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Review

A Review on Electric Vehicles: Technologies and Challenges

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Abstract: Electric Vehicles (EVs) are gaining momentum due to several factors, including the price reduction as well as the climate and environmental awareness. This paper reviews the advances of EVs regarding battery technology trends, charging methods, as well as new research challenges and open opportunities. More specifically, an analysis of the worldwide market situation of EVs and their future prospects is carried out. Given that one of the fundamental aspects in EVs is the battery, the paper presents a thorough review of the battery technologies—from the Lead-acid batteries to the Lithium-ion. Moreover, we review the different standards that are available for EVs charging process, as well as the power control and battery energy management proposals. Finally, we conclude our work by presenting our vision about what is expected in the near future within this field, as well as the research aspects that are still open for both industry and academic communities.

Keywords: Electric Vehicles; Plug-In Hybrid Electric Vehicle; battery charging; batteries technology; charging modes; EV plugs

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1. Introduction

The automotive industry has become one of the most important world-wide industries, not only at economic level, but also in terms of research and development. Increasingly, there are more technological elements that are being introduced on the vehicles towards the improvement of both passengers and pedestrians' safety. In addition, there is a greater number of vehicles on the roads, which allows for us to move quickly and comfortably. However, this has led to a dramatic increase in air pollution levels in urban environments (i.e., pollutants, such as PM, nitrogen oxides (NO_X), CO, sulfur dioxide (SO_2), etc.).

In addition, and according to a report by the European Union, the transport sector is responsible for nearly 28% of the total carbon dioxide (CO_2) emissions, while the road transport is accountable for over 70% of the transport sector emissions [1]. Therefore, the authorities of most developed countries are encouraging the use of Electric Vehicles (EVs) to avoid the concentration of air pollutants, CO_2, as well as other greenhouse gases. More specifically, they promote sustainable and efficient mobility through different initiatives, mainly through tax incentives, purchase aids, or other special measures, such as free public parking or the free use of motorways. EVs offer the following advantages over traditional vehicles:

- Zero emissions: this type of vehicles neither emit tailpipe pollutants, CO_2, nor nitrogen dioxide (NO_2). Also, the manufacture processes tend to be more respectful with the environment, although battery manufacturing adversely affects carbon footprint.
- Simplicity: the number of Electric Vehicle (EV) engine elements is smaller, which leads to a much cheaper maintenance. The engines are simpler and more compact, they do not need a cooling circuit, and neither is necessary for incorporating gearshift, clutch, or elements that reduce the engine noise.

- Reliability: having less, and more simple, components makes this type of vehicles have fewer breakdowns. In addition, EVs do not suffer of the inherent wear and tear produced by engine explosions, vibrations, or fuel corrosion.
- Cost: the maintenance cost of the vehicle and the cost of the electricity required is much lower in comparison to maintenance and fuel costs of traditional combustion vehicles. The energy cost per kilometer is significantly lower in EVs than in traditional vehicles, as shown in Figure 1.
- Comfort: traveling in EVs is more comfortable, due to the absence of vibrations or engine noise [2].
- Efficiency: EVs are more efficient than traditional vehicles. However, the overall well to wheel (WTW) efficiency will also depend on the power plant efficiency. For instance, total WTW efficiency of gasoline vehicles ranges from 11% to 27%, whereas diesel vehicles range from 25% to 37% [3]. By contrast, EVs fed by a natural gas power plant show a WTW efficiency that ranges from 13% to 31%, whereas EVs fed by renewable energy show an overall efficiency up to 70%.
- Accessibility: this type of vehicle allows for access to urban areas that are not allowed to other combustion vehicles (e.g., low emissions zones). EVs do not suffer from the same traffic restrictions in large cities, especially at high peaks of contamination level. Interestingly, there was a recent OECD study that suggests that, at least in terms of Particulate Matter (PM) emissions, EVs will unfortunately not improve the air quality situation [4].

