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Charging Stations for Large-Scale Deployment of Electric Vehicles

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Abstract: The large-scale adoption of electric vehicles will require a charging infrastructure that meets the new needs that will arise. Currently, the charging infrastructure for electric vehicles is still in the early stages of development, not least because of the low number of electric vehicles in use. However, there are still many questions to be answered when it comes to standardization in terms of connectors, DC or AC charging, and power, as well as both operational and economic issues. Although this topic has been the subject of numerous studies over the last ten years, there are still gaps to be filled, particularly with regard to the mix of different recharging strategies (normal, accelerated, fast, induction-track, etc.), as well as the economic and operational aspects. Moreover, the relationship between users and private cars is changing rapidly, and charging behaviors are not yet well established.

Keywords: battery; charging stations; EV; extrapolation; regulation and technology

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1. Introduction

Electric vehicle (EV) charging is a strategic issue for automakers and a major challenge that must be overcome before these vehicles can be compared with combustion-engine vehicles in terms of ease of use [1]. Indeed, the vehicles' limited range and long battery-recharging time, the cost of deploying a fast-charging infrastructure and its significant anticipated impact on power grids, and the high cost of the battery have prompted a number of research projects focusing on the optimization of EV charging infrastructure [2].

The ecological transition is currently crucial. As fossil fuels should be abandoned or phased out, renewable energies must be promoted, and their use encouraged [3]. Over the past several years, the potential of hybrid vehicles and EV has been increasingly recognized in society. For example, recently, the European Union (EU) forbade the production of new internal-combustion vehicles after 2035 (except by the luxury-car industry). Those regulations play an important role in supporting and accelerating the transition to a cleaner and more sustainable transportation system, especially for individually-owned vehicles [4–6].

The number of hybrid vehicles and EV registered each year is increasing steadily [7]. Indeed, since the 2010s, when the democratization of these vehicles began, they have become increasingly common each year, with over 26 million electric cars on the road in 2022. China, Europe, and the United States represent 95% of these sales [8]. Figure 1 shows the evolution in the sales and stock of EV worldwide. Both have increased steadily and quickly.

The trends in sales are more heterogeneous than the number of EV produced, with sales being heavily dependent on state incentives. While China remains the leading market for EV sales, with a global growth of 20% in 2023 compared to 2022, Europe is now the world's second-largest market, with 25% of the market share in electrical cars [8]. This rapid development can be viewed as a consequence of the relatively strict European directive regarding CO_2 emissions for new cars, which targets a 100% reduction for new cars starting in 2035 (European Parliament, "Fit for 55" package, 2021) [9]. At the same time, in the United States, EV sales are still growing and constitute almost 10% of the market.

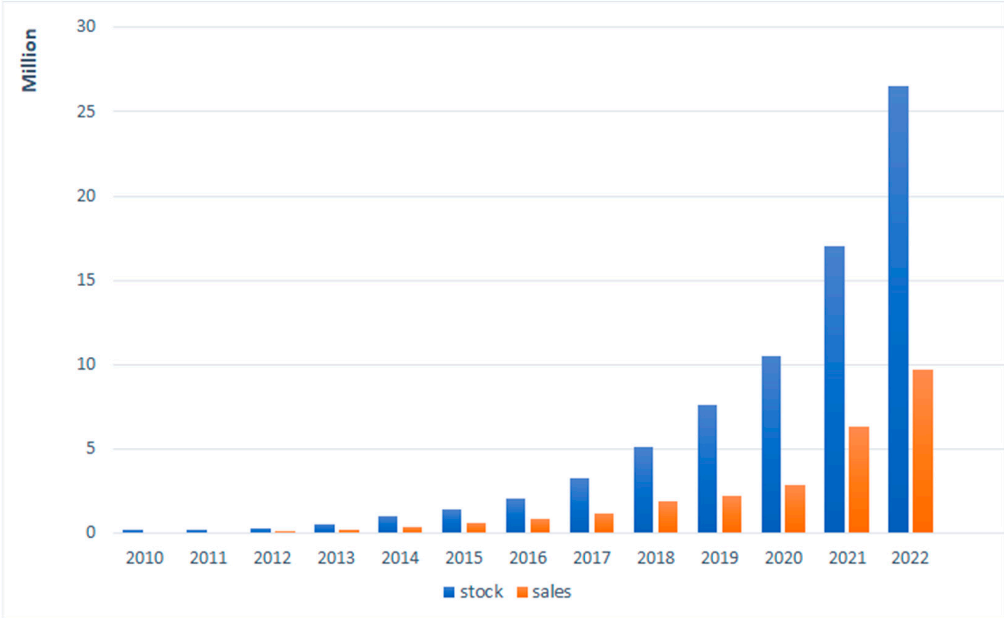

Figure 1. Evolution of global electric light-duty vehicles stock and sales from 2010 to 2022, shown as the mean values for multiple areas worldwide (China, Europe, United States, and others) [8].

The rapid public adoption of EV is also being driven by the growing number of models offered by carmakers. Figure 2 highlights the upward trend in vehicle manufacturers' offerings.

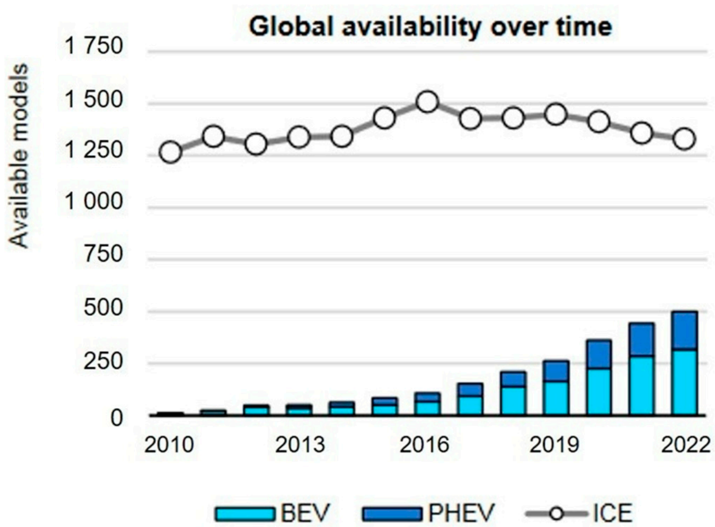

Figure 2. Global availability of car models over time [8].

Today, PHEVs offer a broad spectrum of hybrid solutions, from start-and-stop systems (with low-voltage powertrains ranging from 12 to 48 V) to full hybrid powertrains (90–400 V). Those vehicles have different powertrain systems with batteries of different power that require different recharging systems [10]. Full EV make up the majority of the market [11].

Moreover, charging stations, once rare, are now emerging everywhere. Indeed, the widespread adoption of EVs will be possible only if implementation of the charging system keeps pace [6,12,13]. Everyone is conscious that charging infrastructure is the main barrier to EV use for consumers, and every state is trying to accelerate the expansion of charging structure with initiative and directives, whether for particular areas or on a large scale in areas like parking lots, malls, and fuel and service stations. It is obvious that with the increasing adoption of EVs, the demand for charging points is increasing as well. Currently, there are various types of charging systems; some are more powerful and faster, while some are more ergonomic and easier to use. In addition, the majority of modern EV no longer use Li-Ion. Instead, LiFePo4 or LiMg are more common. These systems are less sensitive to temperature and carry a lower risk of explosion due to large variations in the battery voltage over short periods of time (voltage spike, $\frac{dV}{dt}$). However, these disadvantages of Li-Ion could be caused by the EV battery management system rather than the charging station, which cannot know which kind of battery technology it is recharging [14].

This paper deals with the study, analysis, regulation, and prediction of the penetration of large-scale recharging stations from both the technological (issues and constraints on the grid) and the socio-economic points of view . This work is the fruit of a collaboration among experts from multiple domains, including electrical engineers focused on batteries and hydrogen-powered cars and researchers focused on marketing and the economy. Although numerous studies have been carried out on the technical side, focusing on battery performance and the power of recharging systems [11,15–17], and on the economic side, considering whether the deployment of these systems integrates or fails to integrate user preference [4–6], or both [18,19], the environment is constantly and significantly evolving. Furthermore, the impact of EV charging systems on the grid is leading to the development of new studies, which are revealing new challenges. The authors of this article [20] aim to provide a comprehensive overview of EV charging using renewable energy, addressing key aspects such as resource availability, potential applications, planning considerations, control strategies and pricing models. This article also examines the challenges facing renewable-energy charging stations and proposes potential means of overcoming these obstacles. The work of [21] focuses on planning processes for charging stations and proposes a decision-support tool for planning high-power charging infrastructure for electric vehicles. The proposed decision-support tool aims to help stakeholders in the transportation value chain make informed decisions about infrastructure investment. Another paper in the literature [22] presents a thorough review of over 50 studies on the choice of strategies for fast-charging energy stations. The authors propose a novel classification framework in which to organize and analyze the findings. They evaluate each study based on its level of parameterization, the type of battery cell used, and whether it includes real-world proof-of-concept testing. They critically assess the advantages and disadvantages of each strategy, as well as their cost-effectiveness. Finally, they identify areas where further research is needed before these strategies can be widely applied to BEVs. This study [23] explores the issue of social equity in the provision of EV charging infrastructure. It highlights the challenges of ensuring equitable access to charging stations across different communities. It identifies several strategies that can be used to address these disparities, including local target setting, monetary incentives, and policy incentives. These strategies can help promote the widespread adoption of EVs and ensure that all communities benefit from the transition to electric vehicles. The objective and original value of this article lie in a discussion of the charging methods used in the charging stations, the socio-economical dimensions of charging infrastructure, and the changes in norms and trends in charging stations that are anticipated over the next several years due to the increasing penetration of EV into the markers of France, the rest of Europe, and the world.

This paper is organized as follows: after the introduction, Section 2 presents the technologies used in charging stations. Section 3 focuses on the EV charging stations used in France. Section 4 presents a discussion of charging stations in Europe and worldwide. Section 5 presents analyses and predicts future trends in charging stations and the future of thermal vehicles in view of policy changes and the ecological transition. Lastly, Section 6 offers conclusions and highlights the main contributions of this study.

