

Review

Electric Vehicle Charging Infrastructure along Highways in the EU

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Abstract: One aspect of the competitiveness of electric and plug-in hybrid vehicles is the ability to recharge batteries quickly. Ideally, this process would take no longer than it takes to refuel vehicles powered by conventional fuels. The term fast charging is generally used to refer to alternating current (AC) charging of more than 22 kW and direct current (DC) charging often referred to as fast or ultra-fast charging at high power. Currently, fast charging points are located within the public charging infrastructure, mainly along highways. The purpose of this paper was to analyze the availability of existing charging infrastructure equipped with fast charging points for electric vehicles in European Union countries. In addition, the paper discusses EU policy in terms of zero-emission vehicles and technical issues related to charging infrastructure. Based on a review of the current state of charging infrastructure and plans for its development in light of the EU Green Deal for Europe regulations, it can be concluded that in many regions the fast charging infrastructure for electric cars is still insufficiently developed. Due to the great economic diversity of EU countries, the development of charging infrastructure proceeds at different paces. For this reason, it is important to ensure that fast charging points are located primarily along the TEN-T network and highways.

Keywords: electric vehicle; plug-in hybrid; electric vehicle charging infrastructure; fast charging



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1. Introduction

Transport is the process of moving people, raw materials and goods from the place of origin to the place of destination. Road transport still has the largest share in the transport of goods and passengers. It was estimated that in 2020 the total freight turnover in the EU-27 amounted to 3272 billion tkm. Road transport accounted for 53% of this sum. In 2020, the total transport performance of passenger transport in the EU-27 using motor vehicles was 4446 billion pkm, i.e., the average distance per person was about 10,000 km. Passenger cars accounted for 80.6% of this number, while buses and coaches accounted for 6.6% [1].

Transport is also one of the most energy-intensive sectors of the EU economy. In 2020, the energy used for transporting materials and services accounted for 28.4% of the total energy used by the EU economy. Road transport is still almost entirely dependent on fossil fuels. About 95% of all road vehicles still use conventional fuels (diesel, petrol, compressed natural gas—CNG, liquefied petroleum gas—LPG). The development of the alternative fuels market is hindered, apart from higher vehicle purchase costs, by the lack of charging and refueling stations. In 2020, the total consumption of motor gasoline and diesel in transport amounted to 218,917.6 ktoe (ton of oil equivalent—a conventional standardized energy measure, based on a ton of oil with a calorific value of 41.868 kJ/kg) [1,2].

Between 1990 and 2018, total carbon dioxide emissions of the EU fell by 21.6%. Over that same period, emissions declined in all sectors except the transport sector, which saw a 21% increase in CO₂ emissions [3,4]. Transport is responsible for around 20% of global greenhouse gas emissions, three-quarters of which are accounted for by road transport

(76.7%) [5]. In the EU in 2020, the largest part of emissions was related to passenger mobility and came from passenger cars (59.5%) and buses (11.0%). The remaining 28.2% came from freight trucks [6].

The solution to reducing greenhouse gas emissions in road transport is to increase the number of low- and zero-emission vehicles powered by alternative fuels, such as electricity, hydrogen, biofuels or biogas. EU activities in the field of climate and transport policy are focused on promoting energy-efficient and ecological transport. Many automotive concerns have decided to develop new technologies in the field of electric and hydrogen drives. The idea of electromobility implies an increase in the importance of electric forms of both public and individual transport.

Currently, the electric vehicle market is boasting impressive growth. Thanks to the development of battery technology and the extending range, electric vehicles (EVs) are gaining more popularity. The main advantages of the electric drive are the low noise level and zero emission of harmful substances at the place of operation. Another advantage is the high efficiency of the electric drive. The main disadvantage of electric vehicles is their range. Electric vehicles on a single battery charge still have a shorter range than vehicles with combustion engines, gasoline or diesel [7,8]. The disadvantages of electric cars include the long battery charging process, much longer than refueling. This process is cumbersome for the user, especially during long journeys, as it involves the need to properly plan the route. The charging time of an electric vehicle battery depends on the following factors:

- Energy capacity of the battery (measured in kWh);
- Battery energy level (SOC—state of charge);
- Technically available maximum vehicle battery charging power;
- Technically available maximum power of the charging point—slow, fast and ultra-fast chargers;
- Ambient temperature.

Many papers present an analysis of the efficiency and cost of ownership of electric vehicles [9–11]. Considerably fewer works are concerned with the analysis of electric vehicle battery charging infrastructure facilities. They mainly concern methods of planning and assessing the deployment of charging infrastructure in relation to current and future potential demand. These papers present optimization algorithms for the allocation of charging stations [12–14]. The process of planning the charging infrastructure mainly takes into account the EV users' point of view regarding economic aspects or technical requirements of the power grid.

As shown in the works [15–18] the availability of public charging points is one of the key factors determining the willingness to purchase electric vehicles. The finding of the research presented in the paper [19] shows that the location and density of charging station networks are important aspects that can lead to greater acceptance of EVs and help overcome the phenomenon of range anxiety. As emphasized in the works [20,21] the location of EV charging stations should be comparable to the location of refueling stations with conventional fuels. Availability of public charging stations still needs to be improved in many regions and towns [22–24]. The EU takes action to stimulate the development of electric vehicle infrastructure. In its 2019 Green Deal for Europe, presented in 2019, the European Commission assumes an increase the number of charging stations and charging points for passenger cars and heavy-duty vehicles along the TEN-T trans-European road network.

A number of works provide an overview of electric vehicle charging infrastructure. Many of them present the technical requirements for charging points and the charging process itself. Many works also present the current state of charging station locations. Electric vehicles are already widely used mainly by city dwellers. In addition to daily city driving, electric vehicle users may also choose to travel further afield. Currently, charging an electric vehicle's battery still takes several times longer than refueling a conventional vehicle. Charging with fast chargers can take 20 to 30 min. Traveling long distances in an electric car requires careful planning of the route, taking into account the available charging

infrastructure and the time spent on charging. This prompted the author to investigate the current state of electric vehicle fast-charging stations along highways. In addition, this article aims to discuss EU policy in terms of zero-emission vehicles and to analyze the currently available EV charging infrastructure along high-speed roads in EU countries.

