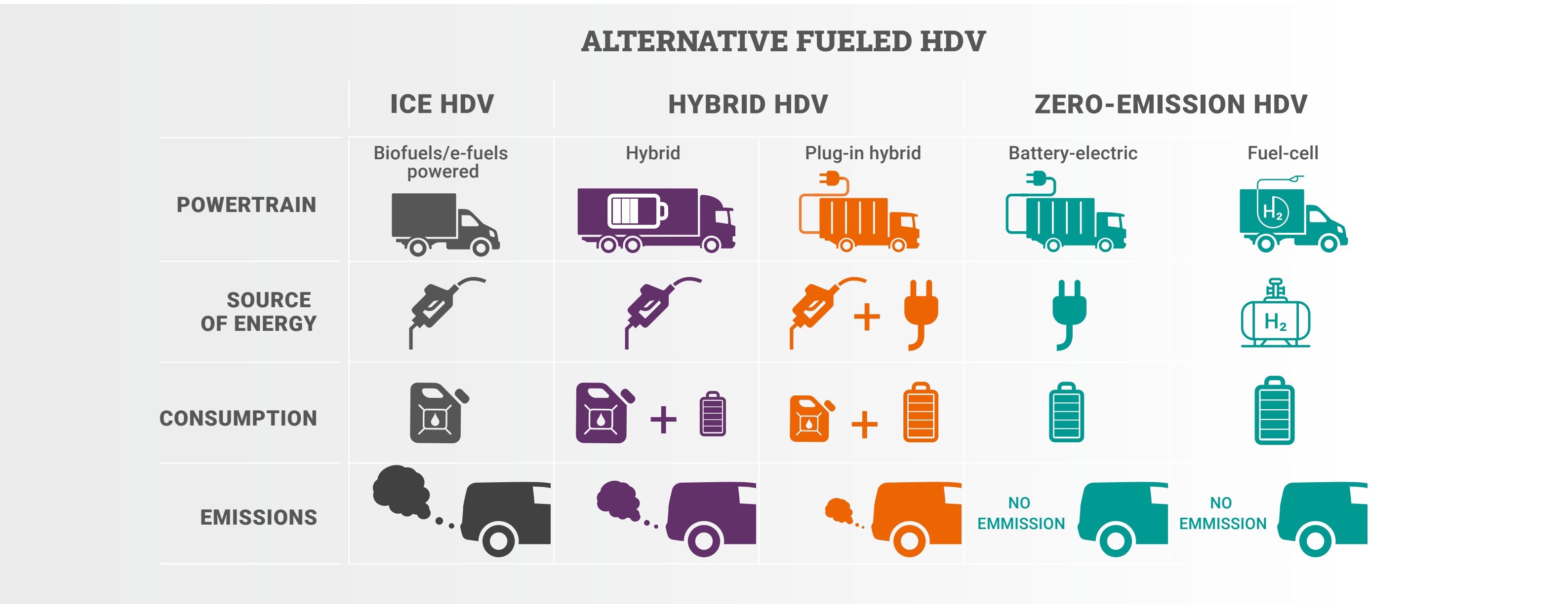


Figure 2: Main features of alternative fuelled HDVs.

1 Introduction, rationale and scope

In Europe, Heavy-Duty Vehicles (HDVs) were responsible for more than 25 % [3] of road transport emissions in 2019. Ambitious plans are in place to strongly decarbonise this hard-to-abate segment by 2050. Although the present sales of new HDVs are still strongly based on diesel models, in the last few years increasing numbers of models based on hybrid and electric motors have been released and their market share has also increased accordingly, indicating that the time is right for a significant change in the European HDV market.

Zero-emission (i. e. Battery Electric [BE] or Fuel Cell) trucks and buses for road transport applications are set to reach commercial maturity in all transport use cases by 2030. Their numbers are already growing fast, especially BE buses for public transport, where the **Total Cost of Ownership (TCO) of BE buses has already proven to be lower** than the traditional diesel solution [14].

It is worth noting that biofuels and synthetic e-fuels, owing to limited availability and high energy costs, are expected to be used only for aviation, maritime transport and agricultural/construction machineries operating in remote areas, where bringing the required recharging/refuelling infrastructure is deemed economically unfeasible.

Local and regional transport is going fully electric with electric buses already a commercial reality, and public transportation will be the first HDV segment to become fully decarbonised, with an expected share of new electric buses > 90 % already by 2030 [14]. BE trucks for local and regional operations are the second HDV segment to hit the road. A fair number of BE trucks are already market available and are being adopted by major transport operators in their daily business. **Depot charging** during night-time covers more than 80 % [33] of the energy needs of these Battery Electric Heavy-Duty Vehicles (BE-HDVs), whereas the remainder 20 % is delivered via the so-called **opportunity charging** solutions at line terminals for public buses or at logistic hubs during loading/unloading operations for trucks. Hydrogen Fuel Cell HDVs are not expected to play a significant role for local and regional transport operations due to the higher cost of hydrogen over electricity.

The **situation for long haul operations remains uncertain** as it is yet to be understood which powertrain technology between BE or Hydrogen Fuel Cell will prevail. The answer will not depend exclusively on the technical and economic performance of the single vehicles but also on the eventual choice of transport operators, which are affected by, among others, social, political and operational drivers. One thing is certain: the public available recharging/refuelling infrastructure is mostly required for long haul operations: should BE technology prevail, the necessity for a good coverage of > 10 MW recharging stations along European highways becomes unavoidable.

The planning of the recharging/refuelling infrastructure along European highways shall be kept under high consideration by all power grid operators to limit the costs for new High Voltage (HV) lines and substations and to be able to deliver the new connections as timely as required by the evolution of the transport sector. To this end, **early engagement with relevant stakeholders is strongly advised to foster the deployment of the required infrastructure**.

ENTSO-E sees the potential of the decarbonisation of the Heavy-Duty segment and is taking a proactive approach to address the challenges of EV-grid integration, not only to minimise the impact of future transport infrastructure into the power systems, but also to optimise its integration in benefit of the electricity network planning and operation. Therefore, ENTSO-E presents this Position Paper as an outcome of a study dedicated to the electrification of HDVs and the expected impact on the power grid, as part of the electromobility topic which shares the same aim.

2 Heavy-Duty Vehicle types and CO_2 footprint

HDVs are widely used in our modern economy, ranging from goods and passenger transport to agricultural and construction machinery. Due to their high energy needs, most HDVs are currently propelled by diesel engines, and their impact on Green House Gas emissions (GHG) is significant.

The European Union (EU), in the pursuit of decarbonisation as well as fostering competition and innovation among European HDV manufacturers, has set ambitious goals for increasing the energy efficiency and reducing the emissions of the different types of HDV, especially focusing on Zero-Emission HDVs for road transport applications, which are already being deployed for the first use cases.

2.1 Road transport – an irreversible shift towards Zero-Emission mobility

Today, there are about 6.2 million trucks and 680.000 buses in circulation in the EU, with an average age of 13.9 years old for trucks and 12.8 years for buses [4], [5]. The vast majority run on diesel (97.8 % of trucks; 94.5 % of buses) as it is the most convenient and capillary diffused fuelling option for professional transport operators; until the 2022 energy crisis, it was also the most affordable option. So far, only negligible low- and zero-emission trucks are in operation.

Under the **"European Green Deal"**, the EU has laid down a consistent set of plans to address the economic and societal changes that will transform our society in the next two decades. Regarding the decarbonisation of HDVs, the position of the European Commission (EC) is clearly expressed in the first section of the document **"Sustainable and Smart Mobility Strategy"** [6], entitled "Sustainable mobility – an irreversible shift to zero-emission mobility", where it is reaffirmed that:

- By 2050 a 90 % reduction in the transport sector's emissions can be achieved and nearly all […] new heavy-duty vehicles will be Zero-Emission;
- [Par. 19] For road transport, zero-emission solutions are already in deployment. [*System] Energy efficiency shall be a criterion for prioritising future choice of suitable technologies […]; and
- [Par. 20] Air and waterborne transport have greater decarbonisation challenges […], due to current lack of market ready zero-emission technologies […]. These modes must have priority access to additional renewable and low-carbon liquid and gaseous fuels as there is a lack of suitable alternative powertrains in the short term.

The EC acknowledges that the production of alternative fuels is currently not sufficient to cover the expected demand, refuting any hypothesis on the massive use of synthetic and biofuels for road transport applications.

Regarding railway transport, the Alternative Fuels Infrastructure Regulation (AFIR) states that while only approximately 56 % of the existing European rail network is electrified, electricity-powered trains comprise more than 80 % of total travelled train-kilometres. However, there are still an estimated 6,000 diesel trains in service today. Different technologies are available to decarbonise them, including direct electrification, battery powered trains and hydrogen applications, whereas the direct electrification of a segment is not possible for reasons of cost-efficiency of the service. Before their deployment, the best locations for such infrastructures should be carefully assessed, and should, in particular, consider deployment in multimodal hubs and urban nodes. The "energy efficiency first" principle should be fully considered in planning and investment decisions.

2.2 Agricultural and construction machineries – what possible decarbonisation?

As mentioned above, not all HDVs are used for transport applications. **HDVs for agricultural, construction works and special duties** are an extremely wide range of vehicles and machineries operated under different conditions, to name a few: cranes, excavators, tractors, drilling and crop harvesting machines, garbage collection, industrial sites movers and mining. Most of these vehicles have limited driving capabilities on regular roads and operate in remote areas far from the highways and the main transport network nodes where a public recharging/refuelling infrastructure can be located. Being optimised for specific tasks, their energy consumption is mostly related to the on-site mechanical job rather than for moving around. The Committee for European Construction Equipment (CECE) and the European Agricultural Machinery Industry Association (CEMA) jointly released a position paper [7] on the strategies to achieve decarbonisation in the agricultural and construction sectors. To briefly summarise, these two segments are committed to achieving striking results in terms of vehicle energy efficiency and developing hybrid powertrains to be propelled with alternative fuels or biodiesel. Due to their short driving range, fully electrified Battery or Fuel-Cell HDVs are deemed economically and technically inconvenient but for a limited set of applications, due to the difficulty of providing the required electricity or hydrogen supply directly on the site of operation. This fact is also acknowledged by EU legislation, which excludes "vehicles used for mining, forestry and agricultural purposes" from the same CO_2 targets for road transport vehicles.

2.3 HDVs for road transport applications

HDVs for road transport applications are all trucks and tractors heavier than 3.5 t as well as all passenger vehicles with more than eight seats, namely buses and coaches. Today, there are approximately 7.5 million trucks in circulation in Europe. They have full driving capabilities on European roads and are subject to the European framework for the transport sector (EU Regulatory box below), which strongly pushes for Zero-Emission vehicles and for the deployment of a public recharging and hydrogen refuelling infrastructure. As mentioned, their overall energy demand cannot be met by alternative fuels or biodiesel due to limited supply and they are thus expected to transition towards full electric technologies such as Battery or Fuel Cell electric. A picture of the most relevant HDV types is provided in Figure 3.