2. Technologies for Charging Stations

2.1. Definitions and Nomenclature

A charging station for EV consists of equipment that supplies electrical energy to recharge electrical or hybrid vehicles. These stations vary in size and capacity, from small stations for personal and private use (herein named “charging points”) to large public stations capable of charging multiple vehicles simultaneously. Charging stations also incorporate different technologies, components (see Table 1), and types of nozzles (connectors). In theory, two charging methods exist: alternative current (AC) and direct current (DC), which are defined by the current shape as sum.

A charging station includes the following components:

Table 1. List of components included in a charging station.

Name of the Component	Utility
Unit control	This component manages the charging process and communicates with the vehicle. It includes a display screen to provide information regarding charging status, such as the amount of energy delivered and the charging time remaining.
Power input	This component is the connecting point where the charging point is connected as an electrical power source. This input can be a plug or a hardwired connection.
Connector (nozzle)	This is the physical connection between the charging station and the car. There are different kinds of connectors, such as type 1 connectors or Combined Charging Systems (CCSs)
Charging cable	The charging cable connects the charging station to the vehicle through the connector. It can be removable or attached to the charging point.
Overcurrent protection (In Cable Control Box)	The overcurrent protection shuts off automatically if the charging point detects an overflow of the electrical current.
Converter (sometimes)	The need for this component depends on the nature of the charging point. Either an AC or DC charging station may need a power converter. In a battery, the current is direct (DC). If a user wants to charge their battery with alternating current, an DC-AC converter is needed.

2.2. Battery Electric Vehicle Recharging Topologies

Most BEVs need to incorporate an onboard charger that allows charging of the battery anywhere there is an electric outlet. However, onboard chargers are limited in power output because of size and weight restrictions related to the vehicle design. Offboard chargers are not limited by these size and weight restrictions; they are limited in power delivery only by the ability of the batteries to accept a given amount of power. While a high-power offboard charger needs less time to charge batteries, the flexibility to charge at different locations is restricted. Another option is an AC/DC charger, which makes it possible to recharge the BEV over several hours [15]. Slow BEV charging (something usually done at home) is not always seen as a drawback. Indeed, such slow charging is always recommended by battery manufacturers to preserve the battery lifespan. In addition, this “home” charging is always cheaper than the fast charging available at the charging station.

This topology for recharging BEVs involves the grid, with both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) power flow. In this context, a common household circuit rated to 240 volts AC and 15 amperes can be considered. These chargers use the standard three-prong household connection, and they are usually considered portable equipment [13]. They convert the alternating current distributed by electrical utilities into the direct current needed to recharge the battery.

A rapid charger has a 400-volt AC outlet and supports a current flow up to 30 amperes. The maximum amount of energy that the car can consume is around 12 kW, or 12 kW/h.

The charging-point AC/AC charger is used to adapt the power, voltage, and current levels from the grid to those requested by the BEV charger. This converter adapts the frequency and voltage to meet the requirements of the car/grid in the V2G operating mode. In addition, this charger can be used to calculate the amount of energy transferred for payment purposes. Nevertheless, for the moment, these devices suffer from a lack of standardization among car manufacturers.

2.3. EV Charging Topologies

Figure 3 illustrates the energy flow of the onboard charger for BEV in the G2V or V2G modes. We consider a common household circuit rated to 240 volts AC and 15 amperes. These chargers use the standard three-prong household connection. This charger converts the alternating current distributed by electrical utilities into the direct current needed to recharge the battery.

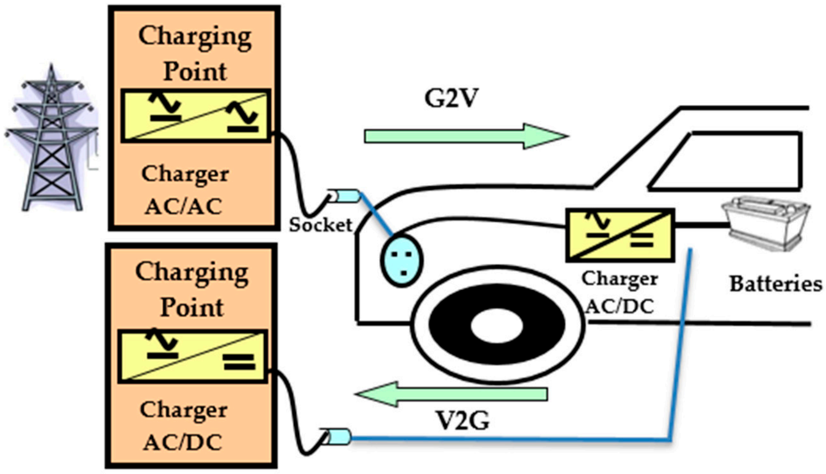

Figure 3. Grid-to-vehicle and vehicle-to-grid power flow (AC or DC (CCS) charge).

Two types of chargers can be found: AC chargers (which are limited in power) and DC chargers (which deliver more power).

A normal household outlet is considered a slow charger. These 240-volt outlets typically have a 16-ampere circuit breaker (or 32 A at maximum), meaning that the maximum amount of energy that the car can consume is approximately 3600 watts, or 3.6 kW/h (or 7.2 kW/h in a single phase). In the case of a three-phase household outlet, 16 A (or 32 A) are available on each phase. Consequently, home charging can be performed under 11 kW or 22 kW power. However, not all BEV accept an AC 22 kW charge. At charging stations, the charging power can be increased in the case of DC power to 250 kW (for some Tesla models) or even more.

Importantly, household charging (wall charger for example) is cheaper and safer for the battery than a fast-charging station, which is generally two or three times more expensive and shortens the lifespan of the battery.

The onboard vehicle charger is an AC/DC current bidirectional converter that acts as a rectifier when recharging the BEV and as an inverter when supplying the grid or the home battery [16]. An example of such a converter's topology is given in Figure 4.

There are various kinds of charging stations, each with their own technologies. Currently, one may find the following: Level 1 charging points, Level 2 charging points, DC Fast Charging Stations (also called Level 3 charging points) and Tesla Superchargers.

The most common topologies for DC charging of battery-powered electric vehicles are as follows:

Single-level topology: this is the simplest and least expensive topology. It uses a single power converter to convert alternating current from the electrical grid into direct current for the battery. This topology is limited to relatively low charge rates, as it is subject to heat-dissipation constraints.

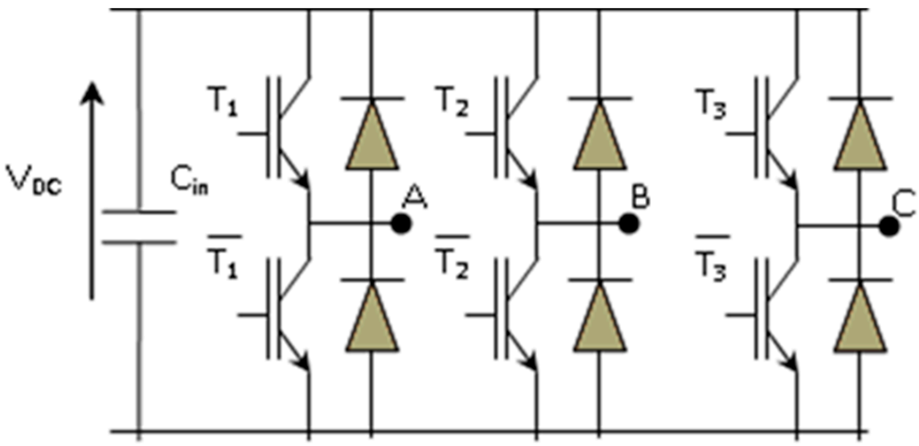

Figure 4. AC/DC and DC/AC current bidirectional converter [13]. T_i are the switchs.

Two-level topology: this topology is more complex than single-level topology but allows for higher charge rates. It uses two cascaded power converters: a buck converter to convert the mains AC into low-voltage DC and a boost converter to convert low-voltage DC into high-voltage DC for the battery.

Three-level topology: this topology is even more complex than the two-level topology, but it enables even higher charging rates. It uses three cascaded power converters: a buck converter to convert alternating current from the grid into low-voltage direct current, a buck-boost converter to convert low-voltage direct current into intermediate-voltage direct current, and a boost converter to convert intermediate-voltage direct current into high-voltage direct current.

One multilevel converter configuration is the Neutral Point Pinch (NPC) configuration, which uses a regulator circuit to maintain the converter's neutral point at a constant voltage level. This regulator circuit uses gallium nitride (GaN) devices to control the current in the switching transistors. GaN NPCs offer several advantages over traditional silicon-based NPCs. They have faster switching rates, enabling higher load rates. They also have reduced thermal dissipation, which extends component life.

2.4. Different Levels of Charging Point

Level 1 charging stations offer the lowest power output, making them the slowest of the levels.

This type of charging uses AC and is rated at around 1.2 kW. Depending on the car's battery capacity, a full recharge can take more than a day; for example, it takes 20 h to obtain 36 kWh, equivalent to 180 km. As of 2022, most new EV models have a range of at least 320 km [15,24].

Level 2 charging stations also use alternating current, but their output power is higher (typically 6.2 to 7.2 kW in a single-phase circuit, up to 22 kW for a three-phase circuit, or 19.2 kW for some commercial stations). This station level is generally the recommended home-charging solution for EV owners. In a public or commercial context, this type of station also offers an excellent balance among performance, simplicity, and cost [25].

Offering impressive power output, Level 2 charging stations take up less space and are less expensive to deploy than Level 3 charging stations (fast DC charging). Level 2 charging stations use a universal SAE J1772 connector compatible with all major North American and European EV models (with or without an adapter). This connector is different from those used for Level 1 charging stations, as it must be compatible with higher power outputs [24].

There are three sub-categories of this type of charging station: residential, commercial, and public. Many of these stations are connected to the grid, making them "smart" charging stations.