The European Union promotes the electrification of means of transport. Due to the different level of development of the electric vehicle market in the member states, there is also a different rate of availability of charging infrastructure. The motivation for this work was to present an analysis of the available infrastructure for fast charging of electric vehicles in EU countries. The analyzes presented in the work show the share of fast chargers in the total charging points in the EU, as well as indicators of the availability of charging points per 100 km of TEN-T, or the number of charging points for every 100 km of 100 km roads by EU country.

2. EU Policy in Terms of Sustainable Transport and Low-Emission Vehicles

The area of the European Union is very diverse both due to the different level of socioeconomic development and environmental pollution. Therefore, all political and legal actions related to EU transport and climate policy must be balanced. Actions undertaken by the EU should not weaken the economies of the member states but should help the environment and societies. EU activity in the field of the transport sector is aimed at reducing its emission intensity, expanding common modern transport networks and increasing the share of low-emission means of transport.

An important document in the area of common EU transport is the Transport White Paper. The first white paper on transport was announced on 2 December 1992. The document was established on the future development of the common transport policy, assuming the opening of transport markets, development of the trans-European network, improvement of safety and unification of social legislation [25].

A transport white paper entitled “Fair payment for infrastructure use: a phased approach to a common transport infrastructure charging framework in the EU” was published on 22 July 1998. The document defines a community approach to the issue of charging for the use of infrastructure. It also identifies four main goals of improving the overall efficiency and use of Europe’s transport infrastructure, promoting fair competition, on ensuring a single market, and improving the stability of the transport system [26].

In the white paper of September 2001 entitled “European transport policy for 2010: time to decide”, the European Commission analyzed the problems and challenges facing the European transport policy in the perspective of the then-upcoming EU enlargement to the countries of central and eastern Europe. One of the objectives was to develop the Trans-European Network (TEN-T) to adapt it to the needs of the broadened Union [27].

On 28 March 2011, the European Commission published a white paper on transport entitled “Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system”. The main objectives presented for achievement were as follows:

- Integration and unification of transport in Europe;
- Significant reduction of CO₂ emissions through the development of modern technologies in internal combustion engines;
- Increasing the activation of cleaner and more efficient means of transport by promoting zero- and low-emission means of road transport and improving the environmental awareness of the societies of member states.

In addition, the document contains a postulate to reduce emissions from transport by 20% in the years 2008–2030 (excluding international maritime transport), and in the period 1990–2050 by at least 60%. The 2011 white paper advocated halving the number of conventionally fueled cars in urban transport by 2030 and phasing them out completely by 2050 [28].

An important document for the promotion of low-emission means of transport is the “Communication from the Commission to the European Parliament, the Council, the

European Economic and Social Committee and the Committee of the Regions Clean Power for Transport: ‘A European alternative fuels strategy’”, published in January 2013. The strategy aims to gradually replace petroleum-based fuels with alternative fuels and develop a long-term policy framework to guide technological development and investment in the diffusion of alternative fuels [29].

The European Union has been working strongly in the fields of environmental protection and global warming in the international arena. The EU was a promoter and supporter of the approval of the Kyoto Protocol. The treaty entered into force on 16 February 2005. The Kyoto Protocol is an international agreement to combat global warming that complements the United Nations Framework Convention on Climate Change. Countries that have decided to ratify the Kyoto Protocol have committed themselves to reducing their greenhouse gas emissions by 2012 by at least 5% of the 1990 level [30].

In 2016, the European Commission published a communication entitled “A European Strategy for Low-Emission Mobility”, which proposed policy measures to accelerate the decarbonization of European transport [31]. The strategy outlines measures to achieve zero carbon emissions, the target set in the 2011 white paper. It also proposes measures to adequately contribute to the objectives of the Paris Agreement.

Based on the above-mentioned documents, the main objectives of the EU policy in the field of transport are:

- Accelerating the deployment of low-carbon alternative energy for transport, from advanced biofuels, electricity, hydrogen and renewable synthetic fuels;
- Removing obstacles to the electrification of transport;
- Transition towards low- and zero-emission vehicles through incentives for the purchase of low-emission alternative energy sources and vehicles, incentives for active travel (cycling and walking), use of public transportation, and car-sharing/pooling schemes;
- Increasing the efficiency of the transport system by maximizing the use of digital technologies, smart pricing and developing infrastructure for low-carbon means of transport.

Another major international treaty promoted by the EU was the Paris Agreement signed in 2015 at the 21st UN Climate Change Conference. The countries that decided to sign the agreement committed themselves to presenting long-term scenarios for reducing greenhouse gas emissions by 2020. One of the main goals of the Paris Agreement was to limit global warming to less than 2 °C and ultimately to 1.5 °C above pre-industrial levels in order to limit the risks and damages caused by climate change [32].

An important internal document regulating the EU’s climate policy is the Green Deal for Europe presented by the European Commission in 2019. The document was established to enable easier overcoming of economic and environmental challenges faced by European transport policy. The GDE assumes achieving zero net greenhouse gas emissions by 2050. The intermediate goal by 2030 is to reduce net greenhouse gas emissions by at least 55% compared to 1990 levels. The document also contains legal regulations responding to the challenges in the transport sector related to reducing energy consumption and increasing the use of the so-called clean energy, more effective use of modern infrastructure and reducing the impact of the economy on the environment [33].

On 14 July 2021, the European Commission announced a package of legislative proposals called Fit for 55. They aim to align EU policies on climate, energy, land use, transport and taxation to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Emission limits for passenger cars and vans have been tightened. Starting in 2030, new cars are expected to emit less CO₂ (compared to 2021) passenger cars by 37.5%, and light commercial vehicles by 31%. CO₂ emission limits have also been adopted for trucks and other heavy-duty vehicles. The new regulations require manufacturers to reduce CO₂ emissions (compared to 2019) by 15% from 2025, and then by 30% from 2030 [34].

Fit for 55 assumes that from 2035 all new passenger cars and light commercial vehicles will be completely emission-free. The regulations require EU member states to expand

electric vehicle charging infrastructure and hydrogen refueling stations. In addition, there are plans to increase the use of sustainable fuels in air, road and maritime transport.

The aforementioned documents show that the actions of the European Union taken over the years are aimed at a significant reduction of greenhouse gas emissions in transport and the promotion of low-emission vehicles. In recent years, there has been a notable trend towards promoting electric vehicles. All new cars and light duty vehicle sold in the EU from 2035 are expected to be zero-emission. With the growing number of electric vehicles, there is a risk of a shortage of charging points.