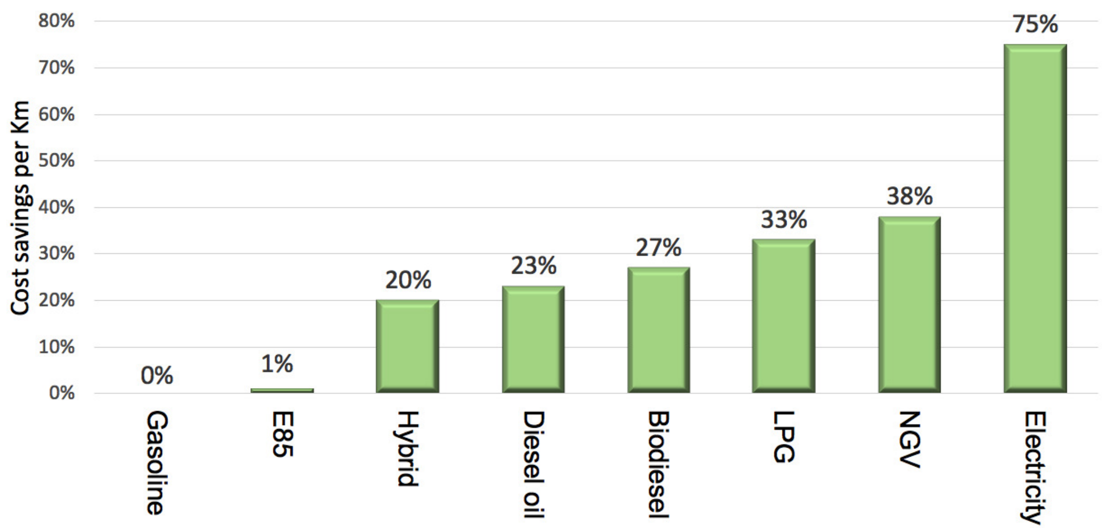


Figure 1. Comparison of savings in cost per kilometer offered by vehicles powered by Gasoline, Ethanol (E85), Hybrid, Diesel oil, Biodiesel, Liquefied Petroleum Gas (LPG), Natural Gas Vehicle (NGV), and Electricity [5].

On the other hand, EVs do, however, face significant battery-related challenges:

- Driving range: range is typically limited from 200 to 350 km with a full charge, although this issue is being continually improved. For example, the Nissan Leaf has a maximum driving range of 364 km [6], and the Tesla Model S can reach more than 500 km [7].
- Charging time: full charging the battery pack can take 4 to 8 h. Even a "fast charge" to 80% capacity can take 30 min. For example, Tesla superchargers can charge the Model S up to 50% in only 20 min, or 80% in half an hour [7].
- Battery cost: large battery packs are expensive.

- Bulk and weight: battery packs are heavy and take up considerable vehicle space. It is assumed that the batteries of this type of vehicles have an approximate weight of 200 kg [8], which can vary, depending on the battery capacity.

In the coming years, EVs will have a very important role in Smart cities, along with shared mobility, public transport, etc. Therefore, more efforts to facilitate the charging process and to improve batteries are needed. The main drawback of the EVs is their autonomy. However, researchers are working on improved battery technologies to increase driving range and decrease charging time, weight, and cost. These factors will ultimately determine the future of EVs.

In this paper, we present a comprehensive survey of the most important aspects of EV technologies, charging modes, and the research carried out by different research teams and labs. Figure 2 depicts the main topics that are presented in the paper. Overall, the insight and contributions of our work are the following: (i) we present an analysis of the existing surveys in the literature, motivating the need of our work, since we present some aspects that had not been dealt with before, and we cover the latest works that are presented in the literature, (ii) we analyze the current worldwide market situation of EVs and their prospects, (iii) we make a thorough review of the battery technologies—from the lead-acid batteries to the Lithium-ion, including the latest technologies, such as graphene, (iv) we review the different standards available for EV charge, as well as the types of connectors that are defined by them, (v) we present the most relevant works related to Battery Management Systems (BMSs), thermal management, and power electronics, and (vi) we conclude our work by discussing what is shortly expected in this field, as well as the research aspects, which, in our opinion, are still open for both industry and academic community.