Level 3 fast-charging stations also known as DC fast-charging stations:

Level 3 charging stations use DC for fast power, offering up to around 80% of a full charge in less than 30 minutes, as announced by many car manufacturers. After that point, the vehicle slows the recharge to protect the batteries [26].

Level 3 charging stations are more expensive to deploy, require more space, and, because of their high power and direct current, require special electrical infrastructures. The investment can be worthwhile, as fast charging is an essential element of a convenient and reliable charging network. Depending on the tariff in force, fast charging may be more expensive, but it allows drivers to get back on the road more quickly [17].

The key differences between Level 1, Level 2, and Level 3 charging stations are summarized below:

Level 1 charging stations are the slowest, but they are also the most accessible and affordable. Level 2 charging stations are a good middle ground, offering faster charging speeds without the high cost or complexity of Level 3 stations. Level 3 charging stations are the fastest, but they are also the most expensive and require special electrical infrastructure [17].

When choosing a charging station, it is important to consider the project's needs and budget.

For those with a short commute who can charge the EV overnight, a Level 1 station may be sufficient. For those with a longer commute or the need to charge the EV more quickly, a Level 2 station is a good option.

For those who need to charge their EV on the go, a Level 3 station may be the best choice.

Charging time can be roughly defined as the ratio between the EV 's battery capacity and the power supplied by the charging system.

Figure 5 shows the fast-recharge control technique, which utilizes a current control from low SOC to 80% and then switches to a voltage control from 80% to 100% of SOC.

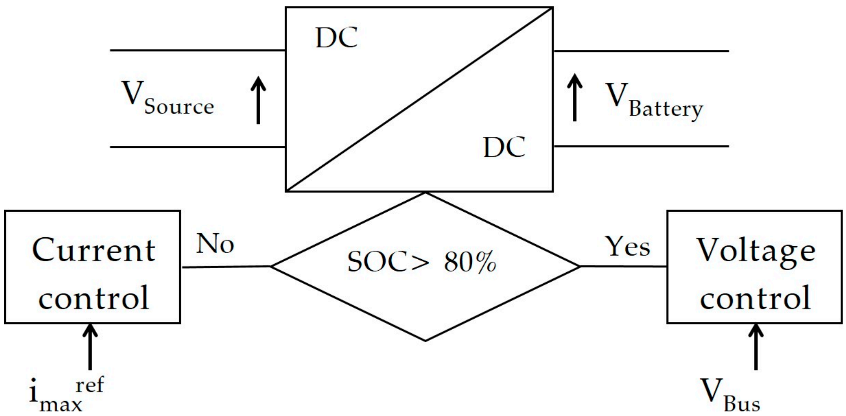

Figure 5. Combined recharging cycle.

The fundamental difference between AC and DC charging for battery-powered electric vehicles lies in the type of electrical current used. Alternating current (AC) is the current used by the electrical grid, while direct current (DC) is the current used by electric-vehicle batteries. In AC charging, alternating current from the electrical grid is converted into direct current by an on-board charger located in the vehicle. The on-board charger transforms the alternating current into direct current at a voltage and current suited to the vehicle's battery.

AC charging is generally slower than DC charging, with charging power ranging from 3.7 kW to 22 kW. However, it is more economical and simpler to implement, which explains why it is the most common charging method for electric vehicles.

With DC charging, direct current is supplied directly from the charging station. The vehicle's battery is therefore charged directly with direct current, without any prior conversion. DC charging is much faster than AC charging, with charging powers of up to 350 kW.

The main differences between the two types of charging are summarized in Table 2.

Table 2. Main differences between AC and DC charging.

	AC Charging	DC Charging
used current	AC	DC
charging speed	Slow	Fast
Cost	Average	Expensive
complexity	Average	Complex

The choice of charging method depends on the EV usage pattern. For everyday use, AC charging is generally sufficient and cheaper. For professional use or long-distance journeys, DC charging may be more interesting because of its rapidity.

The use of an AC charger presents some non-negligible advantages. The main advantage is its compatibility with all electrical cars. They are universally compatible and are also less expensive than DC chargers, with good flexibility. AC chargers are also safer than DC chargers in that the current supplied by the electrical grid is always alternative and lower in amplitude and does not cause rapid aging of the battery. They are also the most suitable charger for all EVs. However, their inconveniences are the slower charging speed and their limited usability in public charging infrastructure.

DC chargers are faster than AC chargers because they deliver more power. Power conversion and efficiency are noteworthy because no conversion is needed when the current is produced as DC. In addition, one of their benefits is their convenience for long trips, which is the product of their fast charge. The main inconveniences are the costs of this type of charger, the complexity of installation, and the energy demands. Additionally, the availability of DC chargers to individuals is limited. Figure 6 summarizes the existing types of nozzles, categorized by their use with AC or DC.

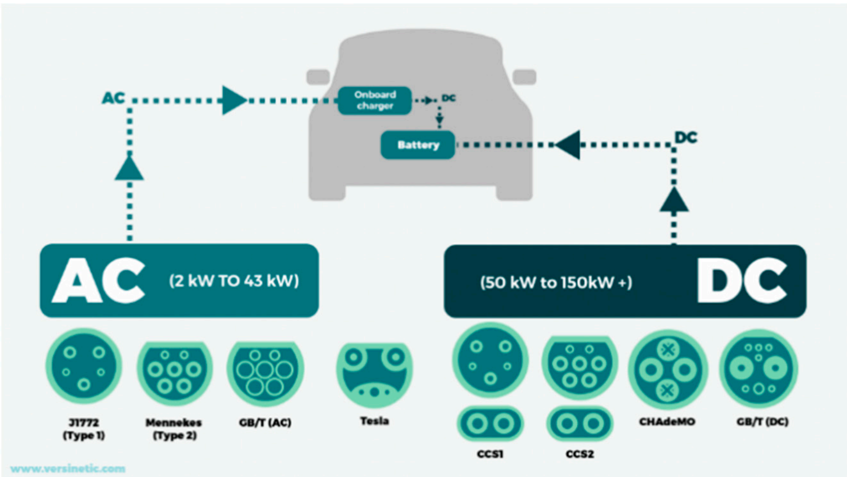

Figure 6. Different kinds of nozzle and the type of charge with which they are used (AC or DC) [27].

Nozzle configurations vary across regions worldwide. However, there is a growing trend towards standardization that is driven by various stakeholders in the EV market, including charging-system manufacturers, automakers, trade associations, and government institutions. This standardization aims to facilitate the adoption and widespread usage of EVs. Table 3 illustrates the types of nozzles currently in use and their technical specifications.

Table 3. Technical specifications of EV nozzles currently in use [18].

Type	Type 1	Type 2 *	Type2 **	CHAdeMO **	CCS Combo 1 & 2		Super-Charger Tesla V3/V4	ChaoJi ***
Power	3 kW to 7.4 kW	3 kW to 22 kW	3.7 kW to 43 kW	62.5 kW	41.5 kW	22 kW to 350 kW	250 kW	400 kW
Current	AC	AC	AC	DC	high AC	high DC	DC	DC
Phase	Mono	Mono	Tri	DC	Mono/Tri	DC	DC	DC
Current maximum	32 A	13 A	63 A	125–200 A	63 A	125 A	-	400–500 A
Number of connectors	5	7	7	10	5 + 2	7 + 2	-	7
Norm	IEC 62196-1 SAE J1772	IEC 62196-2 SAE J1772	IEC 62196-2 SAE J3068	IEC 61296-3	SAE J1772 + 2 pins	IEC 61296-3	-	-
Time needed to fully charge a 40 kW EV battery	18 h	12 h	2 h 30	10′ to 20′	1 h	10′ to 20′	20′	15′

* Mandatory shutter in France: T2-S. ** CHAdeMO 3.0 400A. *** next generation of CHAdeMO.

Type 1 is largely used in Asia and North America but is progressively being phased out in favor of type 2 and CCS. Type 2 is now the European standard for low-power charging stations (Annex II of the repealing Directive 2014/94/EU of the European parliament, 14 July 2021). In China, the GB/T standard took effect at the beginning of 2016, with either AC or DC charges. It is also used in India. AC and DC charges are both used and are involved in determining the types of charging station available.

Figure 7 shows the complexities involved in building charging stations. Indeed, several devices are required, with transformers that reduce the high grid voltage, switchgear and switchboards that connect and disconnect the aftercoming connected devices (in case of fault or maintenance), and sub meters that measure the line consumption of a sector or a geographical zone. Additional transformers might be used to reduce power to the customer's requested voltage. The final point before the charging station is the load centers that distribute the power to different charging points.

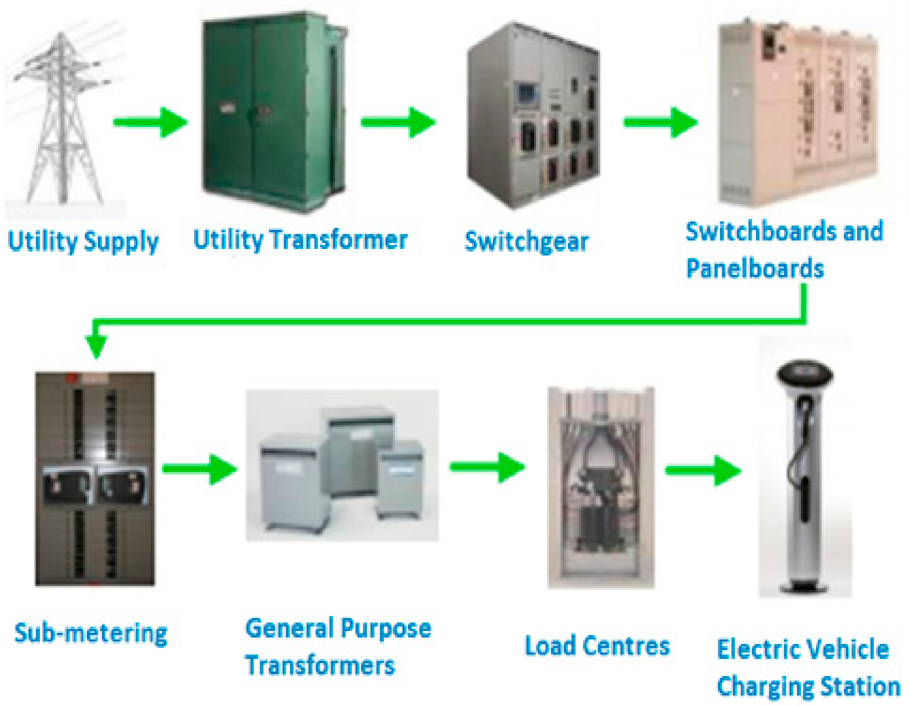

Figure 7. From network to charging station [28].