One of the EU's objectives is to support the transition to zero-emission transport by increasing the network of available charging points for electric cars. To protect against the possibility of a lack of available charging infrastructure, the EU has established directives and regulations on the development of charging infrastructure for electric vehicles. The development of the charging network in the EU is a challenge, given the much slower pace of development of electromobility in central and eastern Europe compared to western Europe. The goal of EU policy is to afford EV users the opportunity to use EVs in every member country, as well as when travelling around the EU on the main highways. It is also important that stations and charging points are technically standardized across member states.

3. Technical Requirements and Classification of Charging Stations

This section discusses the technical requirements for electric vehicle charging stations and points in the European Union. In addition, the classification of charging points and charging systems is discussed.

3.1. EU Legal Framework for Charging Infrastructure

Technical requirements and legal regulations regarding charging infrastructure for electric vehicles were included for the first time in Directive 2014/94/EU on the deployment of alternative fuels infrastructure, also called AFID—Alternative Fuels Infrastructure Directive. The AFID assumed that by 2020 there should be one publicly available charging point for every 10 registered electric vehicles [35]. In 2021, the AFID was repealed and replaced by regulation on the deployment of alternative fuels infrastructure, called AFIR—Alternative Fuels Infrastructure Regulation. The AFIR objectives become binding for EU Member States and are intended to ensure a balanced development of alternative fuel infrastructure across the EU.

The AFIR assumes that the growth of the electric car fleet will be associated with an increase in the capacity of public charging infrastructure. The AFIR imposes specific and stringent requirements for alternative fuel infrastructure, indicating a deadline for achieving infrastructure targets, defined distances between charging points, specific power and charging point capacity. According to the AFIR assumptions, charging stations for light vehicles on the TEN-T network should be located at least every 60 km. By the end of 2025, each station should have a total capacity of 300 kW, of which at least one charging point should have a capacity of at least 150 kW. By the end of 2030, the total power of the stations is expected to double (up to 600 kW), as will the number of points with a capacity of at least 150 kW. Charging stations for heavy vehicles will also be placed every 60 km. By the end of 2025, each of the stations should have a total capacity of 1400 kW, of which at least one point with a capacity of at least 350 kW. By the end of 2030, the total power of the station is to increase to 3500 kW, and there must be at least two points with a power of 350 kW. The requirements for the comprehensive TEN-T network have been set the same as for the base network, although the time for their implementation has been extended (until the end of 2030 and 2035, respectively). AFIR also indicates requirements for hydrogen refueling stations on the TEN-T core network. By the end of 2030, hydrogen refueling stations equipped with a dispenser with a capacity of at least 700 bar are to be available at least every 200 km [36].

According to the assumptions of Fit for 55, by 1 January 2024, Member States are obliged to send the European Commission a project regarding the deployment of appropriate infrastructure and a framework for the development of the domestic alternative fuels market in the transport sector.

Technical guidelines and legal regulations regarding charging stations for electric vehicles in the European Union are included in Directive (EU) 2018/844 [37]. According to the aforementioned directive, EU member states are obliged to:

- Ensure the construction of easily accessible infrastructure that will reduce the costs of installing charging points for individual owners;
- Provide electric vehicle users with access to charging points;
- When implementing electromobility requirements in national legislation, take into account the different conditions regarding, for example, the ownership of buildings and adjacent car parks, the role of private entities managing public car parks or the various functions of facilities (residential and nonresidential).

3.2. EV Charging Station Classification

Wired charging is mainly carried out at publicly accessible points in the EU. It involves the physical connection of the vehicle to the charging point using a wire. With wired charging, depending on the charging voltage, special plugs are used. The charging process is restricted by a number of standards that define the maximum power, charging current voltage, charging current, plug type and charging method.

It is within the competence of the European Commission to establish uniform guidelines for electromobility in terms of basic equipment for parking spaces and installation of charging points in the European Union. Directive 2014/94/EU defines a recharging point as a device that enables the charging of a single electric vehicle or the replacement of the battery of a single electric vehicle. In addition, the Directive includes the concept of a “recharging or refueling point accessible to the public”, which is defined as a recharging point that allows users across the EU nondiscriminatory access and may imply different conditions for authentication, use and payment [35]. Due to the general nature of this definition, some member states define as open to the public those recharging points that are located in public places and are accessible 24 h a day, seven days a week. Partially open to the public are those points that are only accessible during certain hours and under certain conditions of use (such as the requirement to use the associated car park, hotel or shopping mall).

Pursuant to the directive of 30 May 2018, by 1 January 2021, entrepreneurs and investors are required to equip all new and modernized residential buildings with at least 10 parking spaces with infrastructure that will enable the installation of electric car charging stations. Commercial facilities will have to provide 20% of parking spaces with access to such infrastructure [37].

A public charging point for electric cars should be equipped with the appropriate type of plug and security systems (e.g., a residual current device), a user manual, software with a measurement and billing system and a data transmission modem. Appropriate markings, information and warnings, e.g., about hazards, should be provided at stations. For very high-powered DC chargers, additional protection against overvoltage, electric shock and damage is required [38–40].

Public charging points can be direct current or alternating current. At alternating current charging points, the AC (alternating current) taken from the power grid flows in a controlled manner through the charging station via the charging wire to the vehicle. The AC/DC inverter installed in the vehicle, the so-called on-board charger, converts alternating current into direct current (DC), which then charges the battery. AC charging stations do not require electronic conversion systems, which makes them cheaper and chosen mainly by private EV users. Depending on the charging point, charging wire and on-board charger, the maximum AC charging power of the charging point is up to 22 kW. Significantly higher charging powers of up to 500 kW (high power charging—HPC) are possible at DC charging

points. That is why they are called fast charging points or ultra-fast charging points. At DC charging points, the conversion of alternating current drawn from the power grid into direct current takes place using electronic systems that are at the charging station. This is one of the reasons why DC charging is more complicated and expensive. DC charging stations are mainly located at gas stations or public parking lots along highways [41,42].

In Directive 2014/94/EU, charging points are distinguished as standard (<22 kW) and fast (>22 kW) [35]. As a result, charging points below 22 kW are considered equal to those with a charging power of 350 kW, despite the significant difference in charging time.