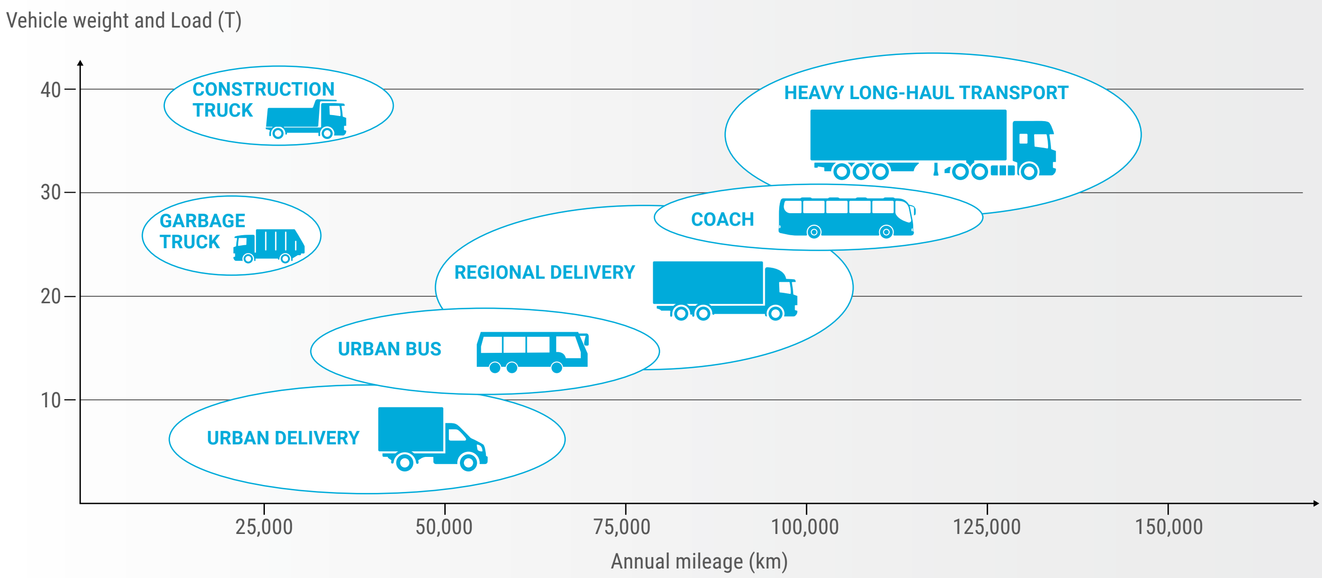


Figure 3: Different types of road HDVs according to annual mileage and weight. RSE elaboration based on [15].

Depending on their operation mode, trucks can be further segmented into long-haul, regional delivery and urban delivery. The HDV fleet is very heterogeneous, with vehicles that have different uses and drive cycles, which directly influence primary consumption and GHG emissions, as well as refuel/recharging patterns.

The total amount of CO_2 emissions from trucks as well as for buses in Europe has slightly increased in the last 20 years [3] despite an overall increase in the energy efficiency of the vehicles and the reduction of CO_2 intensity of fuels, due to the 5 % blending with biofuels introduced in 2006. This overall increase is due to the steady growth of European demand for road freight transportation, as shown in Figure 4, and this is not expected to change significantly in the future [8].

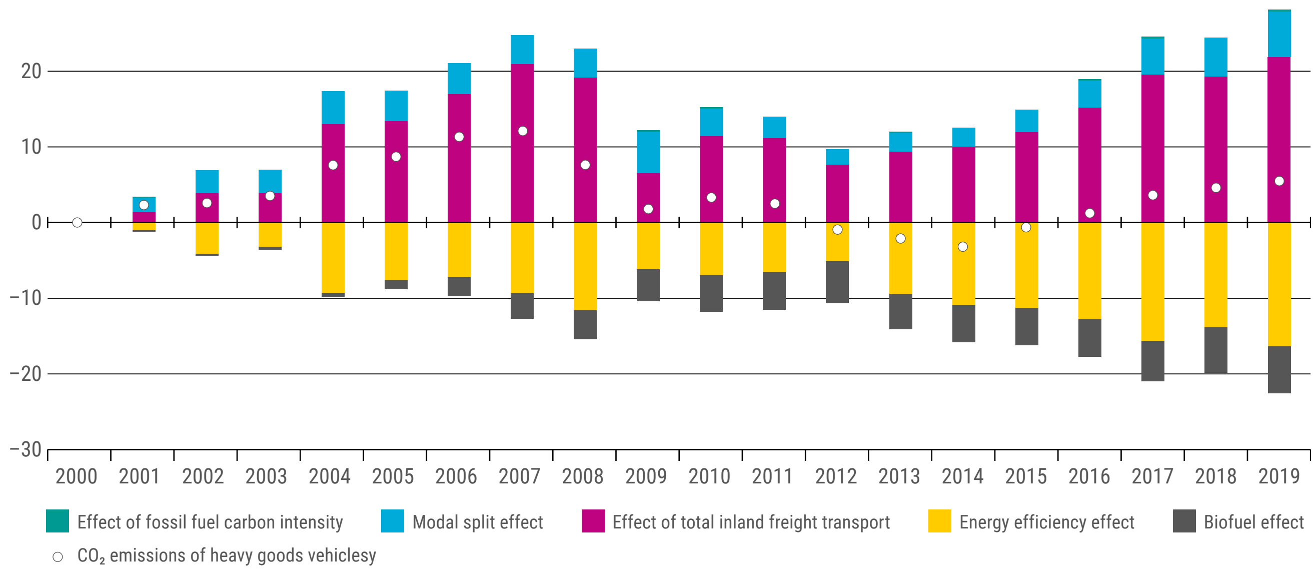
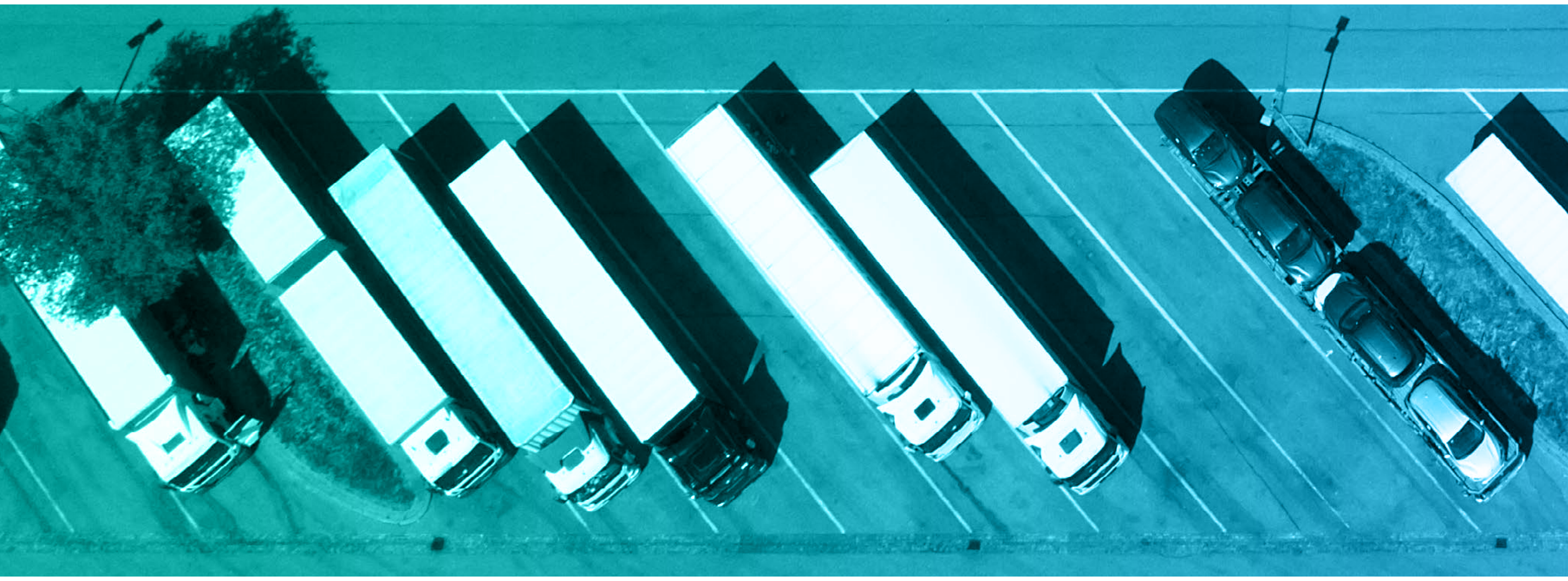


Figure 4: Decomposition analysis of the CO_2 emissions from trucks in the EU-27. Percentages with respect to year 2000 values, contributions of relevant factors [3].



EU Regulatory Framework Impacting HDVs

AFIR

AFIR, part of the EU's "Fit for 55" package of regulatory actions, sets mandatory national targets for the deployment of electric recharging and hydrogen refuelling infrastructure for road, shipping and aviation sectors. The EC proposed AFIR on 14 July 2021, amending the 2014 alternative fuel infrastructure directive (AFID). After the Council and the Parliament set their respective position in the course of 2022, they reached a political agreement in March 2023. The final text was adopted in July by the European Parliament and the Council. AFIR is about to be published and will apply after 6 months of entering into force. Table 1 summarises the requirements for HDVs.

Electric recharging infrastructure					
Target date	**TEN-T network* (minimum coverage length)**			**Safe and secure parking area**	**Urban node**
	Core	Comprehensive	Minimum requirements	Minimum requirements	Minimum requirements
			Power output (aggregated)	Power output (aggregated)	Power output (aggregated)
31 December 2025		15 %	1,400 kW	–	900 kW
31 December 2027	50 %		2,800 kW	200 kW	–
		50 %	1,400 kW		
31 December 2027	every 60 km		3,600 kW	400 kW	1,800 kW
		every 100 km	1,500 kW		
Hydrogen refueling station					
	Core	Comprehensive	Cumulative capacity		Urban node
31 December 2030	every 200 km	–	1 t/day	–	1 HRS

* each direction of travel

Table 1: Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU [Online] [1].

Regulation on CO_2 emissions performance standard on new heavy-duty vehicles

In 2019, the EU introduced its first CO_2 standards for new HDVs with regulation 2019/1242. On 14 February 2023, the EC proposed to review the regulation with more severe targets and extending CO_2 standards to a range of additional vehicle segments [2], including medium lorries, buses and coaches. Table 2 summarises the current regulation and the new proposal.

EU regulation 2019/1242		NEW PROPOSAL: 2023/0042 (COD)	
Year	**CO_2 reduction target***	**Year**	**CO_2 reduction target***
2025	−15 %	2025	−15 %
2030 onwards	−30 %	2030	−45%
		2035	−65 %
		2040 onwards	−90 %
› Dedicated incentive mechanism for Zero and Low Emission Vehicles (ZLEVs)		› Removed current incentive mechanism for ZLEVs as of 2030 (as stricter CO_2 targets should automatically lead to higher shares of new ZEV in the market). › No mechanism to account for the potential contribution of renewable and low-carbon fuels. › Mandatory share of 100 % new zero-emission urban buses from 2030 onwards.	

* Compared to a 1 July 2019 – 31 June 2020 baseline.

Table 2: Current CO_2 emission standards compared to new proposal [2].

Amendment on additional weight for ZEV technologies

Regulation (EU) 2019/1242 introduced an amendment to the Directive 96/53/EC on authorised dimensions and weight for trucks, buses and coaches, permitting 2 Tons of additional weight for new HDVs.

For the long-haul truck, despite the additional weight allowance for zero-emission trucks, the large batteries required in the early years in combination with the relatively low energy density of batteries result in a temporary penalty on the payable load for the long-haul battery electric vehicles (BEVs). According to study [9], for the long-haul BEV the initial penalty of 3,200 kg on the maximum payload in 2020 will reduce to zero by 2030. Similarly, the payload penalty for medium battery will decrease to zero by 2024.

Regulation on driving time and rest periods

Regulation (EC) No 561/2006 sets, for the road transport sector, rules on driving time and rest periods: after a period of 4.5 h of driving a rest time of not less than 45 minutes is mandatory, followed by another 4.5 h of driving. A minimum daily break of at least 11 h overnight is foreseen. The time windows provided by breaks and rest periods can be used for recharging BEV trucks either fast during day or longer overnight.

2.3.1 Location and duration of truck stops in Europe

The identification of the current stop locations of trucks is crucial as these sites could be the optimal locations to begin the installation of charging infrastructure for heavy-duty trucks. The classification of the top 10 % most visited truck stop locations in Europe is summarised in Table 3.

Category		Distance from motorway	Approximate share
Rest areas	directly located to motorway	0–0.2 km	30–50 %
	close to motorway	0.2–1 km	
	without direct motorway access	1–5 km	
Companies and logistic hubs		1–5 km	25–45 %
Ports		n.a.	1–5 %

Table 3: Type of truck stop locations (Authors' elaboration on [10]).

In addition to stop locations, another important parameter for deciding the power for future electric truck charging infrastructure is the duration of stops. The average share of stop durations per location for long-haul and regional trucks is shown in Figures 5 and 6. For both long-haul and regional operation, the shares of short (lower than 3 h) and long (over 8 h) stops account for almost 100 %, while stops of intermediate durations (3–8 h) play hardly any role.