3. France, the Country of EVs?

The history of charging stations in France can be considered to have started in the 2000s. Based on the simple idea of encouraging the use of EVs, the government launched an ambitious project. The goal was (and is always) to reduce the number of new thermal vehicles purchased and to promote the use of EVs.

In 2008, the first charging stations were installed in Paris (and, subsequently, in the other big cities). Here, we discuss the private and public use of these stations. In 2012, the French government demanded at least one space for electrical cars in commercial buildings. The goal was to speed up the development of charging stations. Since 2012, the government has invested in more than 10,000 charging stations. As of 2023, France is one of the countries with the best coverage of charging infrastructure, and the government continues to invest in charging stations, with an objective of 30,000 public charging stations and 100,000 private charging ones.

Distributions and Counting

In December 2022, France had a significant number of charging stations for electrical and hybrid vehicles. According to the French government, there are currently more than 80,000 charging stations in France (cf. Figure 8).

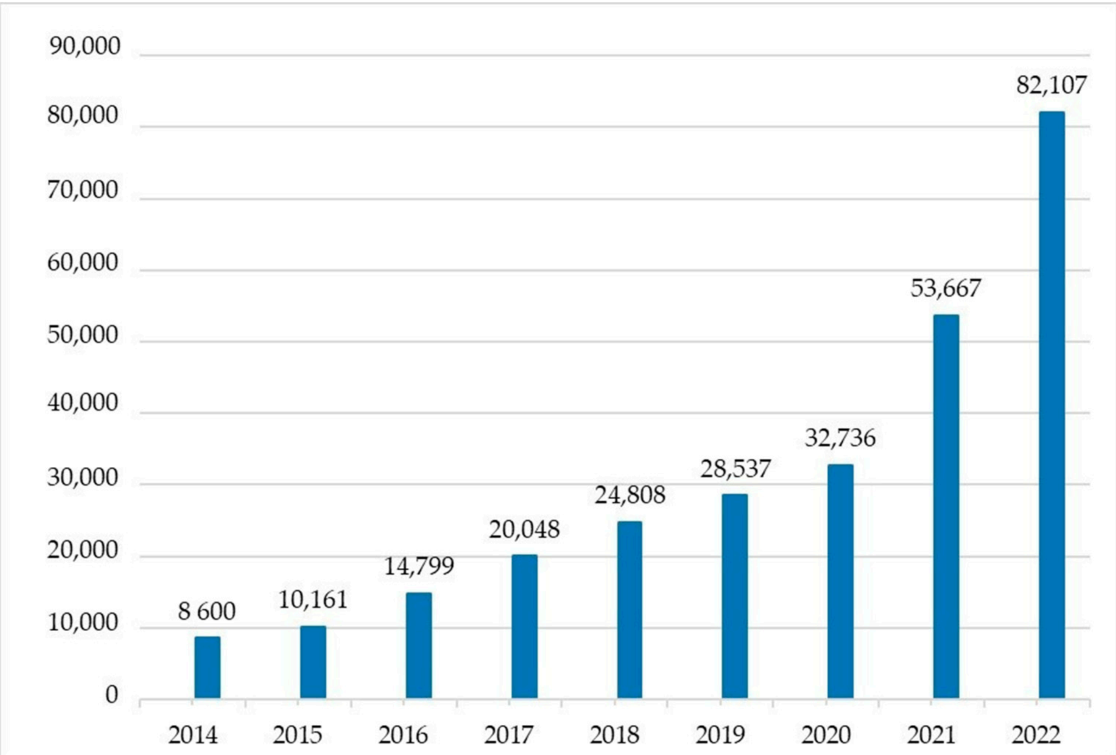

Figure 8. Change in the number of charging stations in France from 2014 to 2022 [29].

Figure 9 presents the increase in the number of charging points since 2018: 1,263,815 charging points were registered at the end of 2022 by ENEDIS (which is the main electricity-distribution-grid operator in France). This number includes all kinds of chargers.

Approximately 94% of these chargers are private installations, and half of these are installed in company-owned properties for their employees and visitors.

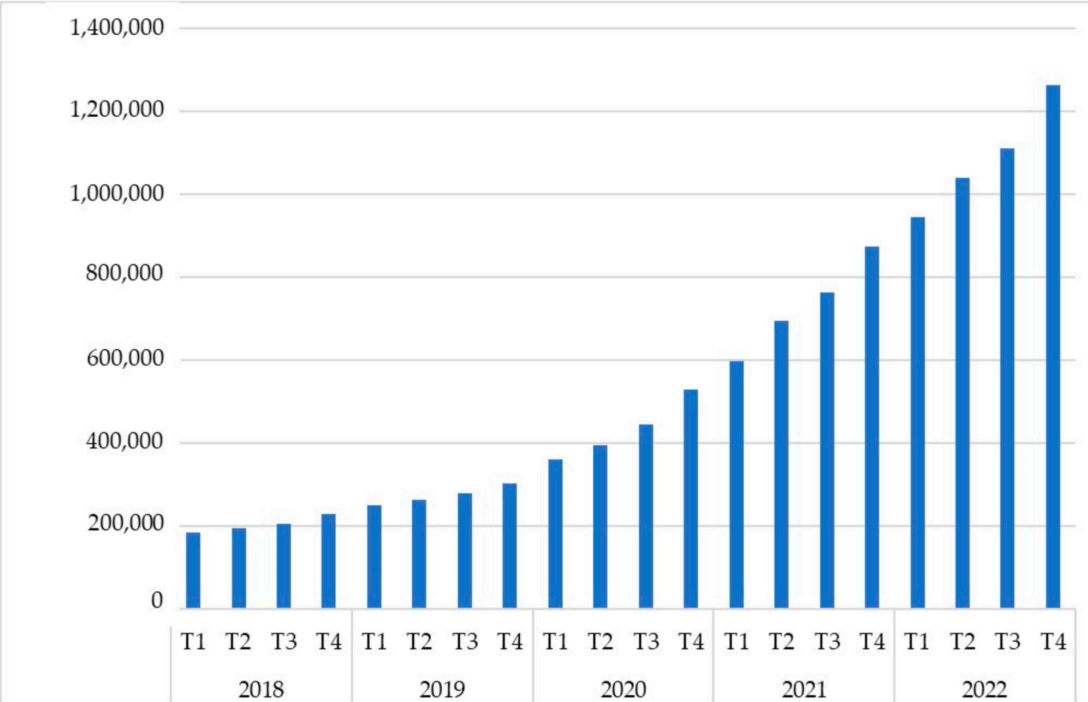

Figure 9. Number of charging points in France in December 2022 [30].

The map in Figure 10 represents the number of charging stations in France and their locations in the country. It can be seen that these charging points are concentrated in the metropoles and big cities [31].

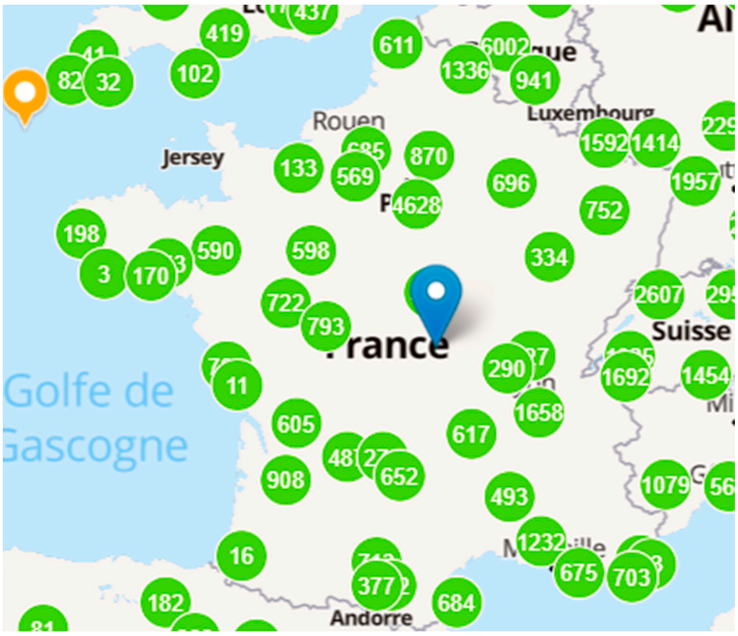

Figure 10. Location of charging points in France [31].

The most common type of charger is the normal one (≤22 kW). According to a report by the French Ministry of Ecological Transition, more than 85% of currently operating stations are on AC charge [32]. Figure 11 presents this distribution.

Currently, as presented in Figure 12, some areas are still poorly equipped due to the difficulties posed by their topography and population density, despite the incentives for small local authorities to deploy these infrastructures [33]. To facilitate electromobility in villages and sparsely populated areas, a new regulation in article L2224-37 of the French "Code général des collectivités territoriales" allows local authorities to install and maintain charging stations [34].