Another classification of electric vehicle charging points can be carried out due to the maximum available charging power depending on the type of power supply. Due to the charging power, AC-powered stations are divided into:

- Points with a charging power below 7.4 kW—called slow AC recharging points, charge with single-phase alternating current; depending on the battery capacity, the charging time can be from 2 to more than 6 h;
- Points with charging power in the range of 7.4 kW to 22 kW—known as medium speed AC recharging points, powered by three-phase alternating current; according to the battery capacity, the charging time can be from 2 to more than 6 h;
- Points with a charging power above 22 kW—called fast AC recharging points, enable quick charging of electric vehicles with three-phase alternating current; charging the battery of an electric vehicle may take less than 1 h.

DC charging points are differentiated according to charging power as follows:

- Points with a charging power below 50 kW—the slowest among DC chargers, called slow DC recharging points—allow batteries to be charged in up to 1 h;
- Points with charging power in the range from 50 kW to 150 kW—known as fast DC recharging points—where battery charging time can be 30 to 40 min;
- Points with charging power ranging from 150 kW to 350 kW—referred to as Level 1 ultra-fast DC recharging points; battery charging time is 20 to 30 min;
- Points with a charging power above 350 kW—referred to as Level 2 ultra-fast DC recharging points; the battery charging time of an electric vehicle is less than 20 min.

IEC 61,851 and IEC 62,196 define four battery charging systems for electric vehicles. The individual charging modes are adapted to the charging power, type of current and the method of connecting the vehicle to the charging point [39,43]. Types of charging modes are shown in Table 1.

Table 1. Types of electric vehicles charging modes.

Mode	Description
Mode 1	charging system with a power up to 3.7 kW, the vehicle is charged with single-phase alternating current of 16 A and 230 V; no communication between the vehicle and the charging point, and charging is carried out by the AC/DC converter installed in the vehicle;
Mode 2	charging system with a power up to 3.7 kW, the vehicle is charged with single-phase alternating current of 16 A and 230 V; charging takes place through the AC/DC converter installed in the vehicle; there is also an additional overvoltage protection IC-CPD that protects electric vehicles against over voltages;
Mode 3	- Option I—charging power 7.3–43 kW, the vehicle is charged with a single-phase or three-phase current up to 63 A and with a voltage of not more than 250 V for single-phase current and a voltage of not more than 480 V for three-phase current; the charging point is equipped with charging sockets and a communication system with the vehicle; - Option II—charging power 7.3–43 kW, the vehicle is charged with a single-phase or three-phase current up to 63 A and with a voltage of not more than 250 V for single-phase current and a voltage of not more than 480 V for three-phase current; the charging point is equipped with a charging cable with a plug and a communication system with the vehicle, charging is carried out by the AC/DC converter installed in the vehicle;
Mode 4	DC charging system with charging power from 22 kW, current up to 125 A and voltage in the range from 50 V to 500 V; the charging point is equipped with a charging cable with a plug and a communication system with the vehicle; charging takes place through the AC/DC converter located in the charging station.

According to the IEC 61851-1:2019 standard, three cases are distinguished due to the possible ways of connecting the vehicle to the charging point [38]:

- CASE A—The charging wire is permanently mounted to the car. The wire has a plug that connects the vehicle to the charging point socket. This connection method is compatible with a Mode 1 or Mode 2 charging system. Case A is described as the standard, but in practice it is extremely rare.
- CASE B—The charging point is connected to the vehicle via a portable AC charging wire with plugs on both ends. One end is connected to the vehicle's charging socket and the other end to the charging station socket. Case B is mainly used in public charging stations. This connection is compatible with the Mode 3 charging system.
- CASE C—The charging wire is permanently attached to the charging station on one side, and the other side of the wire has a plug that is connected to the vehicle's charging socket. This connection is compatible with the Mode 4 charging system.

There is no single standard charging connector in the EU. The AFID Directive assumes that charging points in EU Member States should be equipped with at least the TYPE 2 (AC) standard and the combined charging system CCS (DC) connector. Table 2 shows the currently available types of plugs for electric car users at public charging points.

Table 2. Type of connectors available at public charging points.

Type of Charging Point	Type of Connectors
AC charging points	TYPE 1—SAE J1772—a connector used for free charging stations with a power of up to 7.4 kW; TYPE 2—Mennekes—connector available at single-phase power points up to 3.6 kW and three-phase power points up to 44 kW;
DC charging points	CCS Combo 1—connector that supports direct current up to 50 kW; CCS Combo 2—connector available at fast and ultra-fast charging points supporting power up to 350 kW; CHAdeMO—a connector with a charging power of up to 60 kW, most often used in vehicles of Japanese and Korean manufacturers; Tesla Supercharger—connector for Tesla vehicles, supporting power in the range of 50 kW to 120 kW.

Figure 1 shows the percentage of different types of connectors found in public charging points in the EU [44].

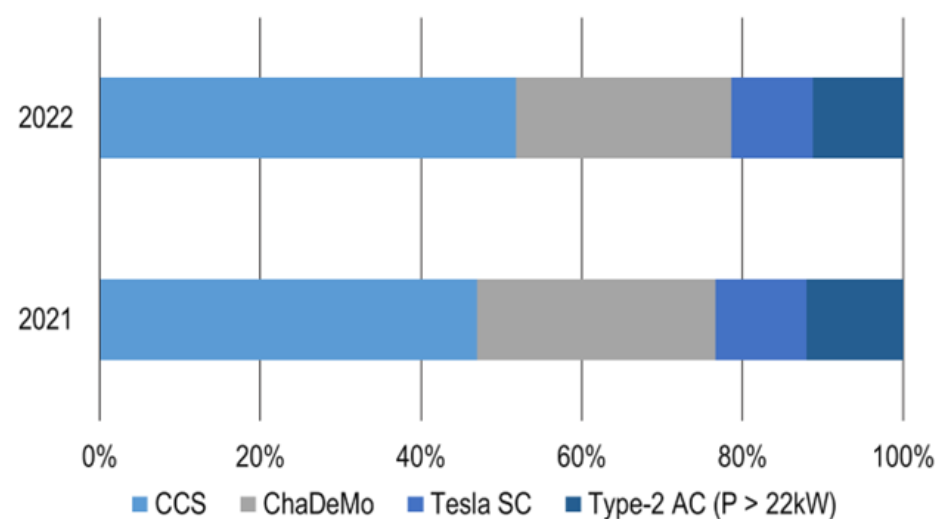


Figure 1. Share of recharging connectors in public charging points in UE.