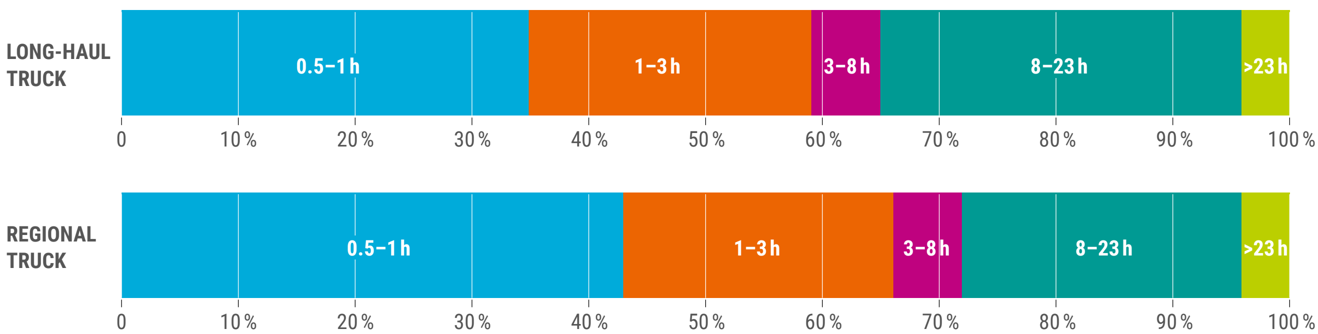


Figure 5: Percentage of stops by duration in long-haul and regional operation (RSE's elaboration based on [10]).

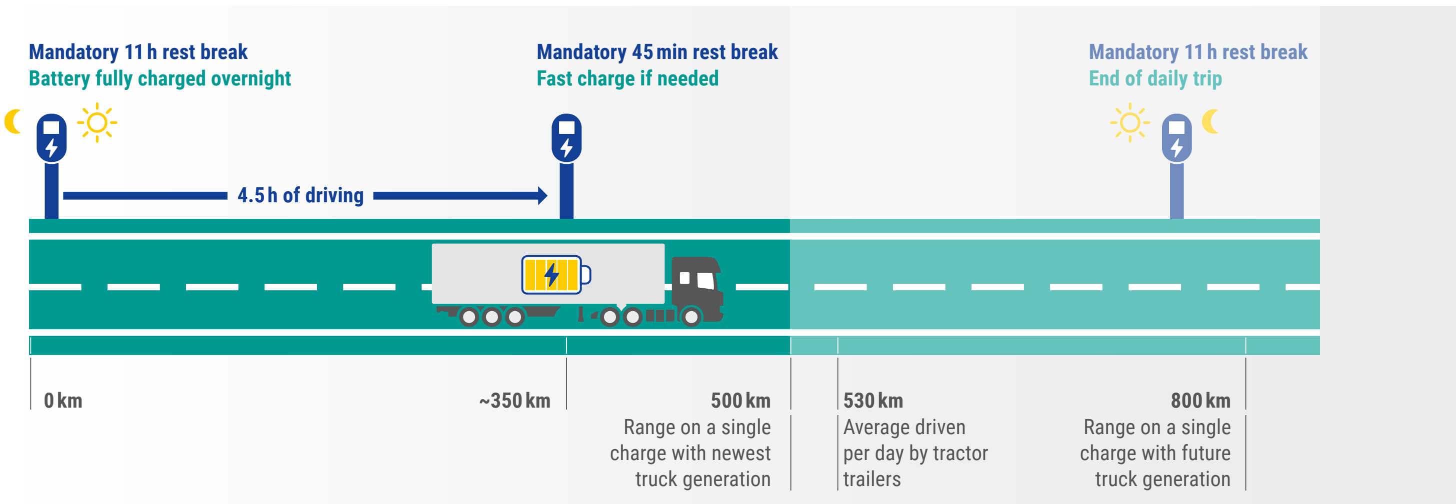


Figure 6: Daily driving patterns of electric long-haul trucks [11].

2.3.2 Driving cycles

A representative driving cycle for a regional haul is represented in Figure 7. The profile covers a 450 km distance. The overall stop time is 1 h 30, however the longest stop time is approximately 10 minutes.

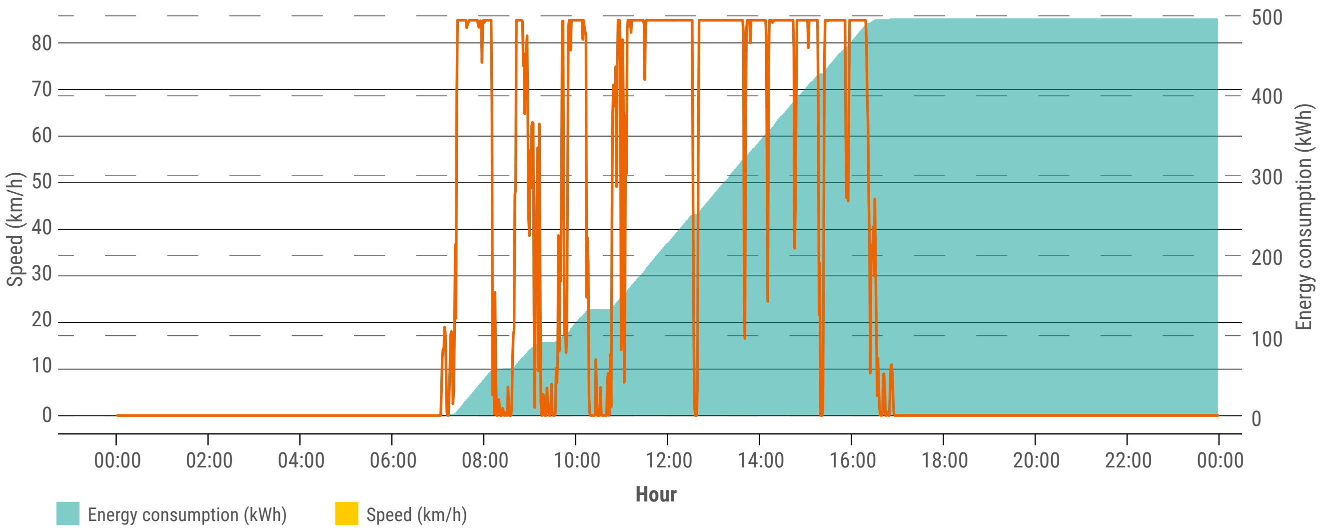


Figure 7: Regional truck representative daily driving cycle (RSE elaborations based on [12]).

Similar profiles have been studied/measured for other use cases. Driving profiles are crucial for deciding the technology of future truck fleets. It is estimated (Figure 8) that 97 % of trucks drive up to 800 km per day, which is compatible with the announced ranges for future generation of BEV trucks.

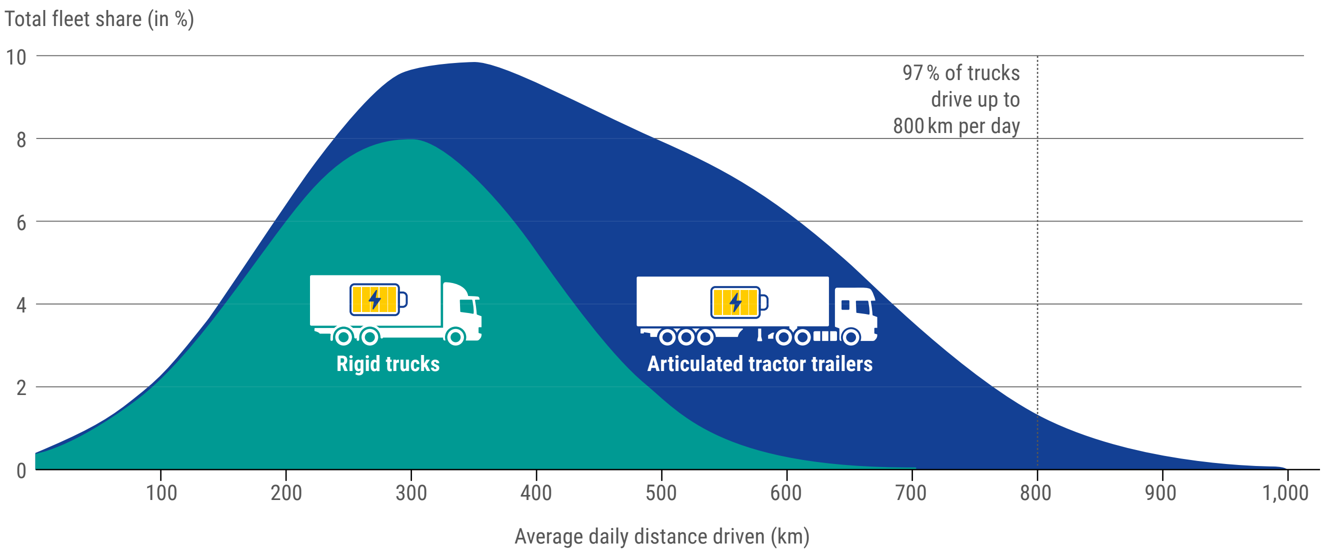


Figure 8: Average daily distances driven by truck in Europe [11].

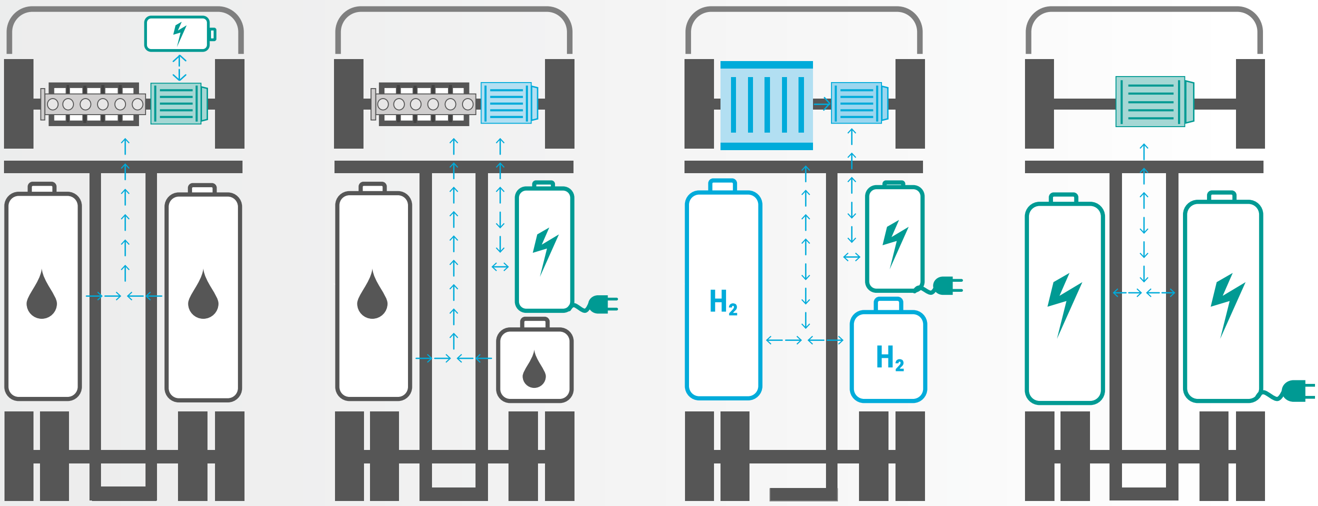
2.3.3 Buses and coaches

Buses are the most widely used form of public transport in the EU, serving cities as well as suburban and rural areas, making up to 56 % of all passenger journeys [3]. With one bus capable of replacing 30 cars on the road, buses help ease traffic congestion. Moreover, they have the lowest carbon footprint per passenger of any form of motorised transport. They are also the most cost-efficient and flexible form of public transport, requiring minimal investments to launch new lines or routes. Buses are also a safe transport mode, responsible for just 2 % of road fatalities in the EU.

Today, approximately 692,200 buses are in operation across the EU, almost half of which can be found in three countries alone: Poland, Italy and France, on average 12.8 years old [4]. Diesel buses account for 93.5 % of the EU fleet. Zero emissions buses continue to gain market share: in 2021, registrations increased 40 %, representing 27 % of new bus sales in the EU, most limited to urban buses.

3 Decarbonise HDVs through electricity and/or hydrogen

Technologies that offer low-carbon road transport are already commercially available. Hybrid solutions combine an internal combustion engine with an electric motor supplied by a battery which, depending on the size, can offer different functionalities (start & stop, brake regeneration, full-electric operation…). BE and fuel cell EVs are considered the most promising options to fully decarbonise heavy-duty transport as they have zero tailpipe emissions.