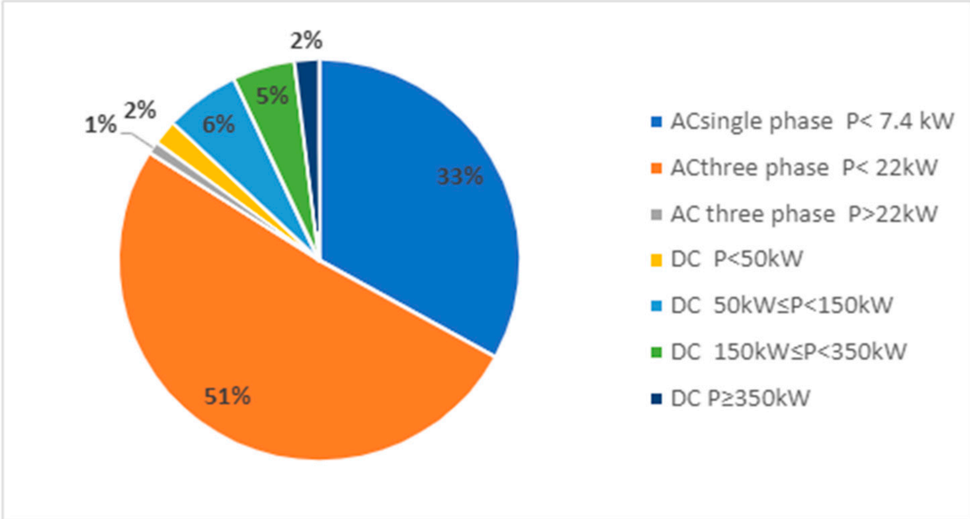

Figure 11. Distribution of charging points by power category.

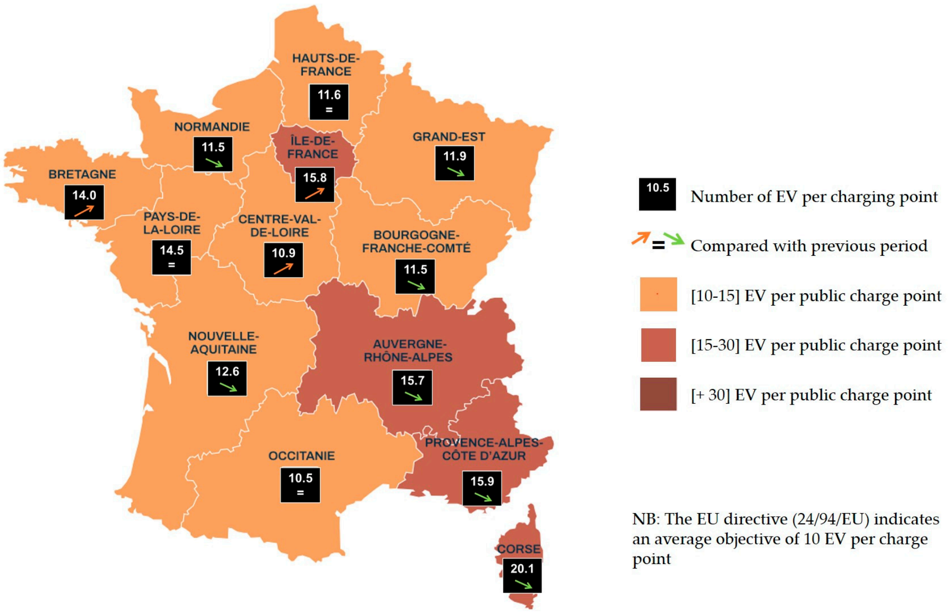

Figure 12. Public charging stations in France as of 31st July 2023 [33].

4. What Is the State of Charging Stations in Europe and Worldwide?

Having completed the discussion of France, let us discuss the state of charging stations in Europe and worldwide.

4.1. The Situation in Europe

Following the example of France, Europe follows an ecologic policy. Indeed, the ecologic transition is a European priority, with directives that tightened in June 2022. Moreover, these charging stations must include one of each type of charger (type 2 and combination).

With the growing interest in EVs, the number of charging stations is also increasing. In 2010, there were almost 5000 charging stations, whereas in 2022, there were more than 285,500. The trend from 2010 to 2022 is shown in Figure 13.

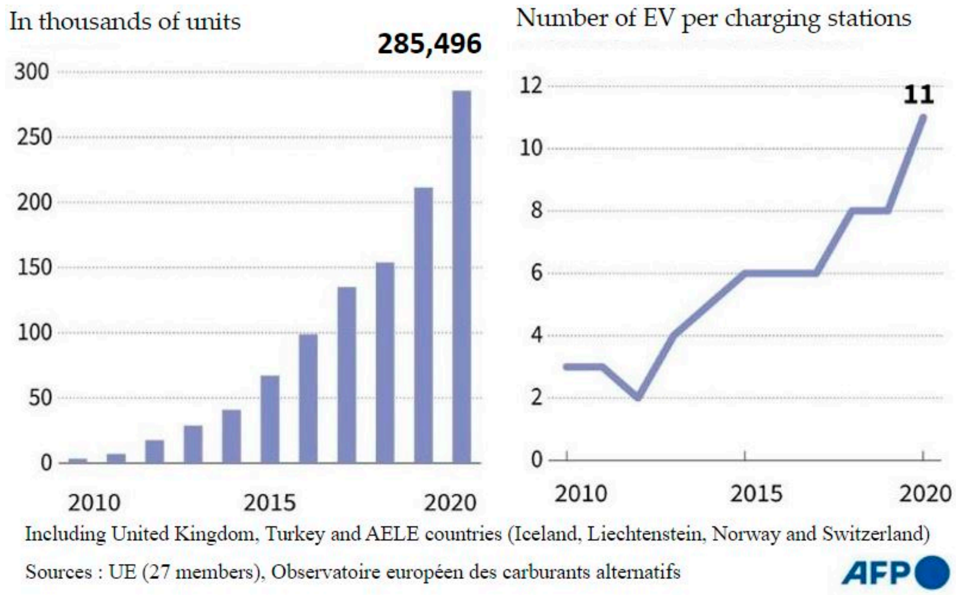

Figure 13. Change in the number of charging stations in Europe from 2010 to 2020 [35].

The growth is exponential, as shown in Figure 14. As in France, regulations have been implemented to encourage Europeans to install charging stations. The European Union continues to invest in this policy. The amount of charging infrastructure increased by 580% from 2015 to 2021.

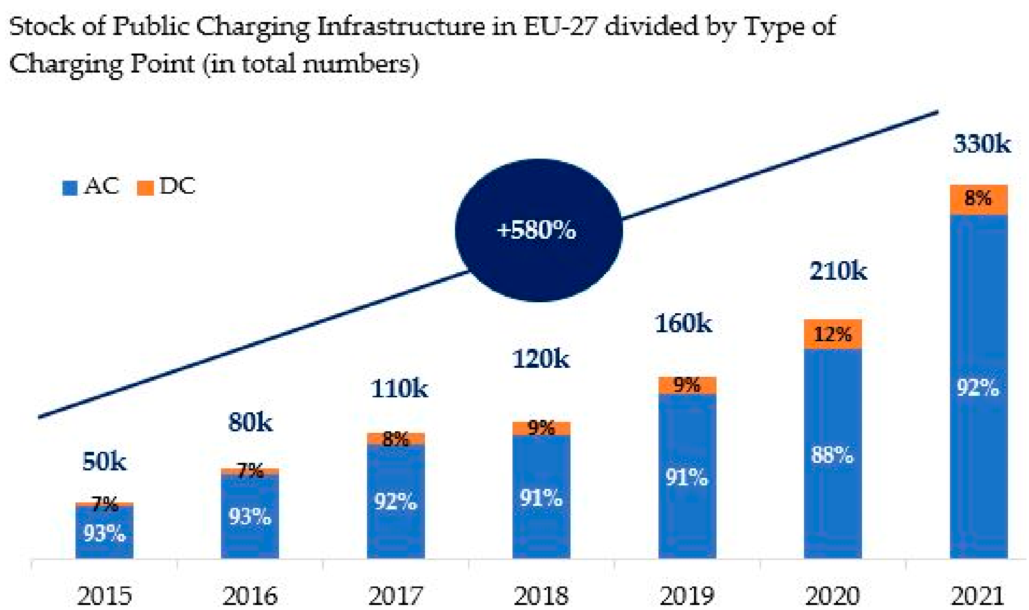

Figure 14. Growth of charging infrastructure in Europe from 2015 to 2021 [36].

The countries with the most charging stations installed are the Netherlands, Germany, and France. These three countries have 70% of all of the charging stations in Europe. Figure 15 presents the number of charging points in Europe by mid-2021.

4.2. The Situation in the World

The rest of the world is following the European trend. Currently, the estimated number of public charging points worldwide is around 2.7 million. This quantity represents a 55% increase from 2021 and includes only public and a subset of private charging points.

Among these 2.7 million charging stations, more than half are slow chargers. One million are installed in China, 460,000 in Europe, and 74,000 in the USA.

These leaders stand out by virtue of strong policies supporting EVs and charging points.

Figures 16–18 represent the above information.

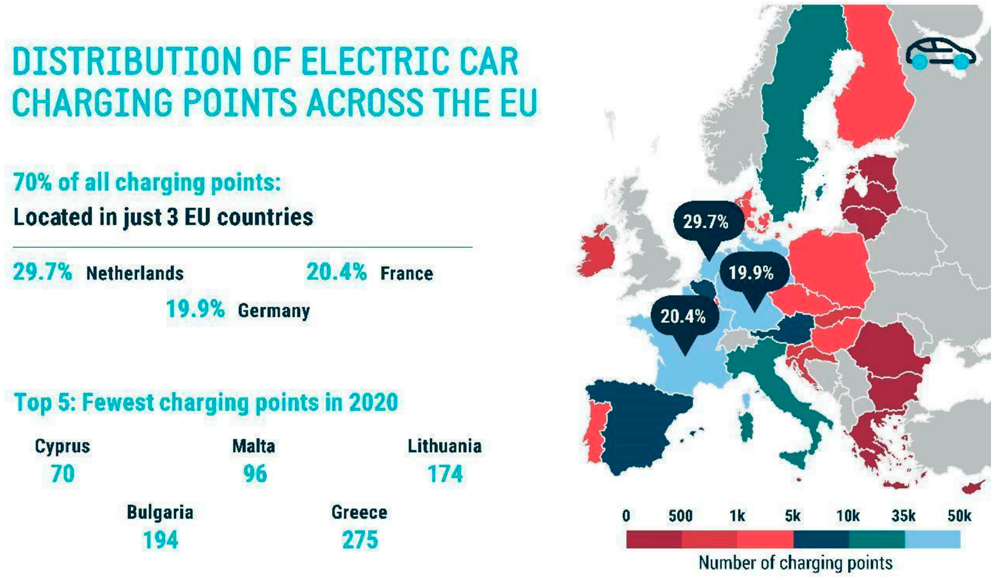

Figure 15. Number of charging points in Europe by country [37].