Among the types of EV charging connectors available, CSS-type connectors account for the largest share. CSS connectors are half of all available connectors at public charging points in the EU. CHAdemo plugs also have a large share (about 30%), as a result of the large number of Japanese and Korean EVs used by Europeans [44].

3.3. Electric Vehicle Charging Point Locations

High-powered charging points are primarily installed along highways or travel service areas. They ensure that batteries are recharged in the shortest possible time. In a report presented by the European Court of Auditors titled “Infrastructure for charging electric vehicles: more charging stations but uneven deployment makes travel across the EU complicated”, it is estimated that the EV charging time with the ultra-fast charger is 20 min [45]. The planning of public EV charging infrastructure in urban areas and the planning of public EV charging infrastructure along highways are different. Charging points along highways should ensure safe distances between charging points for all electric vehicles, as well as the safety and availability of electricity supplies.

Researchers in the field of electric vehicles analyzed fast charging systems in terms of their availability for long-distance electric vehicle travel on highways. Most of the work is focused on estimating the optimal number of fast charging points along major road networks. For example, in the works [46,47] present a methodology for estimating the minimum required number of fast charging stations located along motorways in European countries. Estimated cost-effectiveness of their operation and country-specific results were also determined.

Another issue discussed in the literature is the optimal localization of the network of fast charging points along highways. There are many factors involved in optimization algorithms, including: number of electric vehicles, travel distance, charging duration, existing chargers, availability of power grids, or economic factors. For instance, in the works [48–50], a model for estimating the optimal location of fast charging stations was proposed, taking into account the interdependence between transport and energy networks. In the study [51] the range of an electric vehicle was included in the model. The authors of the work [52] took into account in their charging infrastructure location model the length of the charging station service radius and environmental factors, such as the ability to adapt the location, land value or power supply reliability. In planning the location of the charging station, the authors of the paper [53] took the possibility of public funding and the demographic factors of the region into account.

Many papers present analyses of limitations and barriers in the development of fast charging networks. One of the basic challenges is connecting the charging station to the power grid already existing in a given area. It entails increased investment outlays. A key concern is the higher overall power demand, resulting in grid instability [54,55]. There are many papers describing the impact of fast charging points on the power grid. A number of issues were identified, e.g., increased peak system demand, increased losses in the power system, violation of the voltage regulatory limit, possible overloading of transformers, distribution grid and wires [56–58].

The charging power has a significant impact on the costs of installing the charging infrastructure. The higher the charging power available at the point, the higher the construction cost of the station [59]. According to the report [60] the cost of energy charges for the operator (owner) of the charging station does not depend solely on the number of charges carried out and the total energy supplied. An additional cost is the fee for using a specific available peak power selected in the energy supplier’s tariff. Based on the results of the studies presented in the papers [61,62] fast charging stations can be profitable if they are located in places frequently visited by drivers are located near commercial and service outlets offering coffee or food.

4. Electric Vehicle Charging Infrastructure in EU

Electric car users most often charge their batteries using home chargers. In 2021, 61% of electric vehicles were charged at home and 15% at the workplace. Around a quarter of electric vehicles in use in the EU were charged using public chargers [63]. In 2021, there was a marked increase in the number of public charging points for electric cars. As mentioned earlier, charging of EVs can take place via direct current (DC) and alternating current (AC) chargers (Figure 2) [44].

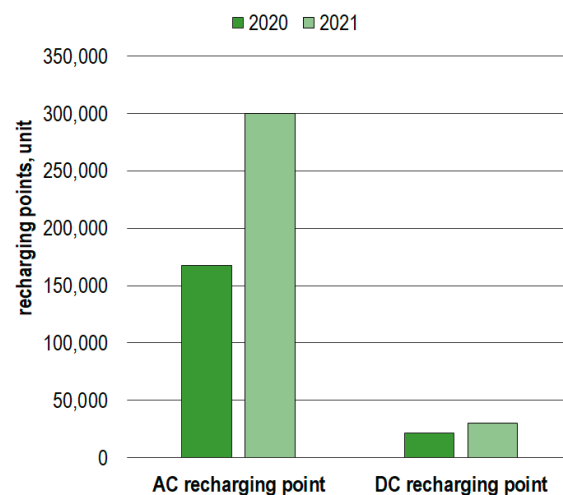


Figure 2. Public charging points by charging current.

Most public chargers in the EU use alternating current. They account for 90% of all public charging points. Compared to 2020, the number of public DC chargers increased by 44% and the number of public DC charging points increased by 30% (Figure 3) [44].

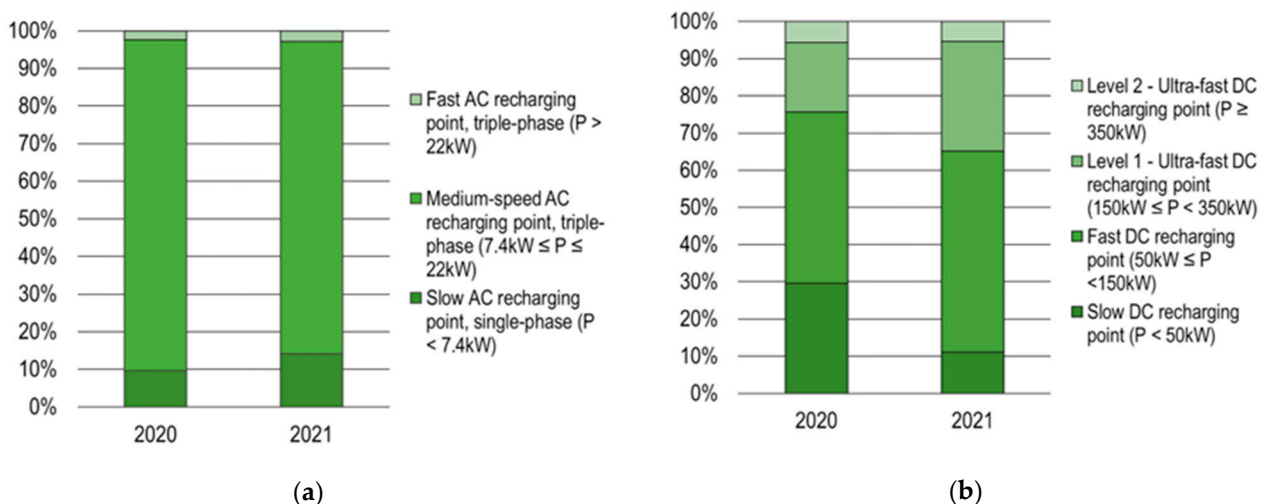


Figure 3. The share of fast and slow chargers at publicly accessible (a) AC charging points and (b) DC charging points.