Hybrid

The vehicle is mainly driven by an ICE. A small electric drive (5–20 kW) supports the ICE for temporary boost, limited brake regeneration and stop-start functionality. The electric motor is supplied by a small size low voltage battery (12–48 V / 2–5 kWh).
The battery is charged by the ICE while driving. Only refuelling operation is requested. No impact on the electricity grid.

Plug-IN Hybrid

The powertrain consists of a battery powered electric motor in parallel or in series with on ICE. The electric drive system can provide all or a substantial fraction of traction power for all operations (50–80 km).
A substantial portion of braking energy can be recuperated in the energy storage system. The battery is typically charged from the grid, however, recharge through the ICE is also possible.
Limited impact on the electric grid due to marginal use of the electric energy and primary consumption of diesel fuel.

Battery electric

The vehicle is driven by an electric motor. The whole power to supply the motor is provided by a large sized battery (100–900 kWh). A dedicated infrastructure is required to recharge the battery.
Zero tailpipe emissions to supply from 7 kW to 375 kW. Zero Well-To-Wheel emissions if electricity is generated from RES. Relevant impact on electric grid.

Fuel Cell

The vehicle is driven by an electric motor. The electrical power for the motor is provided by a fuel cell which generates electric power from hydrogen and oxygen. Hydrogen needs to be stored at a high pressure 350–700 bar to improve its energy density. A dedicated refuelling infrastructure is necessary to handle high pressure refilling.
A low size battery is used for boosting acceleration without oversizing the fuel cell pack; this battery can also have a plug for independent charging. As no combustion is required to generate usable energy, fuel cell electric vehicles (FCEVs) present zero tailpipe emissions.
Zero Well-To-Wheel emissions if hydrogen is produced from RES. Indirect impact on electric grid (electrolysers producing green hydrogen).

3.1 Models' availability and ranges

The number of new ZE-HDV models is expanding across all global markets. As of 2023, **40 models of BE truck models** and **50 models of electric buses** are already available in Europe. Much fewer **models of fuel-cell trucks** and buses are available. Nevertheless, several manufacturers (Daimler, Nikola, Hyundai, MAN) have announced the start of series production of fuel cell trucks from 2024 [13]. Some manufacturers are developing both Battery and Fuel cell technologies.

Many truck models offer ranges above 300 km which are suited for urban and for return-to base regional operation. Some declared endurance ranges reach **800 km for BE truck** and more than **1,000 km for fuel cell trucks**, which have the opportunity to be compatible even with long haul operations (Figure 9).

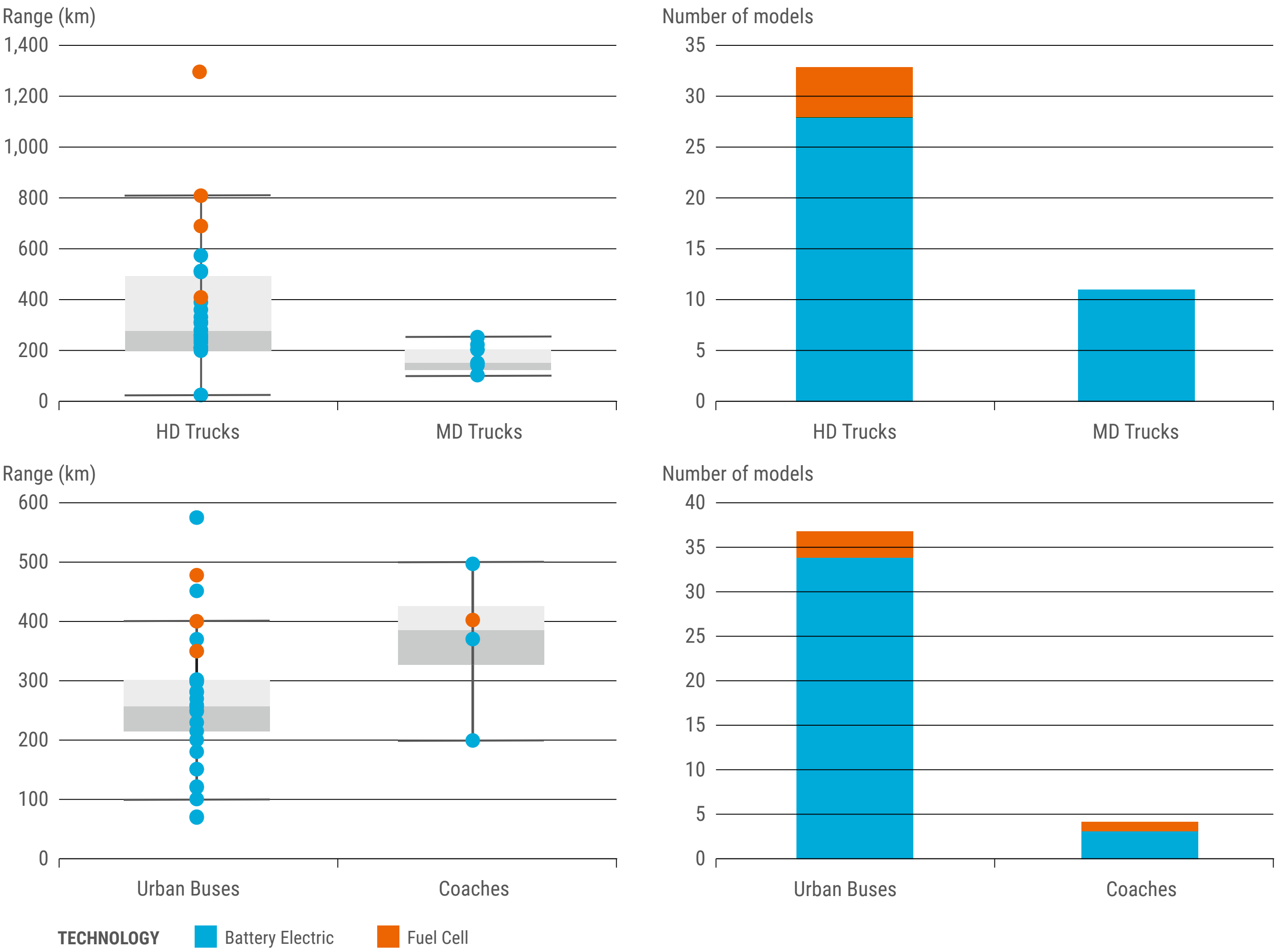


Figure 9: Available models of BE and fuel-cell trucks and buses in Europe (2023) (authors' elaboration on [13]).

The higher technological readiness of BE trucks and buses, compared to Fuel-Cell vehicles, is an initial reason leading to the adoption of the BE technology in the next few years. However, there are other points which make BE technology more competitive:

- **Economic reasons:** as presented in the box **"HDV TCO"** of this paper, BE trucks will be more convenient than Fuel Cell trucks, until green hydrogen reaches much lower production costs than currently.
- **Operational complexity:** hydrogen technology, compared to BE technology, is associated with a higher operational complexity, due to safety rules, maintenance, space for refuelling stations and the logistics infrastructures to supply hydrogen to the station.
- **Efficiency at parity of operation:** FC vehicles are generally consuming more than twice the amount of primary energy than BE vehicles. On the other hand, by decoupling hydrogen production from hydrogen consumption, it is possible to exploit seasonal storage, therefore gaining in infrastructure efficiency (less RES curtailment, lower peak for grid design capacity).

HDV Total Cost of Ownership

The logistic sector is highly cost driven and, in the switching from ICE to Zero Emission technologies, the TCO of the different vehicles is a key decision factor for transport operators.

Furthermore, technical requirements such as vehicle range and recharging and refuelling times, as well as payload or possible constraints such as the insufficient availability of recharging and refuelling infrastructure, are also important criteria for the transition.

Urban buses represent the HDV segment with the quickest and widest adoption of zero emission technology. In Europe, BEV buses have already achieved TCO parity with ICE buses [14]. As regards trucks, the TCO analyses in the timeframe 2020–2040 for urban, regional delivery and long-haul trucks have shown the following results. It is worth mentioning that fuels/electricity costs, included in operational costs, suffer from different excise duties, taxes and levies.

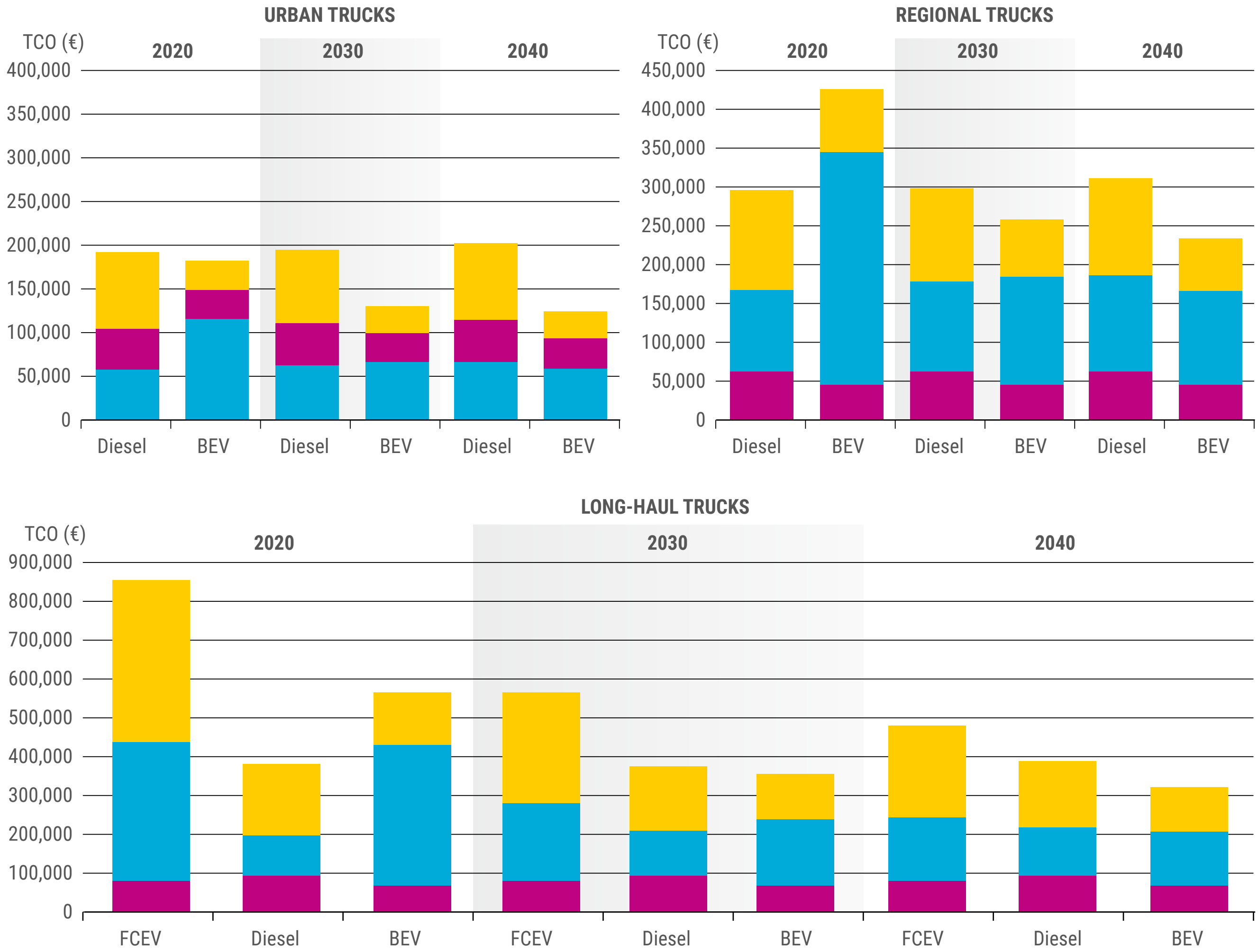


Figure 10: Total Cost of Ownership in the logistic sector (RSE's elaboration based on [9]).

› **Urban BEV** trucks are **already cost-competitive** as compared to their diesel equivalents: higher vehicle purchase costs are offset by lower operational costs.