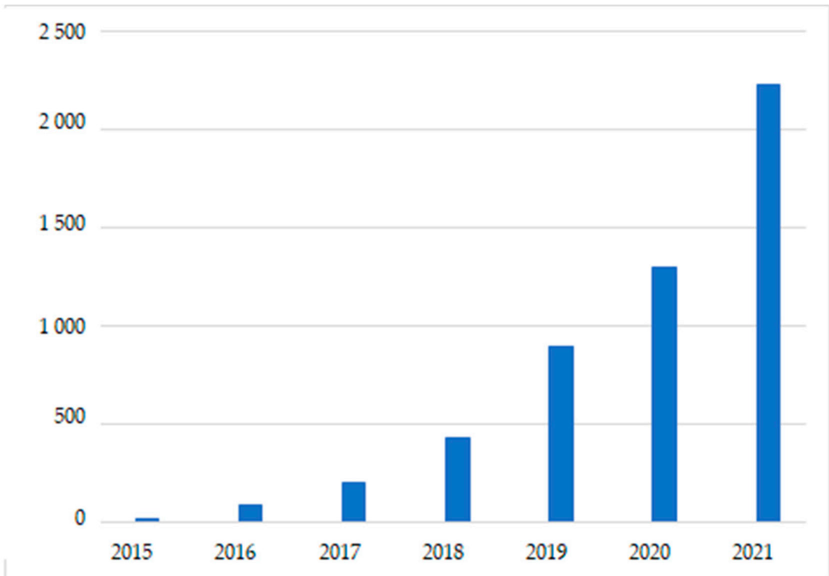

Figure 16. Growth of charging stations from 2014 to 2021 worldwide (in millions) [30].

As in France and Europe, the growth worldwide has been exponential. From 20,000 charging stations in 2014 to 2 million in 2021, this growth is significant.

As explained in the introduction, the leaders in EVs are China, the USA, and Europe. Other countries, like Brazil, South Korea, Japan, and Canada take parts in the evolution shown in Figure 18.

Figure 19, below, shows the distribution of each kind of charging station. It is interesting to notice the increase rate of the fast-charging type.

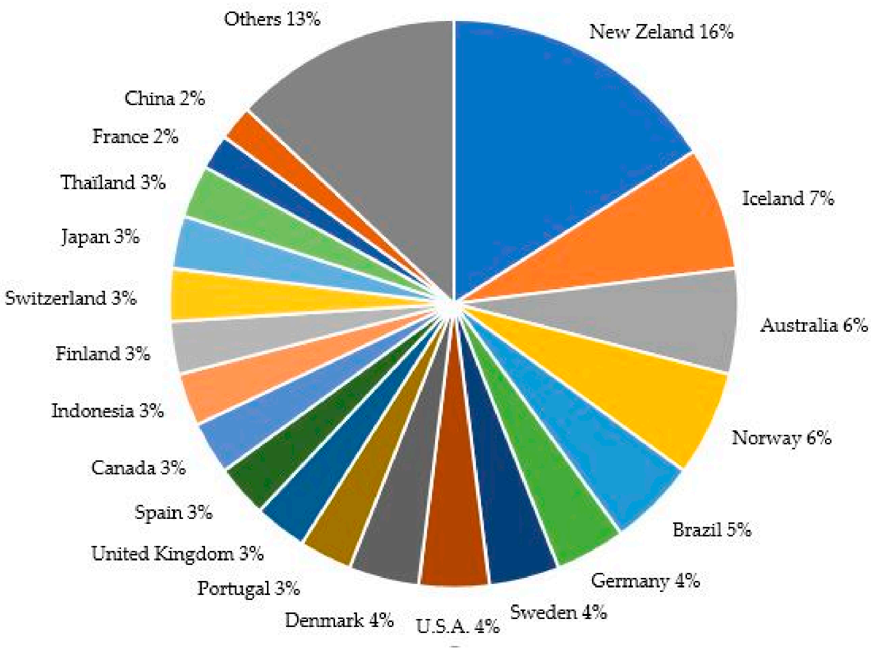

Figure 17. Number of electric light-duty vehicles per public charging point by country among countries that are the main users of EVs [38].

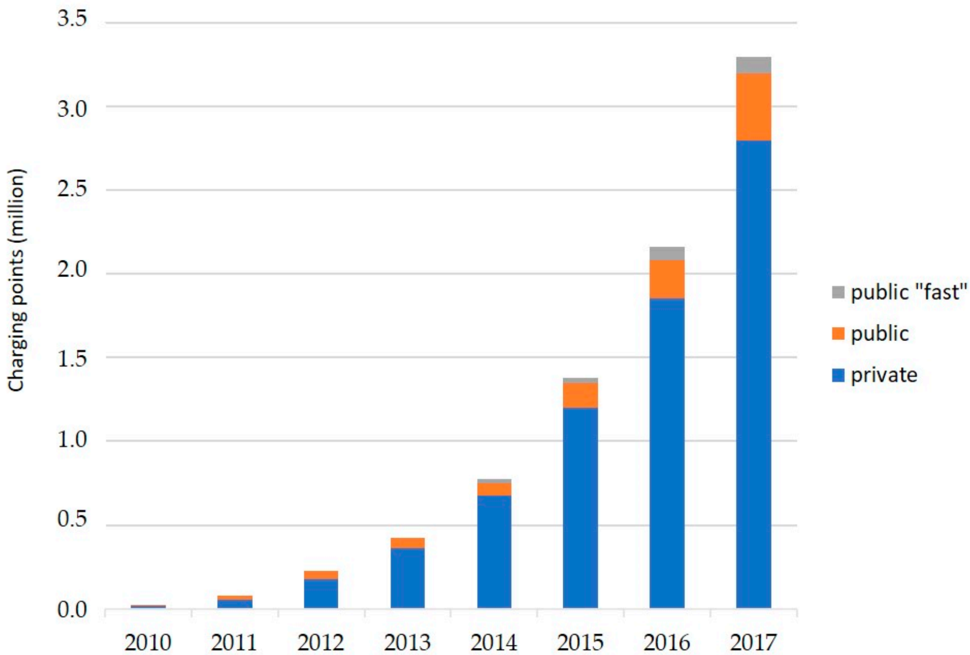

Figure 18. Growth in worldwide infrastructure from 2010 to 2017 and proportion of different kinds of charging stations [39].

According to the International European Agency, by 2030, public charging points will represent around 10% of all charging points for light-duty vehicles, representing a total of 40% of charging capacity for these vehicles.

The number of public charging stations will increase to represent 30% of all charging stations by 2030, in line with the increase in the share of electrical energy attributed to EV, as shown in Table 4.

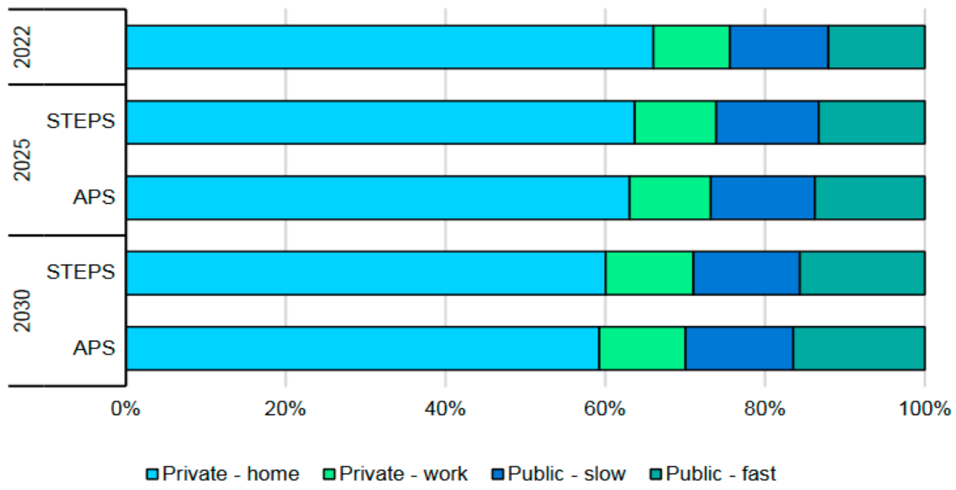

Figure 19. 2030 forecast of the number of charging stations worldwide and their charging capacity [38].

Table 4. Share of electricity consumption by EVs relative to final electricity demand by region and scenario, 2022 and 2030 [38].

Country/Region	2022	Stated Policies Scenario 2030	Announced Pledges Scenario 2030
China	0.8%	3.8%	4.0%
Europe	0.7%	4.7%	5.7%
United States	0.4%	5.4%	6.3%
Japan	0.1%	1.7%	2.2%
India	0.1%	1.7%	2.5%
Global	0.5%	3.2%	3.8%

As of the end of 2022, China owned nearly 65% of public slow chargers because access to home chargers is limited.

The considerable impact of EVs on energy production must also be considered. This extensive use of charging stations needs to be matched by growth in the capacity of the power grid [39].

Countries will have to manage peak load and carefully plan electricity infrastructures to respond to the demand imposed by private chargers, which are currently mostly installed in Europe, the USA, and China. Some approaches are already being studied, generating a new circular business model that includes, for example, the following steps: (1) improve the power of EV charging stations; (2) enable large-capacity energy storage inside charging stations; (3) coordinate with local distribution networks to redirect the power flow; and (4) coordinate charging control with network loading conditions [39].

4.3. Differences between France and Other Countries

It is worth noting that the standards are not the same in France as in the other countries discussed here, despite an exponential increase in the number of EVs. The standard in effect depends on the types of charging points, the electrical supply mode, the type of nozzle, the power of the charging station, and the politics of the country. All these factors influence the construction rate. Social aspects such as the driver's residence (single-family home, apartment, ...) and population density also have an impact. For example, in the USA, 80% of EV owners live in single-family homes, where 50–80% of all chargers are housed.