Among the charging points with alternating current, the most available are chargers with an average speed of charging with three-phase current with a power range from 7.4 kW to 22 kW (Figure 3a). Their share of all publicly available charging points was 88% in 2020 and 83% in 2021, respectively. Fast chargers account for only around 3% of generally available AC charging points in the EU.

When analyzing publicly available DC charging points, fast chargers with a power range of 50 kW to 150 kW are the most numerous (Figure 3b). They account for half of the

publicly available DC chargers. The number of ultra-fast DC chargers is growing. Due to the charging power, there are two types of ultra-fast chargers: level 1—with a power in the range of 150 kW to 350 kW, and level 2—with a charging power above 350 kW. Among all publicly available DC charging points, their share was 24% in 2020 and 35% in 2021, respectively.

Fast chargers allow an electric vehicle's battery to be recharged in a short time span. The availability of fast charging points is particularly important for electric vehicle users travelling long distances. Fast chargers in 2021 accounted for 11% of all publicly available chargers in the EU (Figure 4).

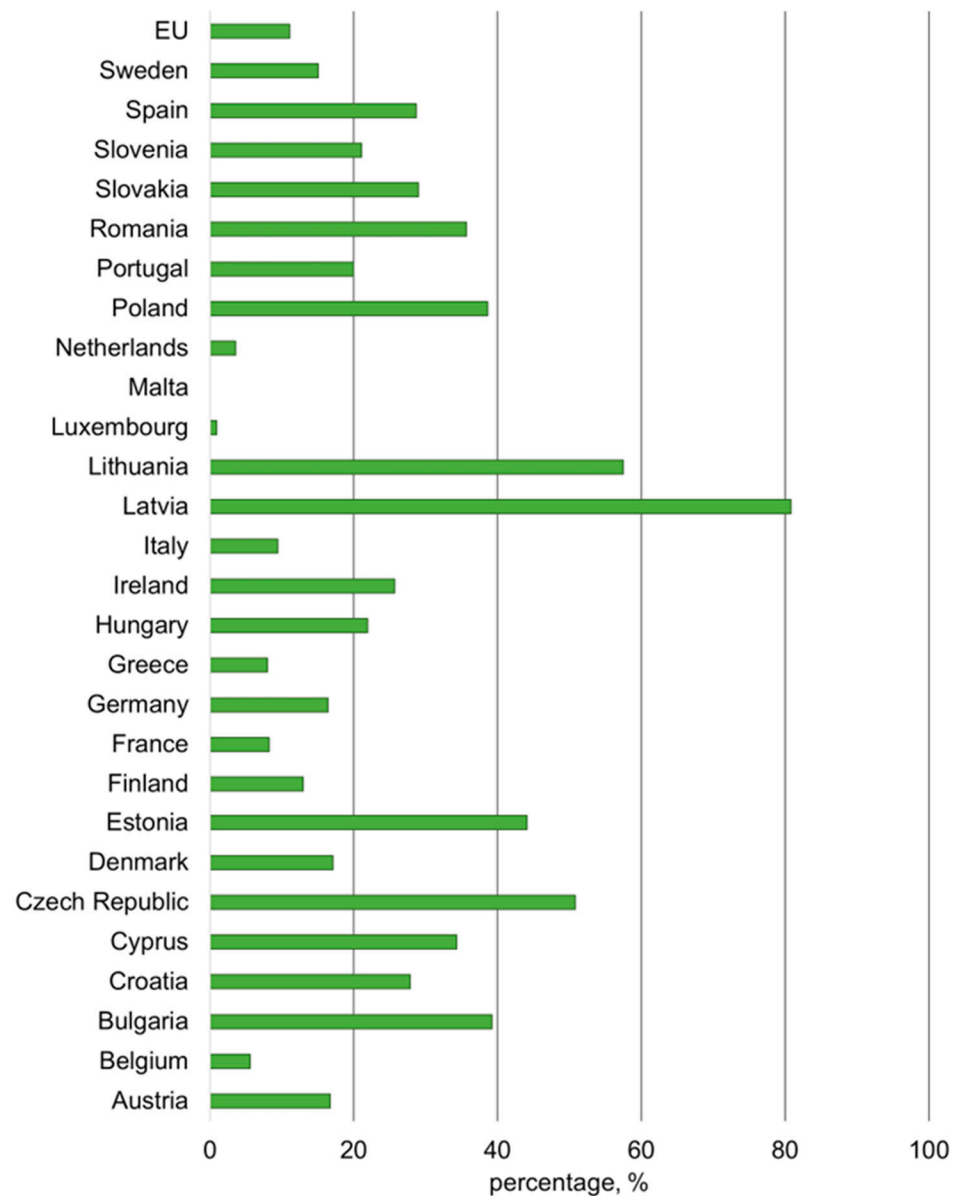


Figure 4. Percentage share of fast chargers in public charging points in the EU, by country.

In Latvia, 81% of all public charging points have fast chargers. In Lithuania, the share of fast charging points in the overall public charging infrastructure is 60%. In the Czech Republic, half of the charging points offer the possibility of fast charging. The lowest share of fast charging points (less than 10%) in the entire charging infrastructure is recorded in Malta, Luxembourg, the Netherlands, Belgium, France, Italy and Greece.

One of the indicators showing the availability of public charging points for electric vehicle users is the number of charging points per 100 km of roads (Figure 5). The largest

number of public charging points for electric cars per 100 km of roads are in the Netherlands (48 charging points) and in Luxembourg (35 charging points). In Germany, there are 20 public charging points per 100 km of road. In 13 EU Member States, there are less than 2 public charging points per 100 km of road [64].