› **Regional BEV** trucks will become **cost-competitive** over their diesel counterparts **before 2030**.

› **Long-Haul BEV** trucks, according to expected technological improvements, will become **cost-competitive** over their diesel equivalents **within 2030**, whereas **FCEV** will be the less competitive option even if fuel cell vehicles became widely available [15].

› If hydrogen price falls below **4 €/kg** and in the event of extraordinary high mileages (approximately 1,000 km/day), **FCEV** could be an option for trucks.

4 Charging/Refuelling patterns and infrastructures

4.1 Recharging infrastructure

Plug-in charging is the most widespread solution for BE-HDV. The current most common connector technology is the Combined Charging Systems, type 2 (CCS Combo2) [16], but the situation will likely change after the adoption of the Mega Charging Standard (MCS) [17], which is expected by 2025.

The distinction between different charging use cases is relevant as the charging use cases 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, as shown in Table 4 and Figure 10.

Charging pattern	Infrastructure access	
	Private	**Public**
En-route charging	N.A.	Along motorways
Opportunity charging	Logistic hubs, terminals, depots	Urban nodes
Overnight charging	Depots	Safe and secure parking areas

Table 4: Charging locations according to the charging pattern and the infrastructure access

4.2 Taxonomy of charging use cases

Combining the location, charging needs and possibility of exploiting slow charging for grid services provision, the different use cases can be categorised according to their impact on the power grid, as in Figure 11. En-route charging along motorways will be necessary for concluding routes in long-haul applications, while Depot overnight recharging is expected to cover approximately 80 % of total energy demand for BE-HDV.

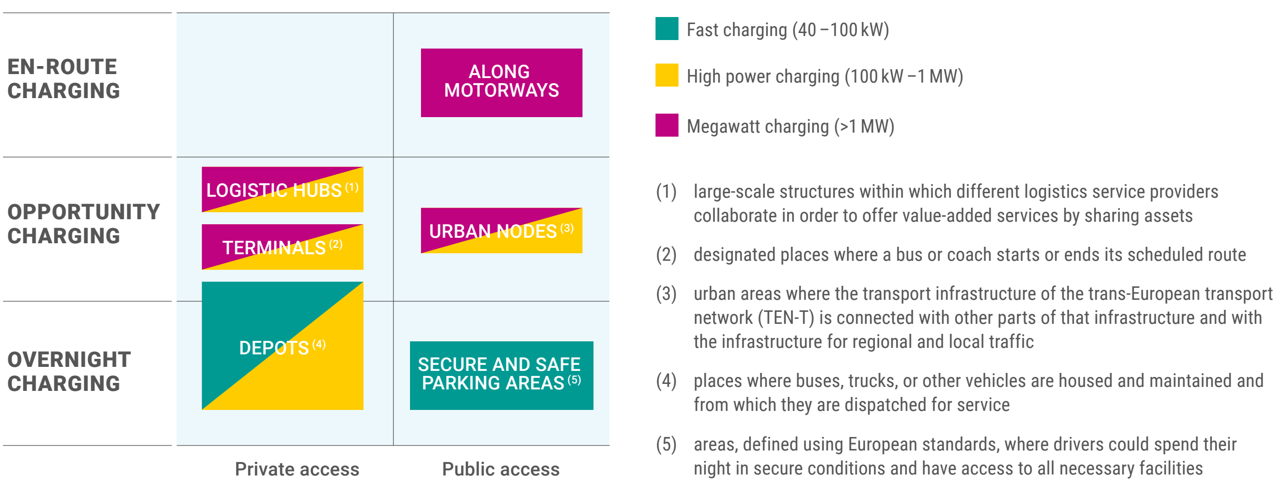


Figure 11: Taxonomy of charging use cases according to their grid impact.

Electric Road Systems (ERS) can provide power to trucks while driving. There are three main concepts: inductive coils in a road, conductive connections between the vehicle and road, and catenary lines. These options may be promising in terms of total capital and operating costs and could support the operational flexibility of logistic operators [24]. However, ERS are not yet available for commercial use, but only as demonstration or pilot projects. Due to the requirement of precise coordination of routes, comprehensive investments and installation measures, it is highly unlikely that catenary systems will be applied on all freight transport routes [21]. Possible developments of ERS will cover fixed shuttle services and motorway stretches with the highest intensities of truck traffic.

4.3 Refuelling infrastructure

Hydrogen Refuelling Stations (HRS) can be realised according to many different designs depending on how the hydrogen is produced, delivered, stored and dispensed. Hydrogen can be produced in central units and then delivered to the HRS by tube trailers, in gaseous or liquid form. Liquid hydrogen presents a higher storage density, and such trailers can transport more hydrogen than gas trailer. Another option is to supply gaseous hydrogen via pipeline. This could be the cheapest alternative for long transportation. However, hydrogen pipeline is available in limited regions in Europe, and the initial cost for building such infrastructure can be very high. Hydrogen can also be produced on-site with a local electrolyser integrated in the HRS. This configuration avoids fuel transportation from the production site to the HRS, which may be costly and inefficient, especially in remote areas (Figure 12).

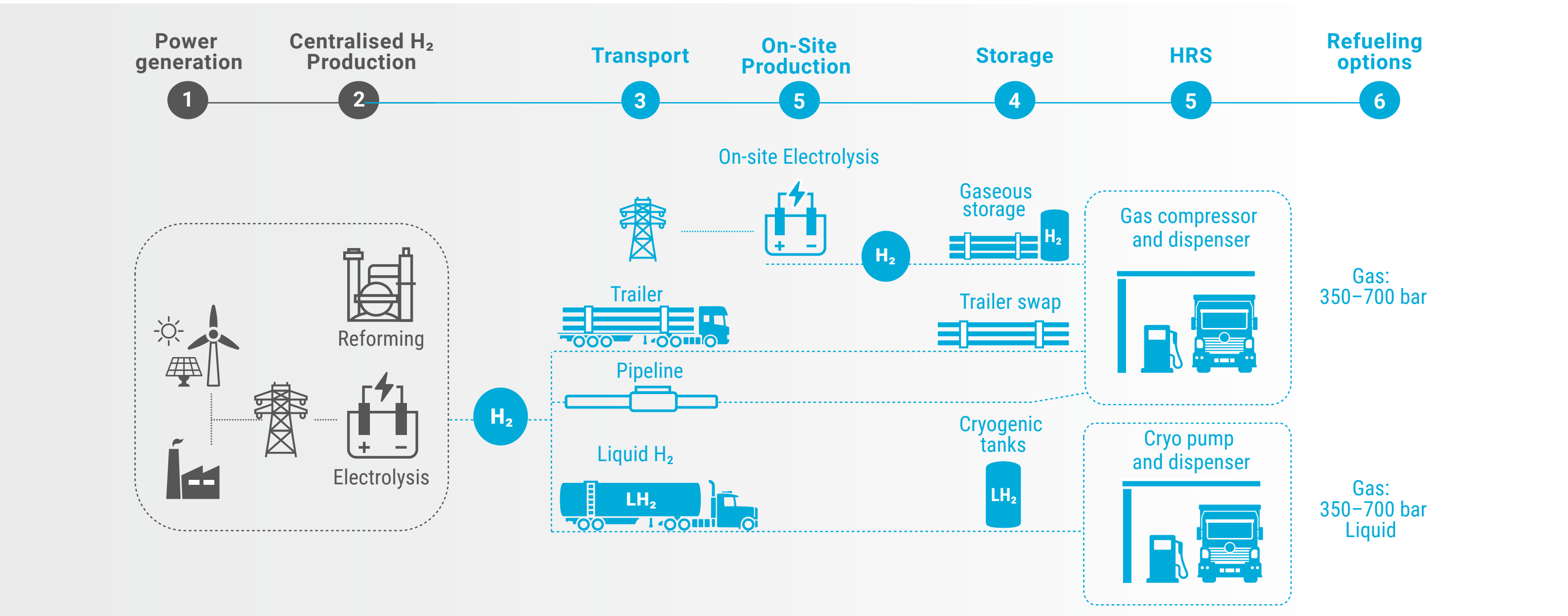


Figure 12: Hydrogen supply and refuelling system (RSE's elaboration based on [25]).

Refuelling options for Light Duty Vehicles (LDVs) and buses are already established: 700 bar gaseous refuelling for LDVs and 350 bar for buses [25]. For trucks, the 350-bar technology is suitable for short-range operations with lower hydrogen onboard storage requirements. On the other hand, the 700 bar technology would allow higher energy density and shorter refuelling time, desirable for long-haul operation. The first fuel cell trucks with 700 bar technology have been already announced. Another interesting option is to refuel HDV directly with liquid hydrogen. This solution is being pursued by one Original Equipment Manufacturer (OEM) to achieve high range (due to higher energy density), but supply infrastructures are not yet fully available.

A synthetic comparison of pros and cons of Battery and Fuel Cells drivers' experience (i. e. electricity charging and Hydrogen refuelling) is provided in Table 4, which can be analysed vis-à-vis the projected penetration of both technologies in different segments (Figure 11).

Different but complementary technologies	
Hydrogen refuelling station	**Megawatt charging station**
Fast refuelling in 10–15 min	Longer recharge time > 45 min–1 h with present technology; upcoming hyperchargers will handle the recharge in 15–30 min
Opportunity to optimise hydrogen production profile vs hydrogen consumption profile	High instantaneous recharge power
Lack of existent and capillary network	Ongoing infrastructure development
Technical complexity in refuelling operations	Easy plug-in and charging operations

Table 5: Comparison between electricity charging and hydrogen refuelling experiences (RSE elaboration based on [26])

HRS with on-site electrolyser

Hydrogen transport via road transport is expensive and energy consuming; for this reason, producing hydrogen on-site is an interesting option that can improve the energy efficiency, grid integration, costs and reliability of hydrogen supply. This configuration is particularly interesting from the grid perspective as it will require a proper and dedicated connection to the grid.

Efficiency: with on-site production there is no need for transporting hydrogen from a central unit to the HRS, which currently occurs by trailers, with additional consumption and emissions.

Grid integration: HRS equipped with on-site production requires adequate connection to the electricity grid depending on the hydrogen refuelling demand and the operation profile of the electrolyser. Once the connection to the grid is established, the HRS with on-site electrolyser can act as a balancer to the grid. 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 or energy, such as wind and solar power.

Costs: although a centralised system can achieve lower costs for hydrogen production, the higher cost for transporting hydrogen to the HRS might offset the advantages of large-scale hydrogen production.

Reliability: on-site production can increase the reliability of the refuelling station, which would not depend on an external supplier for the hydrogen supply.

5 Evolution of Zero-Emission HDV and infrastructures

5.1 Evolution of HDV fleets

BE vehicles will play a major role in urban and delivery medium-truck, while will share the market with the fuel cell technology in the long-haul application with predictable operation. It is expected that fuel cells could cover most of the long-haul segment with low predicable route and operation (Figure 13).

POTENTIAL LONG TERM POWERTRAIN SHARES BY SEGMENT AND USE CASE* (2040+)

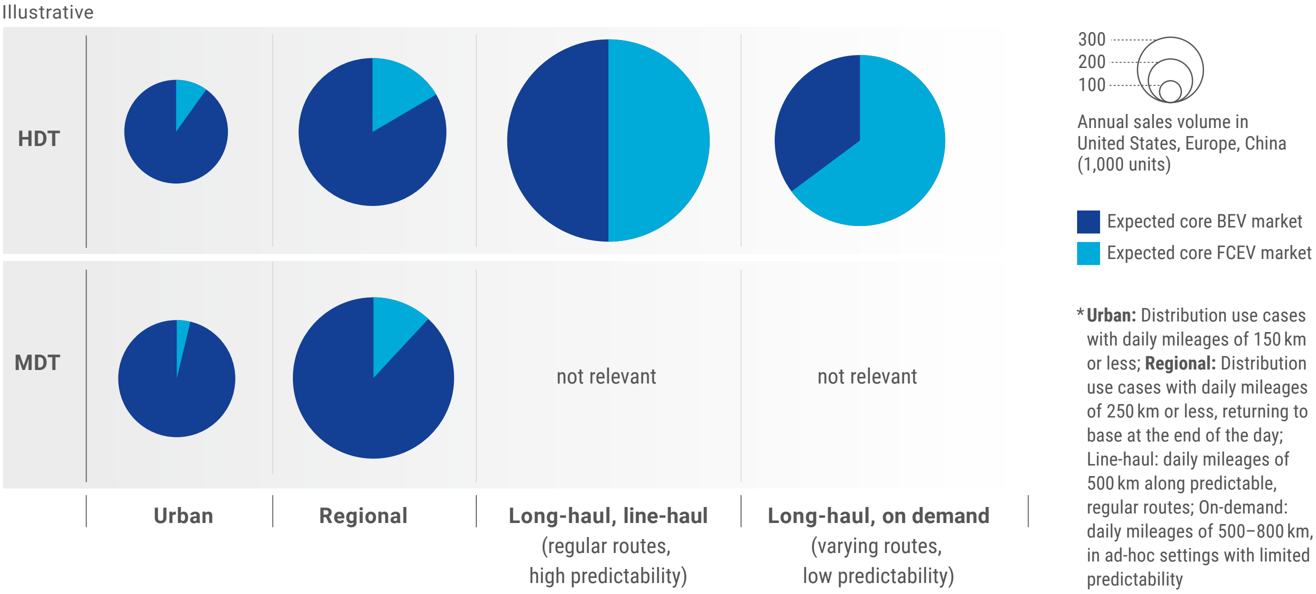


Figure 13: BE and Fuel cell powertrain share penetration (McKinsey & Company [32]).