5. Issues, Challenges and the Future of Charging Stations and EVs

This last section deals with the future of charging stations. Statistics and new possibilities are presented.

5.1. Politics of Ecological Transition and the Disappearance of Thermal Vehicles

In recent years, with the emergence of EVs, the disappearance of ICE has become a major 15-year goal. For example, in France, and more generally in the UE, starting in 2035, the sales of ICE vehicles will end, with all vehicles sold thereafter to be exclusively electrical. In general, governments are setting targets and timelines for phasing out the sales of thermal vehicles. Additionally, governments are investing in the expansion of charging-infrastructure networks in order to support the adoption of electrical cars. This expansion includes public installations and encouragement of private installation.

In this way, countries will accelerate the ecological transition by reducing their carbon emissions. New standards restrict the rate of emissions, affecting not only countries, but automobile manufacturers as well. Cars must pollute less to be sold, and these developments are watched carefully by institutions.

Finally, awareness campaigns have encouraged drivers to switch from ICE to hybrids, and then to the fully electric cars, which are considered to be the optimal choice. Each year, the number of thermal cars bought decreases (sometimes by a large amount) and the number of electric cars increases.

5.2. New Technologies?

Currently, some new technologies are being tested. These new technologies aim to improve the efficiency and functionalities of charging points. Some such technologies are listed in Table 5 below:

Table 5. Descriptions of some new technologies for charging stations.

New Technologies	Explanation
High-power charging	This technology delivers more power to electric cars. The power ranges from 100 kW to 350 kW and reduces the time needed for recharging. High-power charging is useful for long-distance travel.
Ultra-fast charging and XFC	This technology represents an improvement over high-power charging. These charging stations can deliver 400 kW and more.
Smart charging	Smart charging optimizes the charging process by considering multiple factors, including the condition of the network, energy prices, and user preferences. Smart charging helps to ease the load on the network.
Wireless charging	Wireless charging eliminates the physical contact between the charging stations and the EVs. Like an induction charge for phones, it uses electromagnetic fields to transfer energy. However, in general, it delivers less power than a classic charging station.

All these technologies contribute to the development of charging stations and aim to improve users' comfort and experience. Although these technologies are still in the research-and-development stage, they will soon be available to the public.

5.3. Estimations and Extrapolation

It has been seen previously that the number of charging stations is growing exponentially. This trend is discussed on three scales: in France, in Europe, and worldwide, and the predictions offered here are drawn from these estimates.

In France, the number of charging stations increased from 8600 in 2014 to 82,107 in 2022. Based on these data, we extrapolate to future numbers, as follows in Equation (1):

$$y = 2 * 10^{-229} * e^{0.226*t} \quad (1)$$

For this model, R^2 = 0.9767. R^2, the coefficient of determination, is an index of the quality of the linear regression model. The value of the coefficient of determination is between 0 and 1. The closer it is to 1, the better the linear regression matches the real data.

Even including 2020, the year when the COVID-19 pandemic began, the model shows a clear trend. Of course, the predictions of this model will hold only if the trend in the number of EV sold continues to grow as it has in the past.

By 2030, according to the model, there will be about 650,000 charging points in France.

The stated goal of the French government is around 400,000 charging points by 2030. The distance between the theory and the reality is the result of the increase in maintenance costs. Also, it will be difficult to implement a 14.85-fold increase in the number of charging stations, considering the significant investments that will be needed and the rate of EV adoption in France. Additionally, the rate of growth will begin to flatten region once there are enough recharging stations in a given region/country. Furthermore, much remains to be done to educate auto drivers in the use of these technologies. As of September 2023, according to the French Ministry of Energy Transition, the average availability rate of charging points was 82%.

For Europe, the trend is the same as that in France, growing from 5000 charging stations in 2010 to 285,000 in 2020. Based on the number of charging stations available in Europe in recent years, Equation (2) predicts future numbers in exponential form:

$$y = 3437 * t^2 - 1.382E + 0.7 * t + 1.39E + 10 \quad (2)$$

with an R^2 (coefficient of determination) equal to 0.9917.

As is logical, the rate of growth estimated for Europe is greater than that for France, especially as there may be 1,000,000 charging stations before 2030. However, the same problems exist in Europe as in France and similarly manifest in a difference between the reality and the theory: investments, the evolution of the European Union rules, and the financial incentives for EV buyers in Europe.

Worldwide, the growth in EV infrastructure is faster than that in Europe, where it is faster than that in France.

The development of charging stations is increasing exponentially. The number is predicted to grow from 20,000 in 2016 to 2,000,000 in 2030 and is not predicted to stop immediately, as estimated in Equation (3). In countries like China and USA, which aim to set the standard for the world, the numbers will reach records. Based on the number of charging stations over the world in recent years, Equation (3) predicts the number of charging stations that will be established in the years to come.

$$y = 11250 * t^3 - 7E + 0.7t^2 + 1E + 11t - 9E + 13 \quad (3)$$

The prediction model shows the potential of the charging stations. According to the model, there should be 3,000,000 in 2021, and there will be 4,000,000 in 2023.

Figures 20–22 show predictions of the number of charging stations in France, in Europe, and worldwide based on the numbers of charging stations in recent years and mathematical equations extrapolating the trends over future years. The extrapolations are based on either polynomial or exponential functions in order to fit with the actual data. The least-squares error is shown at the bottom of Figure 20 and represents the accuracy of the extrapolation. These predictions could be useful for grid management and utility companies, helping them provide the right quantity of electricity to charge the expected number of EVs.

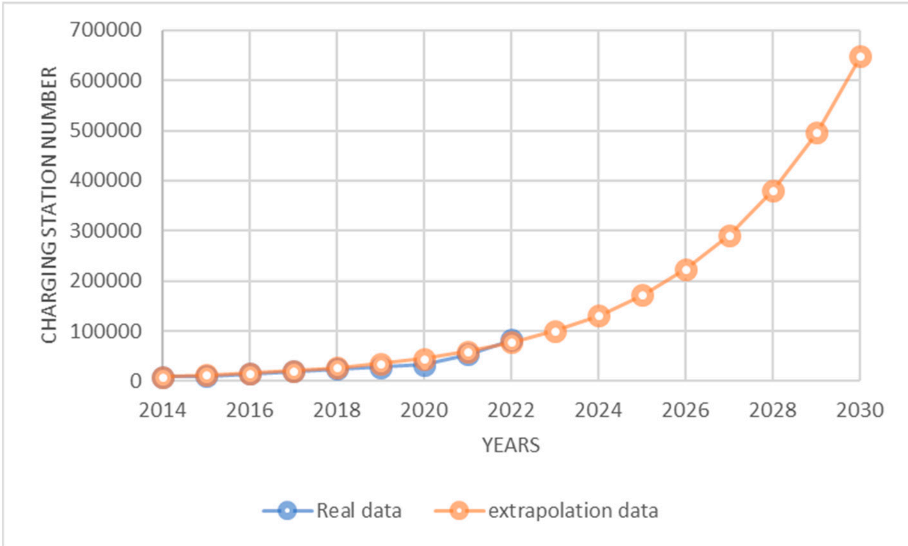

Figure 20. Predicted number of charging stations in France for years up to 2030.

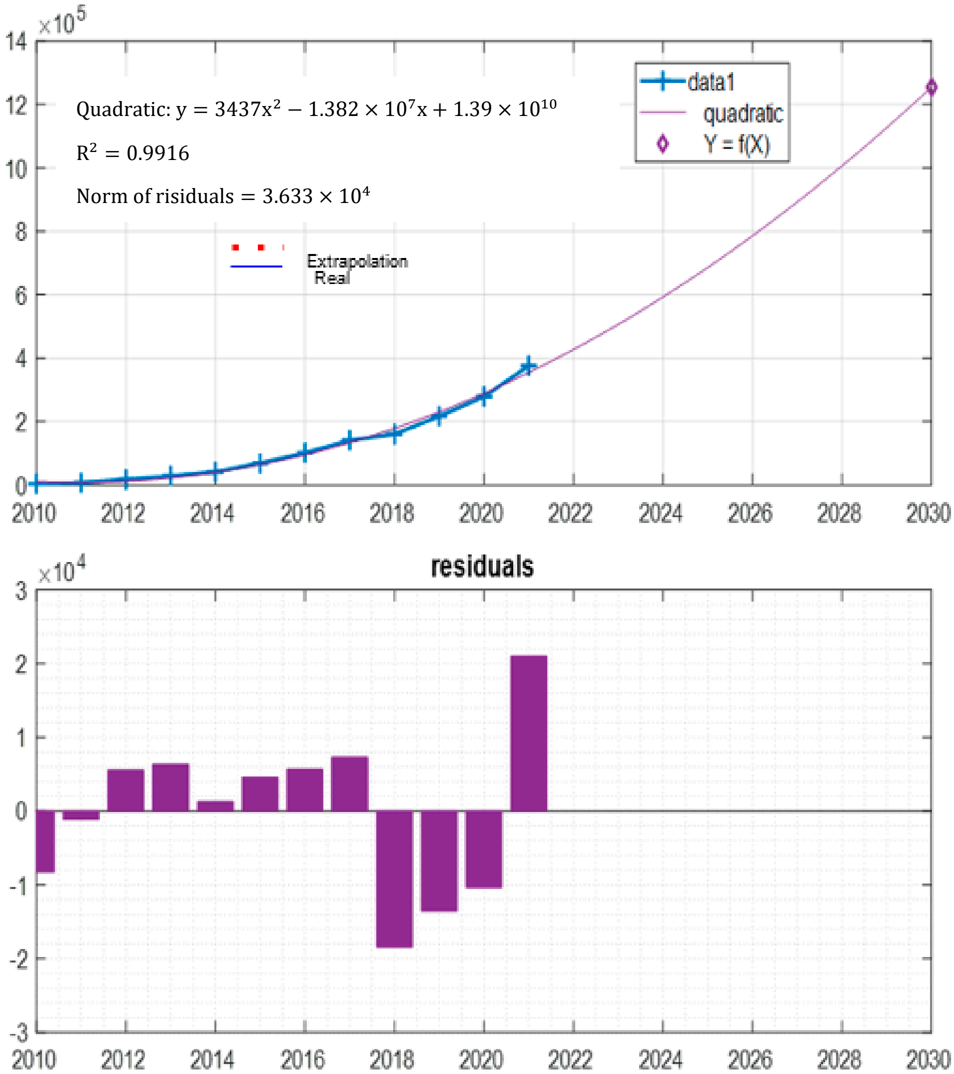

Figure 21. Extrapolation of the trend in the number of charging stations in Europe for years up to 2030.