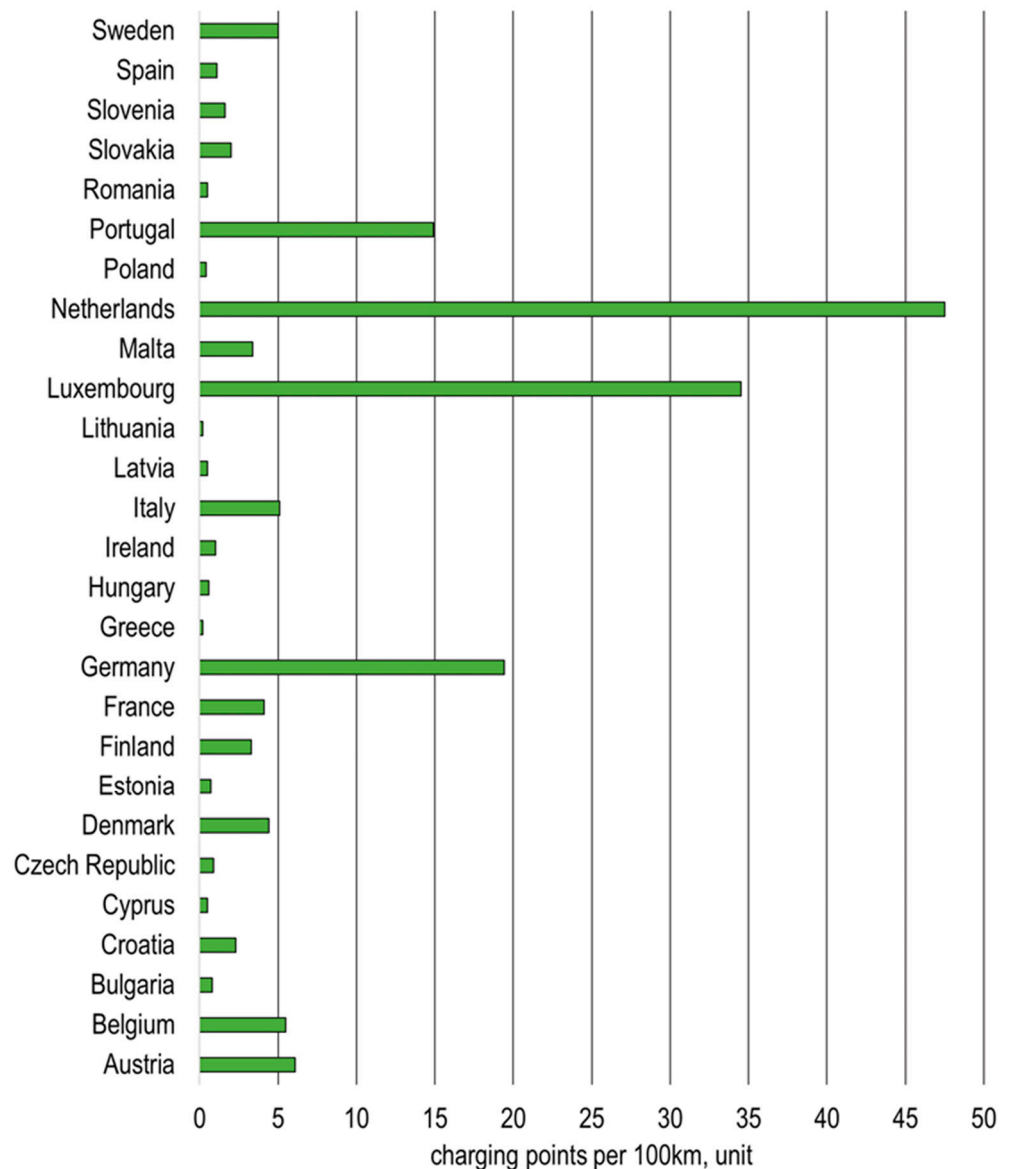


Figure 5. Number of charging points for every 100 km of 100 km roads in EU, by country.

Another indicator of the availability of charging infrastructure for electric vehicles is the ratio of the number of charging points per 100 km of roads within the TEN-T network. Trans-European Network-Transport (TEN-T) is a trans-European road network that was established by a decision of the European Parliament and the Council on 23 July 1996 [65]. The current TEN-T policy is based on Regulation 1315/2013 of the European Parliament and of the Council [66]. The TEN-T network is part of the Trans-European Networks (TEN) program, which assumes the development of road, rail, water and air transport corridors in the European Union countries, facilitating and accelerating the transport of goods and greater mobility of passengers. An effectively functioning transport system within the EU contributes to the improvement of the functioning of the single internal market, stimulates the economic growth of the region, and increases the competitiveness of individual member states and the entire EU on a global scale. The TEN-T network is

constantly being developed, modernized and adapted to the appropriate infrastructure. Green Deal for Europe places particular emphasis on the development of infrastructure for alternative vehicles. Figure 6 shows the number of fast combined charging system (CCS) chargers for every 100 km of TEN-T network in European Union countries [45].