5.2 Evolution of recharging network

The transition to decarbonised HDVs requires a contextual roll-out of a suitable public infrastructure, especially for long-haul operations. The AFIR proposal (Figure 14) specifically addresses dedicated targets for HDV public recharging/refuelling infrastructure:

- distance-based targets along the **TEN-T network**;
- targets for **overnight recharging infrastructure** in "secure and safe parking areas"; and
- targets at **urban nodes**.

The main remarks are:

- AFIR targets for both opportunity charging points at urban nodes and overnight public charging points in parking areas seem especially low compared to these sources.
- The minimum power output, especially for recharging points along motorways, should be revised. Power output levels of 350 kW are a good start for trucks with a high number of stops and longer mandated driver breaks but might not be sufficient in the event of driver's breaks being close to the legal minimum. Higher minimum levels of power output (> 500 kW) might be considered in the AFIR. The sector itself is also working on higher power output levels such as 1 MW and above.

PUBLIC ACCESS RECHARGING INFRASTRUCTURE SCENARIO (2030)

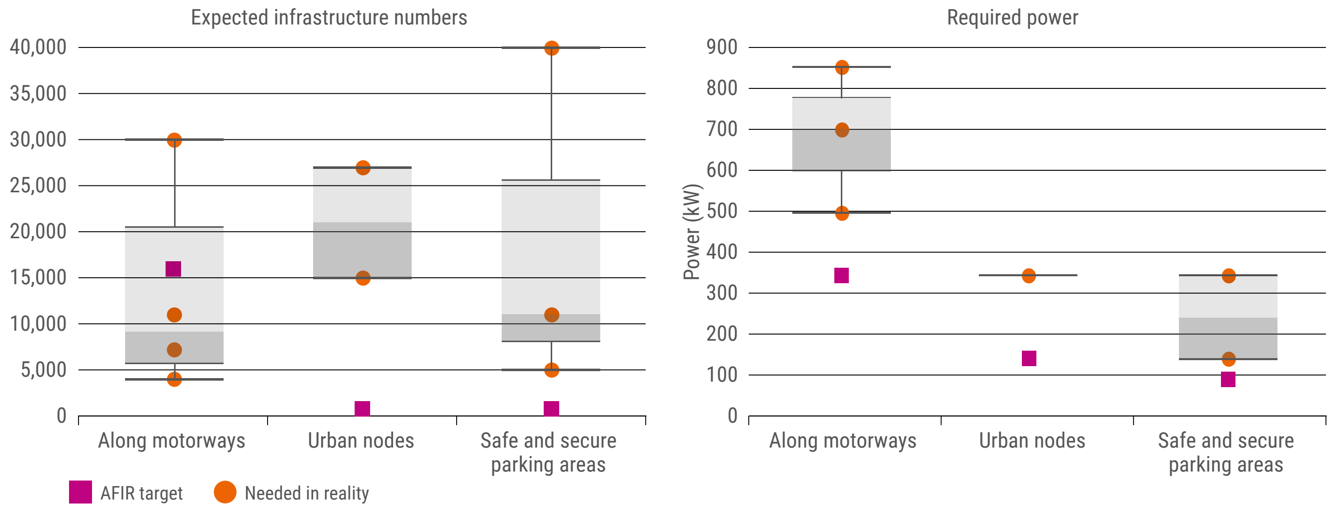


Figure 14: Public access recharging infrastructure scenarios (2030) [27] [34].

No targets are defined for private access locations. However, the parallel development of private infrastructure is crucial because overnight charging and destination charging are expected to cover most of the recharging needs. As the infrastructure realisation may be challenging for private actors, support from public authorities will be necessary. Projections for private accessible recharging (Figure 15) show that depot charging points are expected to be dominant, probably covering 80 % share of total energy demand [27].

PRIVATE ACCESS RECHARGING INFRASTRUCTURE SCENARIO (2030)

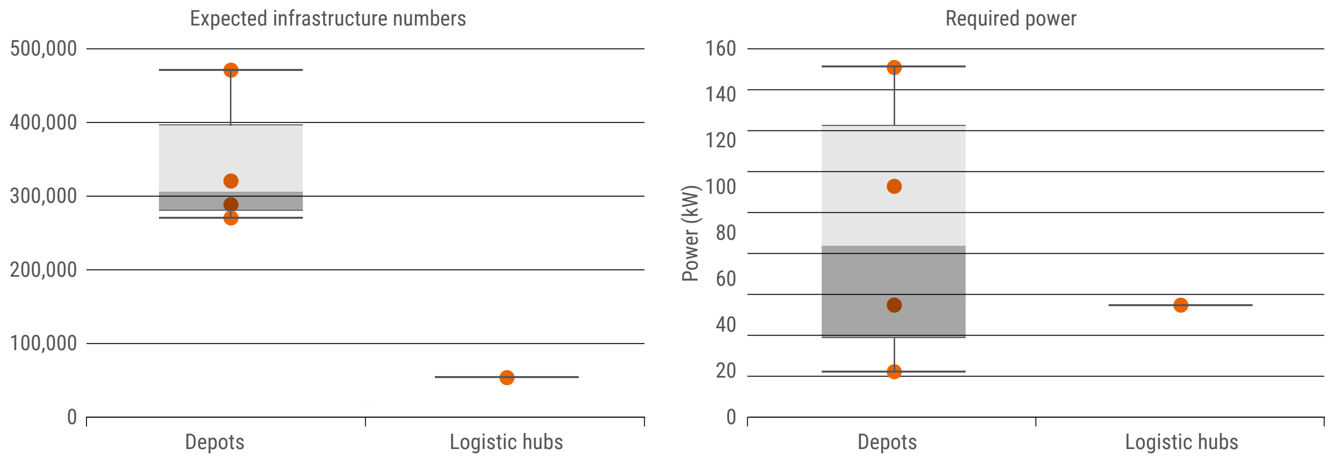


Figure 15: Private access recharging infrastructure scenario (2030) [27] [34].

5.3 Evolution of refuelling network

As of 2021, **144 HRS were in operation in Europe**, the majority of which are located in Germany, France, Denmark, the Netherlands and Belgium [28], mostly for passenger cars.

Regarding the general targets for the future deployment of hydrogen refuelling points, as set by AFIR, two discordant opinions have been found. Transport & Environment, in its reaction to AFIR proposal [29], notes that as it is not yet clear whether Fuel-Cell Electric Trucks will be a mass phenomenon, the European Council and Parliament should cut back on the hydrogen refuelling infrastructure ambition and focus on public funding for the mature technology of BE Trucks. Instead, ACEA reports that from the mid-decade on, the Fuel Cell models will increase significantly and be a suitable option for high payloads and long-haul operations. According to ACEA, a hydrogen refuelling station for trucks should have a minimum daily capacity of at least six tons of H_2 with at least two dispensers per station.

6 HDVs' impact on the power system

The significant energy and power demand from HDVs raises challenges regarding their impact on the electricity grids. On the other hand, HDVs present more predictable patterns compared to cars, especially buses and urban/regional trucks that travel on fixed predefined routes with return to-base operation. This facilitates the prediction of the charging behaviour and a good assessment of the recharging needs. This chapter discusses the integration of HDVs into the power system, including the forecast on electricity demand, the related recharge power, connection characteristics and potential for flexibility.

6.1 Electricity demand

Producing electricity for charging or hydrogen for refuelling will inherently increase the electricity demand from this segment. In Europe[3], BEV and Plug-In Hybrid Electric Vehicle (PHEV) buses are expected to ask for up to 30 TWh of electricity by 2030 (Figure 16). Similarly, electrified trucks will require almost 32 TWh of electricity by 2030 [24]. With respect to the overall demand from electrified road transport, which also comprises cars and vans, HDVs will also contribute to half of the total electricity consumption in 2030.

The electrification of HDVs will clearly play a relevant role in the electricity consumption from the transport segment. Despite this important contribution, HDVs will account for a minor share (approximately 3 %) of final electricity consumption in 2030. From these numbers, it emerges that the electrification of HDVs will not raise significant challenges to the power system in terms of electricity demand. As illustrated in the next section, the key implication for HDVs is their additional power demand regarding grid availability and capacity.

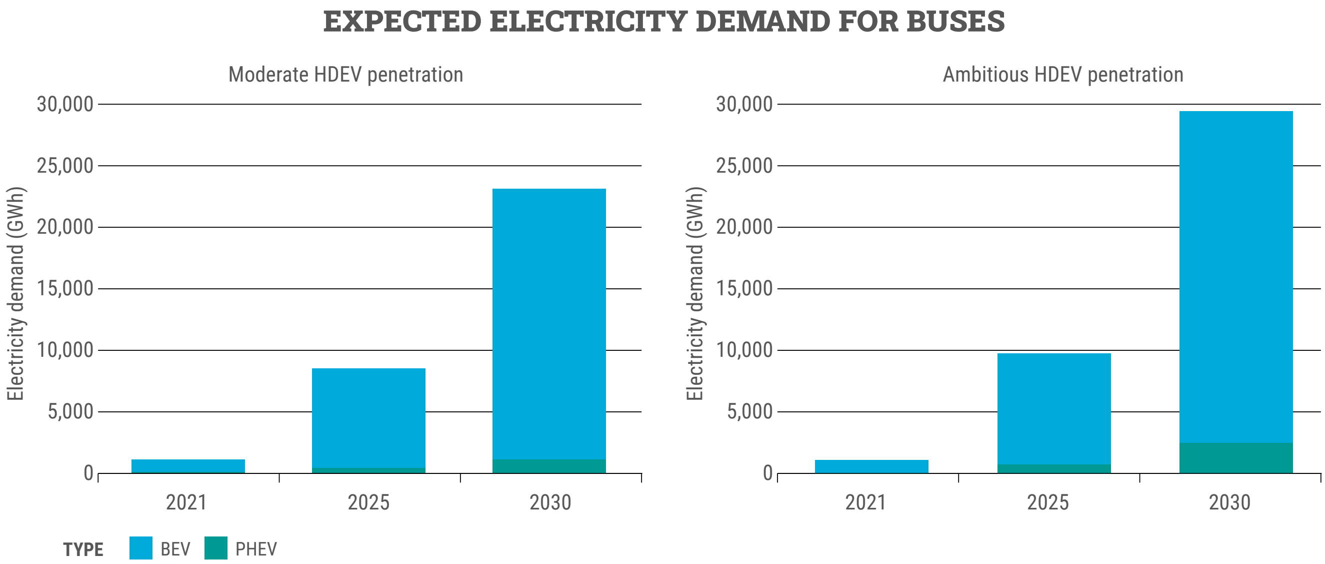


Figure 16: Expected electricity demand for buses in Europe (data based on [24]).