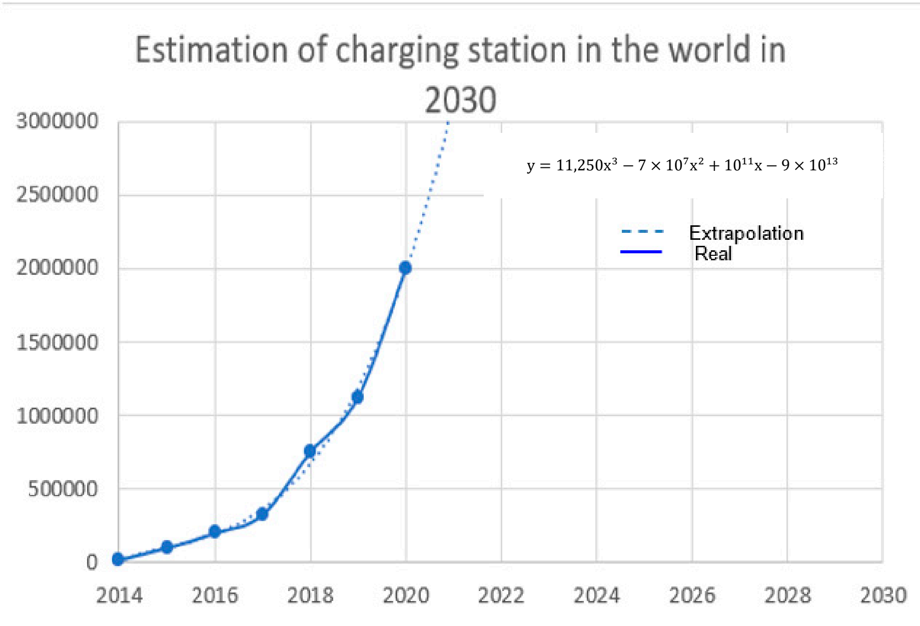

Figure 22. Extrapolation of the trend in the number of charging stations for years up to 2030.

6. Discussion, Limits and Conclusions

The development of charging stations is crucial to enabling the uptake of electric vehicles (EVs), but it is still in its early stages. Despite increasing research efforts, forecasts and assumptions about the organization of charging station networks are often inconsistent. Recently, the French association for the development of electric mobility published a comprehensive report based on multiple studies to provide a clear vision of EV charging infrastructure in France. This report highlights the lack of consistent forecasts and the difficulty of obtaining realistic figures: between the low and high numbers given in the main statistical studies, the difference is approximately 18.6%. Estimating the number of charging stations is just one aspect of the challenge. Table 6 shows the difficulty of forecasting even for state institutions.

France's EV charging-infrastructure-expansion strategy aims to ensure there will be a sufficient number of charging stations to meet the needs of EV owners across the country's diverse regions of varying population densities. This strategy involves implementing a four-tiered approach to charging-station deployment, encompassing high-power chargers along highways, public charging stations in urban areas, EV chargers in parking garages, and destination charging stations at tourist destinations, hotels, and workplaces [40]. This comprehensive approach addresses the heterogeneity of population density and forecasts a decline in private charging installations, with public charging becoming the primary source of EV charging by 2030 (56% in 2030 versus 80% in 2022). To optimize power delivery and ensure efficient energy management, smart charging technologies are also being adopted, enabling charging stations to communicate and coordinate with each other and with the grid. This proactive approach to the development of EV charging infrastructure positions France to support the growing EV market and transition towards a cleaner transportation system.

The European Commission is considering three scenarios, which are defined by the type of charging station (slow or fast public recharging points), the capacity of batteries, and territorial coverage. The global number of the 27 UE is an underestimate; in 2030, more than 15 countries did not install enough charging stations to provide sufficient recharging infrastructure (confere last commission staff working document impact assessment; Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:0aacf271-e576-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF#page=50) (accessed on 18 december 2023).

Table 6. Number of public EV charging stations in 2030: some forecasts [29,30,32,38,41,42].

France						
Forecasts (year)	2022			2030		
Sources	IAE [38]	Statistica [30]	AVERE [43]	IAE [38]	AVERE [43]	Extrapolation data
Estimated number of public charging stations	83.7	82.1	82.1	-	330 to 480	650
Europe						
Forecasts (year)	2022	2030				
Sources	IAE [38]	EU [44] current policies	EU [44] Policies Options	IAE [38]	Transport & Environment Association *	Extrapolation data
Estimated number of public charging stations (in thousands of units)	518	2304.5	3500.7 to 3573.5	2380	2200 to 2900	1250
World						
Forecasts (year)	2022	2030				
Sources	IAE [38]	-	-	IAE [38]	-	Extrapolation data
Estimated number of public charging stations (in thousands of units)	2700	-	-	12700	-	not estimated

* Transport & Environment Association: https://www.transportenvironment.org/wp-content/uploads/2021/07/01%202020%20Draft%20TE%20Infrastructure%20Report%20Final.pdf (accessed on 1 January 2021).

The charging-station infrastructure of the future is still under construction and faces many constraints. Firstly, there are technical considerations regarding both batteries and charging infrastructure. Key research areas include finding the best balance between charging-system capacity and battery longevity, using more sustainable battery materials, connecting to the grid, facilitating communication between vehicles and power systems, standardizing systems, and developing a circular economy model for EVs and batteries, particularly for battery reuse and refurbishing.

Secondly, there are significant financial concerns at two levels: the cost of installing charging stations for investors and the overall cost of electric mobility for users. Governments are making significant efforts to promote the adoption of EVs by providing financial assistance and incentives for both investors and users. Additionally, countries have announced substantial budgets for the deployment of fast-charging stations. Nevertheless, the situation remains highly variable globally, taking into account differences in the type of housing (for instance, a higher prevalence of single-family homes in the United States, with these homes containing more than 80% of private charging points), population density across countries (the need for more public charging systems in major cities), and political structures (for example, the challenges faced by small-town mayors in installing charging stations for their residents in some French villages). However, there are still unanswered questions about the division of responsibilities between public and private charging points and the optimal economic distribution of slow, fast, and ultra-fast charging systems. This lack of visibility makes it difficult to precisely forecast numbers of charging stations and the distribution of types.

Thirdly, the acceptability of EVs to end users depends on a variety of factors, including the cost, time, and range compared to internal combustion engine (ICE) vehicles, as well as the higher purchase price of EVs. The decision-making process should consider factors such as price, user habits, intentions, and acceptance of the technology. There is still significant variation in these factors, even within the European Union. While nations are working to standardize technical components, there is still much to be done to optimize payment systems. These adjustments require user education, and there is still a great deal of uncertainty about user behavior and acceptance of EVs compared to other mobility solutions.

Finally, the increase in the number of EVs and the use of charging stations raises concerns about the capacity of the power grid and the need to regulate electricity consumption. Researchers are exploring solutions to regulate peak electricity consumption, such as grid-to-grid technologies. Long-term planning and anticipation of demands on the global charging system are essential to preventing the overprovisioning of charging infrastructure and the inefficient deployment of fast charging stations. Furthermore, with substantially lower carbon emissions, renewable charging infrastructure presents a compelling alternative approach.

In conclusion, charging stations have immense potential, and their growth is still in its beginning stages. New technologies are emerging, and countries are continuing to develop their infrastructures and policies accordingly. Technical standards have been established to simplify the use of charging stations and, consequently, of EVs. However, there is still much to be done, particularly in Europe, to harmonize payment systems and provide users with sufficient relevant information to ensure proper implementation of the Trans-European Transport Network (TEN-T) [40]. Charging stations play a critical role in the ecological transition. The increasing numbers of charging stations and EVs will undoubtedly have an impact on the grid and on electricity demand. Of course, EVs are the solution to overcoming fossil-fuel depletion, but only if electricity or hydrogen is generated using clean, sustainable, and renewable sources, which presents another challenge.

The originality of this work lies in the collaboration of researchers from diverse disciplines, including electrical engineering, control systems, economics, and marketing, to use trends to forecast the numbers of charging stations in France, Europe, and worldwide, and to explain the pace of EV development and charging station deployment based on regulations and costs.

This work has demonstrated a steady increase in the number of battery-powered vehicle charging stations worldwide. However, it is not enough to consider only the battery without taking into account the full lifecycle effects, particularly the impact on the electric grid, which influences the design of new battery models. The increasing adoption of EVs will also lead to a significant increase in electricity demand.

Both researchers and companies are exploring the best methods for recycling or reusing used batteries. Three main approaches are being investigated: remanufacturing, reuse, and disposal [43,44]. For instance, second-life car batteries could be employed as home-storage solutions.

Researchers are also considering designing batteries with fewer polluting rare materials and developing a new generation of chargers, V1G (Automated Unidirectional Smart Charging) and V2G. These chargers offer the ability to manage the power grid more efficiently and in a flexible way [41] by reducing peak usage levels. The V2G system allows power from the EV's battery to be fed back into the grid.

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Acronyms

BEV	plug-in-Battery Electric Vehicle
CCS	Combined Charging System
EV	Electric Vehicle
G2V	Grid to Vehicle power flow
ICE	Internal Combustion Engine
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State Of Charge
TEN-T	Trans-European Network for Transport
V2G	Vehicle to Grid power flow

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