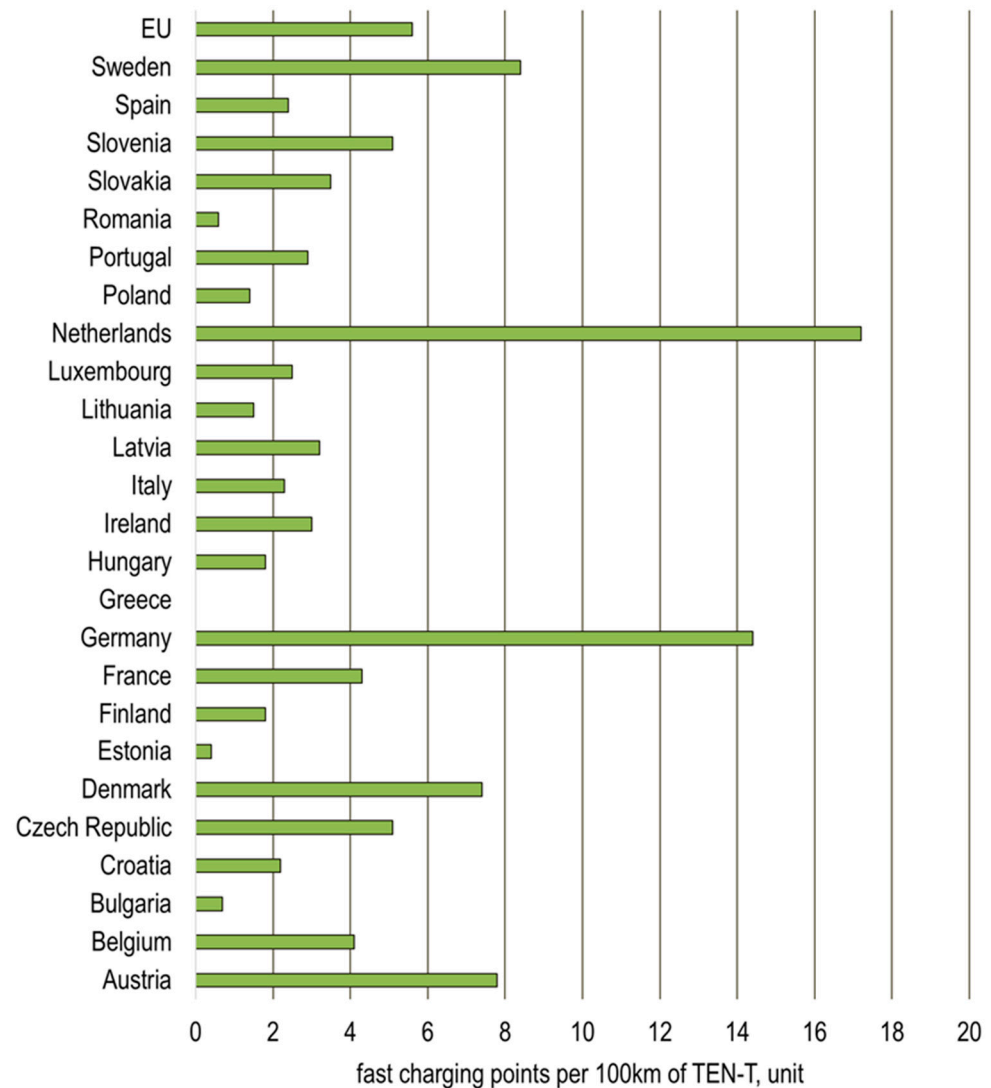


Figure 6. Number of fast combined charging system (CCS) chargers for every 100 km of TEN-T network in EU in 2020, by country.

On average, there are five publicly available fast charging points for electric vehicles per 100 km of the TEN-T network in the EU. The largest number of publicly available fast chargers can be found along the TEN-T routes in the Netherlands and Germany, respectively, with 17 and 14 charging points per 100 km of the TEN-T network. In eight EU Member States, there are less than two fast charging stations per 100 km of the TEN-T network. In Romania, Bulgaria, Estonia and Greece, there is not even one fast charging point per 100 km of the TEN-T route.

5. Plans for the Development of Electric Vehicle Charging Infrastructure in EU Member States

In the Alternative Fuels Infrastructure Action Plan established in 2017, the European Commission estimated that the number of publicly available charging points must increase from the then available 118,000 points to 440,000 in 2020, then to around 2 million in 2025 [67]. In GDE, the estimated value of charging stations to be achieved in 2025 was

changed, assuming the level of 1 million publicly available charging points. According to the Strategy for Sustainable and Smart Mobility adopted in 2020, by 2030 there will be a need for 3 million public charging points for electric vehicles [68]. The EV Charging Masterplan for the EU-27 estimates that the development of electric vehicle charging infrastructure will require investments of around 280 billion euros. Of this total, around EUR 185 billion will be allocated to charging infrastructure for cars, 50 billion euros to light commercial vehicles and 45 billion euros to charging infrastructure for trucks and buses [69].

In many EU Member States, strategies and plans for the development of electric vehicle battery charging infrastructure have been set. Italy plans to build 21,400 fast and ultra-fast charging stations by the end of 2025, including 7500 on highways or in rural areas [70]. Finland assumes 1 fast charging point for 100 electric cars by 2030. A total of 13.2 million euros has been reserved for the expansion of the infrastructure for charging electric vehicles and the infrastructure for alternative fuels [71]. In France, 7 million public and private EV charging stations are planned by 2030 [72]. One million charging stations are to be available in Germany by 2030. The German government will support the development of a network of public charging stations by 2025. There are also plans to make it mandatory to have at least one charging point for electric vehicles at every gas station in Germany [73]. Scandinavian countries are also planning to expand the charging network for electric cars. The government initiatives of Sweden, Denmark and Norway concern public charging infrastructure and payment solutions that can be used in all Nordic countries [74].

Central European countries also plan to develop electric vehicle charging infrastructure, but not on such a scale as in western European countries. Up to 800 fast charging stations for electric vehicles will be built in the Czech Republic by 2025, thanks to investments of around CZK 5 billion. In Slovakia, it is planned to build 228 ultra-fast charging stations and 500 DC charging stations by 2027 [75]. In Hungary, the number of charging points is expected to increase to at least 5900 points by 2030 [76]. Poland imposes the building of at least one 350 kW charging station for every 60 km of route along the TEN-T network [77].

6. Conclusions

Charging infrastructure for electric vehicles is a crucial factor in enabling the continued growth of these vehicles. This review seeks to highlight key issues related to the availability of charging points along highways for EV users. Several important findings were drawn regarding the availability of charging services in individual EU member states. First of all, it should be noted that in many member states the charging infrastructure for electric cars is still poorly developed. Especially when it comes to the possibility of fast charging, which greatly facilitates long-distance EV travel. In 10 EU Member States, there is not even one public charging point per 100 km of roads. On the other hand, in four countries, there is not even one fast charging point per 100 km of the TEN-T network. The share of BEVs and plug-in hybrids is expected to grow, and battery-related technology will undergo rapid development. Therefore, it is important to understand how these simultaneous changes will affect the requirements for fast charging infrastructure.

Another issue to be considered is the adaptation of charging infrastructure for heavy duty vehicles. HDVs are equipped with a battery with high energy capacity, so charging time is and will continue to be a major obstacle to the spread of electric drives in heavy duty vehicles. Although the European Parliament is setting short-term targets for new HDV fleets, there is no solid economic and technical basis for the spread of electric drives in this type of vehicles.

Economic issues are important in the more widespread use of fast charging infrastructure. Due to the high costs of building fast charging points, private investors are not interested in this type of investment. The promotion and deployment of private charging infrastructure could complement publicly available infrastructure.

Although the EU Member States have set a long-term strategy and infrastructure planning for charging vehicles with electric drive, the number of charging points will increase gradually. Due to the large economic diversity of European Union countries, the development of the charging infrastructure will progress at different levels. It is therefore important to ensure that fast charging points are located primarily along the TEN-T network and highways.

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