3 EU27, Norway, Iceland, Switzerland and United Kingdom.

EXPECTED ELECTRICITY DEMAND FOR TRUCKS

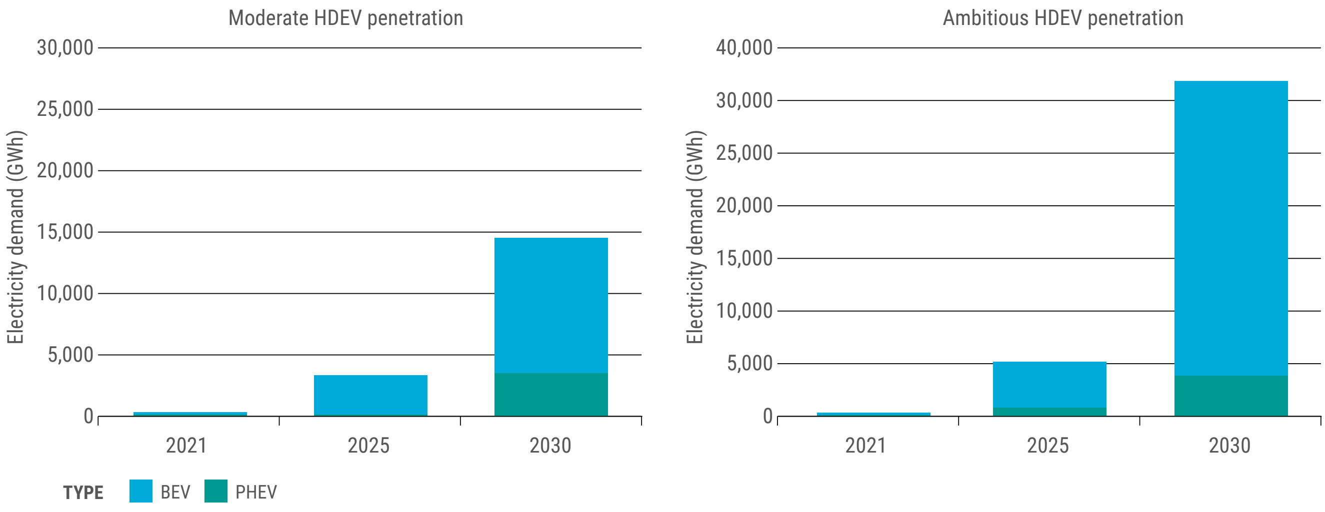


Figure 17: Expected electricity demand for trucks in Europe (data based on [24]).

6.2 Power demand and connection characteristics

The electrification of HDVs will indeed have a significant impact on demand profiles, particularly in terms of increasing the peak power load. This surge in demand will primarily occur during the late evening and night hours when vehicles return to the depots after their service. The peak power demand is a crucial factor for power systems, and it is estimated that by 2030, the simultaneous recharge of BE-HDVs will introduce a peak power demand of up to 20 GW, corresponding to approximately 5 % of the total peak power load.

Moving from peak power load form to the local power demand from ZE-HDV, the charging needs can be very different depending on the use cases. In the period to 2030, most of the HDVs will be involved in urban and regional duty, with :return-to-base operation. The recharging of this first wave of HDV will largely rely on depot charging.

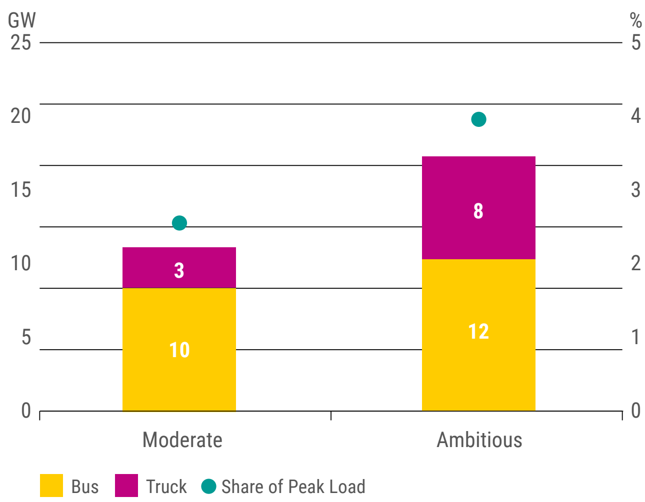


Figure 18: Peak power from HDEVs and contribution to overall load in 2030 (RSE elaboration based in IEA data [30].

6.2.1 Depot recharging

According to the literature, for trucks coming back to the depot, approximately 80 % of the energy recharged by electric trucks will be delivered at the depot [33], whereas destination charging covers 15 % of the total energy, and public charging about 5 %. New electric buses are equipped with battery packs (> 400 kWh) able to complete a single service day without intermediate recharge. This means that for buses, the share of depot charging can be even higher. The concentrated load from depot charging could reach up to 5–6 MW for fleet of 150 BE-HDVs. In the event this additional demand exceeds the available capacity of the local grid, upgrades became necessary. Network upgrades might encounter public opposition and land restrictions, especially if depots are located in dense urban areas. **Coordinated planning driven by early engagement of local authorities, fleet managers and grid utilities is essential to anticipate public acceptance and potential land use issues, and to establish a feasible and timely power-delivery schedule.**

6.2.2 Logistic Hubs

Logistic hubs represent an important location where both short-haul and long-haul trucks can exploit the loading/unloading stops for opportunity charging. The required capacity of the network connection here can range between 0.5 MW/hectare and 1 MW/hectare. An average logistics area with a size of approximately 125 ha implies a connection capacity of 60 MW. Strong HV networks in the vicinity of logistics hubs will therefore become crucial to enable HDV charging. Planning, permitting and construction of substations and HV lines usually take several years. **Advanced planning is key to ensure the timely delivery of new connections to logistic hubs.**

6.2.3 Long Haul

Long-haul BE trucks will necessarily rely on en-route charging to complete their long-range mission. The total installed power for BE-HDV charging along the TEN-T core is expected to range between 5 GW, according to the AFIR minimum target, up to 11 GW by 2030 [31]. Depending on the expected traffic volume, mega-charging stations along motorways will require 15–35 MVA network connections, which usually occur at high voltage level but can also occur at MV level, depending on Member State specificities. To ensure efficient and reliable charging, **coordinated planning** driven by the early engagement of fleet managers and relevant mobility and energy stakeholders is essential to establish a feasible and timely electricity infrastructure delivery schedule.

Thanks to this, TSOs can use a system-aware **proactive approach to pre-identify locations along motorways where the high voltage grid connection may be available or may be easily extended**. This – together with effective grid planning evaluations – will help to limit the cost of grid upgrades and ensure that the **charging infrastructure can be installed in a timely and cost-effective manner**. This also implies having **clear and non-discriminatory connection requirements for all "stationary" installations connected to the electricity network, in compliance with the standard categorisation in the Network Codes and harmonised requirements for onboard (movable) converters**.

6.2.4 Hydrogen stations with electrolysers

As recalled previously, due to the high cost of hydrogen transport, HRS in remote areas may be equipped with on-site electrolysers for local hydrogen production, in light of regulations for the definition of the location of hydrogen production as stated in the EU rules and methodologies. The size of the connection will depend on the hydrogen refuelling demand and the operation condition of the electrolyser. Assuming a non-stop electrolyser operation, a grid connection of 10 MVA satisfies an HRS with 4 tH_2/day capacity, which serves approximately 80 truck-refilling operations.

6.2.5 Recharging stations with stationary batteries

For all the previous cases, 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. However, 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.
- 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.

So far, it is not clear what the technology mix will be for the above use cases. In any case, all infrastructures would require powerful grid connections. **Grid operators, driven by a proactive approach, should plan the setting up of high-voltage connections to serve the major traffic corridors, to ensure that the grid is ready to accommodate the additional load from ZE-HDV.**

Use case	Grid impacts	Opportunities
Depot charging	Connections < 10 MVA.	High potential for implementing smart charging strategies (load shifting, off-peak charging) and demand response due to fleet predictability and long rest periods.
	Possible requirement of new MV connections and MV/LV substation upgrade.	Flexibility potential dependent on the fleet operation.
Logistic hub charging	Connections around 60 MVA.	During the day, limited flexibility potential, due to short breaks with durations close to the time needed for fast charging.
	Possible requirement of dedicated HV substations.	During the night, interesting opportunities for reducing energy procurement costs and facilitate RES integration.
HRS with on-site electrolyser	Connections of 15–35 MVA.	Limited demand response flexibility due to short surplus connection time.
	Possible requirement of MV/HV connections.	Possible higher power system participation if buffer electric storage (stationary battery) is installed.
En-route charging	Connection < 10 MVA (< 4 T H_2/day).	Opportunity to optimise hydrogen production vs refuelling request, no simultaneity between them.
	Possible requirement of new MV connections and MV/LV substation upgrade.	Possibility to adjust electrolyser working point depending on grid operation.

Table 6: Possible grid impact and opportunities per main HDV charging use case

6.3 Flexibility potential from HDV

The larger battery size and the higher charging power required by HDV might suggest great potential for flexibility. With smart charging infrastructure, and smart management capabilities, access to relevant data (from recharging infrastructure and vehicles), and updated rules, the charging process can be adapted to both the conditions of the power system and the needs of HDV operators, facilitating their integration into the grid. In general, flexibility services can be divided into three main segments in which HDV fleet can provide their support:

- **Wholesale market:** Varying pricing from spot market can drive the charging process, incentivising HDV fleet operators to exercise their flexibility, for example, by shifting the timing of charging, to minimise cost. Other opportunities include flattening the peak demand and filling the "valley" of demand by incentivising late morning/early afternoon charging in systems with high solar penetration, and nighttime charging following wind production. This would deter evening charging, which may otherwise increase peak demand.
- **System balancing:** a fleet of HDVs can adjust their charging levels to provide upward and downward regulation to support real-time system balancing. Technically, depots can participate in all three balancing types (Frequency Containment Reserve [FCR], automatic Frequency Restoration Reserve [aFRR] and manual Frequency Restoration Reserve [mFRR]), but FCR and aFRR are most suitable, given the batteries' potential to react to frequency deviations almost instantly.
- **Congestion Management:** a fleet of HDVs can also provide flexibility at distribution and transmission level by managing their power consumption for the purpose of congestion management. In this case, the physical location of the asset, such as an HDV depot, is crucial for solving spatial bottlenecks in the electricity network. An attractive market for congestion management with incentives for HDV and other decentralised assets is necessary to allow for the participation of flexibility service providers.

HRS with on-site electrolysers can also play a role in providing flexibility services to the grid. Electrolysers are controllable loads capable of adjusting their operating points. Thus, hydrogen can be produced opportunistically from the electricity grid and, once produced, conveyed in the storage unit. Technically, electrolysers can participate in frequency services, voltage control and congestion management. Flexibility also increases in the case of oversized electrolysers and a more powerful connection to the grid. However, response time and controllable range of power are critical parameters. Commercially available electrolysers are not designed for quick responses but rather for long-duration hydrogen production. Specific control systems might be required to exploit the full capability of electrolysers.

Although research on the HDV flexibility potential is still in its infancy, some authors have started investigating the potential for HDV smart charging, and some main trends can already be identified:

- **Depot charging**, especially overnight, is the best candidate for implementing **smart charging** strategies, due to the long rest periods.
- **The HDV impact on the grid can be reduced through mitigation strategies**, most of which consist of flattering the peak demand and pricing schemes that encourage off-peak charging.
- **Smart pricing and time-varying network tariffs can encourage smart charging behaviour** by accurately reflecting the true cost of using the grid; this incentivises transport operators to integrate their HDVs and other flexible resources into the grid in a manner that benefits everyone.
- Smart charging can offer **financial benefit for fleet operators**.

More research and demonstrations with end-users are necessary to fully understand the charging opportunities, costs, and framework conditions for enabling flexibility services from HDV charging. TSOs can collaborate with stakeholders such as fleet operators and manufacturers by introducing pilots to **gather experience** on the grid impacts and customer acceptance of time-varying tariffs, and to assess the actual flexibility potential.

6.4 TSO hands-on experience

TSOs are also participants in the deployment of the necessary infrastructure for the decarbonisation of the transport sector. Several examples are highlighted below where TSOs show their proactive attitude to anticipating the EV Infrastructure through coordinated planning and innovative solutions to foster the transport sector integration.

TSO Projects Promoting the Integration of EV Infrastructure

GreenSwitch Project – ELES (Slovenia)

This project aims to identify the optimal locations regarding both power availability and transport HDV demand. A long multiyear procedure was required to prepare a state spatial plan with environmental compliance for all investments into the HV infrastructure. ELES addressed this by proactively involving local municipalities and Distribution Grid Operators, and by fostering the deployment of electric public transportation. Projects proposed as common interest projects (state-municipality) required the preparation of a much faster municipal spatial plan. Two charging parks under construction, Novo Mesto and Kranj, feature direct proximity to electricity infrastructure and highways to address current and future transportation demands. Recently, ELES has obtained an official mandate to develop multiMW Hypercharges on the main highways as part of National Grid development.

In addition, ELES is developing a planning tool which represents a digital twin of the electro-transport system and comprises five crucial models (road, mobility, space, power, price) and an AI-based orchestration service that combines models into a powerful analytical tool.

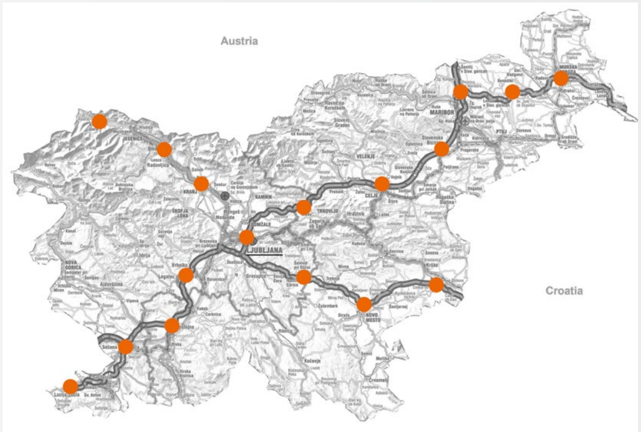


Figure 19: Optimal EV Locations (reference https://www.greenswitchproject.eu/)

Speed-E Project– REN (Portugal)

The Portuguese TSO REN has developed an innovative grid connection solution to supply EV charging directly from existing transmission lines. The innovative solution includes a tap to an existing transmission line and a special small substation that transforms directly from Very High Voltage to Low Voltage using Power Voltage Transformers, to supply EV charging points.

This solution complements the conventional solution of supplying EV charging from the distribution grid, contributing to solving potential constrains in the distribution grid induced by the new power demand associated to EV adoption. In addition, it enables the TSOs to have an active role in contributing to address the challenges associated with the electrification of mobility, in cooperation with distribution system operators, particularly in remote areas where distribution network is weak.

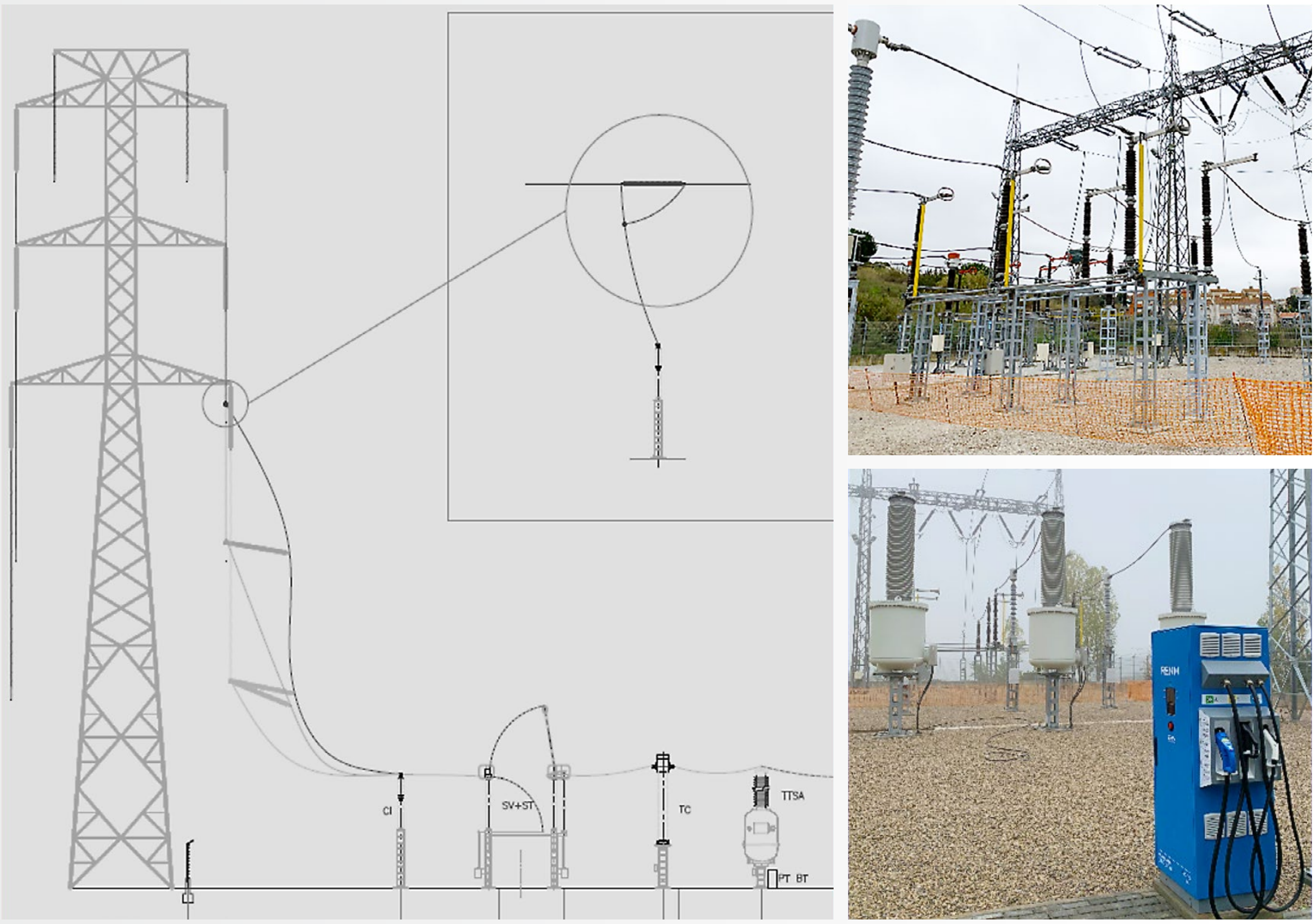


Figure 20: Schematic of the architecture of the REN solution (reference https://www.speed-e.pt/en/index.html).

7 Conclusions

This Position Paper assesses the most relevant characteristics of the deployment of the HDV segment, with a particular focus on its impacts on the electricity network. The common efforts from European decision-makers towards a massive integration of electric vehicles (direct and indirect electrification) set the stage for a rapid increase of these technologies and put pressure on electricity network operators to anticipate the oncoming challenges to accommodate the extra capacity required in the coming decades. The development of suitable charging infrastructure and the adoption of smart charging strategies currently represent a major gap for all relevant stakeholders in the electromobility value chain.

After a deep assessment within our TSO Members, ENTSO-E considers electromobility as a powerful resource for both the decarbonisation of the transport sector and for the optimal provision of flexibility services. An optimal vehicle-grid interaction will guarantee environmental and economic value for European citizens while improving the reliability of the electricity system. Thus, all the involved actors should cooperate to promote the deployment of necessary transport infrastructure in a coordinated and proactive manner.

The electromobility environment has become extremely dynamic, so ENTSO-E is proposing key messages according to the key findings of the assessment described in this Position Paper. This aims at setting up a sound and sustainable framework for the deployment of HDVs and to take advantage of the existing synergies and opportunities. Positive effects will be shared among different stakeholders, first and foremost the European citizens, who are final users of both energy and mobility services, and who shall benefit from cleaner transport and energy systems.

8 References

[1] AFIR: Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU [Online], Available **here**.

[2] European Commission: "Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2019/1242 as regards strengthening the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, and repealing Reg," 2023.

[3] European Environment Agency: "Decarbonising road transport – the role of vehicles, fuels and transport demand," EEA, 2021.

[4] ACEA Trucks factsheet. Available **here**.

[5] ACEA Buses factsheets. Available **here**.

[6] European Commission: "Sustainable and Smart Mobility Strategy – putting European transport on track for the future," 09 12 2020. Available **here**.

[7] CECE and CEMA: "Reducing CO_2 emissions: the potential of modern agricultural & construction machinery," 2018. Available **here**.

[8] European Commission: "Questions and Answers: Revision of the CO_2 emission standards for Heavy-Duty Vehicles," 14 February 2023. Available **here**.

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

[10] Fraunhofer ISI: "Truck Stop Locations in Europe," 2021. Available **here**.

[11] Agora and Transport & Environment, "Elektro-Lkw schneller auf die Straße bringen", 2022.

[12] National Renewable Energy Laboratory: "Drive Cycle Analysis Tool". Available **here**.

[13] CALSTART, "Global commertial vehicle – Drive to Zero". Available **here**.

[14] ICCT report "Heavy-duty zero-emission vehicles – Pace and opportunities for a rapid global transition, International Council on Clean Transportation", May 2022.

[15] Plötz, Patrick – Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany: "Hydrogen technology is unlikely to play a major role in sustainable road transport", 31 January 2022.

[16] DAF: "DAF introduces charging stations for electric vehicles", Available **here**.

[17] Charin: "How to prepare for the Megawatt Charging System: The business case for co-investment in CCS and MCS", 2022. Available **here**.

[18] ABB: "Electric bus pantograph up". Available here.

[19] Siemens: "Fast Charging Systems for eBuses". Available here.

[20] IPT Technology: "IPT Charge Bus". Available here.

[21] 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.

[22] Electreon: "Wirelessly charge electric vehicles". Available here.

[23] 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.

[24] IEA: "Global EV Outlook 2022", 2022.

[25] H_2 Mobility: "Overview Hydrogen Refuelling For Heavy Duty Vehicles", 2021.

[26] Fuel Cells and Hydrogen 2 Joint Undertaking: "Hydrogen Roadmap Europe", 2019.

[27] E-Laad: "Truckers komen op stroom", 2020. Available here.

[28] Clean Hydrogen JU: "HRS Availability Map", European Commission. Available here.

[29] Transport & Environment: "AFIR - Heavy Duty Vehicles", 2021.

[30] International Energy Agency: "Global unmanaged and night charging EV load profiles in the Sustainable Development Scenario 2030", 2023. Available here.

[31] ICCT: "A Review Of The Afir Proposal: Public Infrastructure Needs To Support The Transition To A Zero-Emission Truck Fleet In The European Union", 2022. Available here.

[32] McKinsey & Company: "Preparing the world for zero emission trucks", 2022.

[33] Transport & Environement, "Unlocking electric trucking in the EU: recharging in cities", 2020. Available here.

[34] ACEA, "Heavy-duty vehicles: Charging and refuelling infrastructure," 2021. Available here.

Abbreviations

AFIR	Alternative Fuel Infrastructure Regulation
aFRR	automatic Frequency Restoration Reserves
BE	battery electric
BE-HDV	Battery Electric pack HDV
BESS	Battery Energy Storage Systems
BEVs	battery electric vehicles
CECE	Committee for European Construction Equipment
CEMA	European Agricultural Machinery Industry Association
CO_2	Carbon-dioxide
ENTSO–E	European Network of Transmission System Operators
EU	European Union
ERS	Electric Road Systems
FC	Fuel-Cell
FCR	Frequency Containment Reserve
FC-HDV	Hydrogen Fuel Cell HDV
GHG	Green House Gas emissions
HV	High Voltage
HDVs	Heavy-Duty Vehicles
HRS	Hydrogen Refuelling Stations
HVDC	High Voltage Direct Current
LDVs	Light Duty Vehicles
LV	Low Voltage
ICE	Internal Combustion Engine
mFRR	manual Frequency Restoration Reserves
MV	Megavolt
MVA	Megavoltampere
OEM	Original Equipment Manufacturer
PHEV	Plug-In Hybrid Electric Vehicle
RES	Renewable Energy Sources
TCO	Total Cost of Ownership
TEN-T	Trans-European Transport Network
TSOs	Transmission System Operators
TYNDP	Ten-Year Network Development Plan
ZE-HDVs	Zero-Emission HDVs
ZLEVs	Zero and Low Emission Vehicles
V2G	Vehicle-to-Grid

Contributors

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