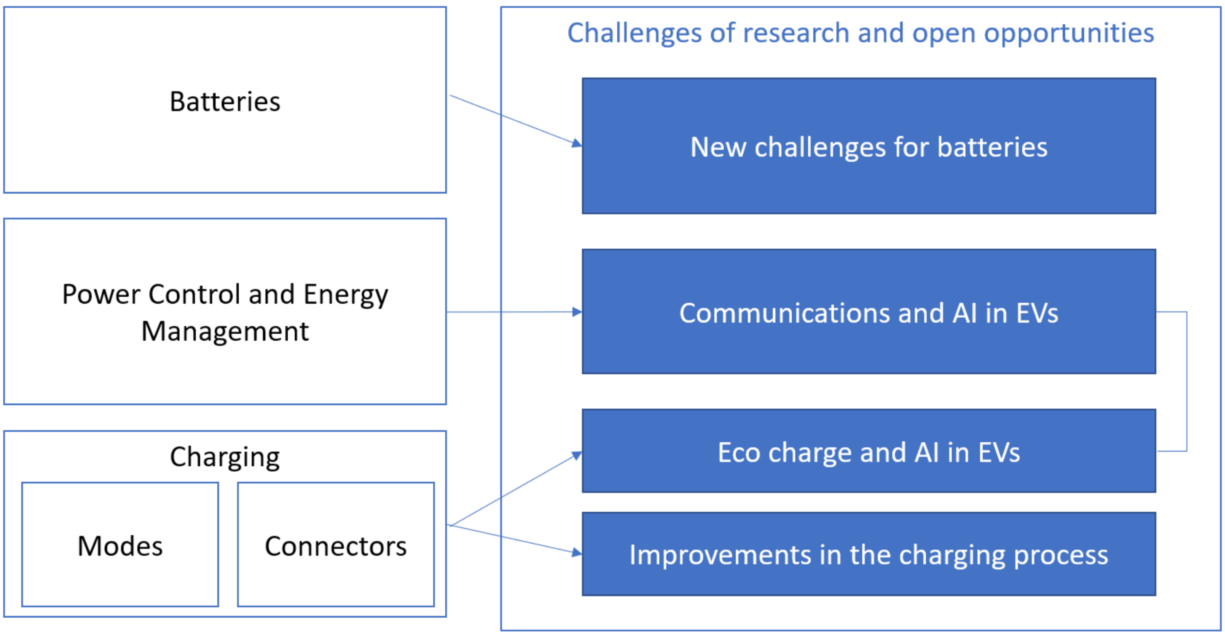


Figure 2. Topics included in our work.

The remainder of the paper is structured, as follows: Section 2 presents the most relevant surveys available in the literature, and motivates the need of our work. Section 3 presents an overview of the market, highlighting a taxonomy of the different types of EVs, the evolution of sales of EVs, and the current market situation. In Section 4, we discuss the most remarkable features of the batteries, and the different types of batteries according to their technology. Section 5 shows the diverse existing standards for charging the EVs, the different charging modes of each standard, as well as the types of connectors defined by them. Section 6 explores the energy management in EVs, we especially focus on Battery Management Systems (BMSs), thermal management, and power electronics. In Section 7, we discuss aspects that are related to the EVs, which, in our opinion, should be explored, that still require to be improved, or that present challenging opportunities to the scientific community. Last, but not least, Section 8 presents the main conclusions that were obtained from the realization of the present work.

2. Existing EV-Related Surveys

In the last decade, there has been a significant progress in several aspects that are related to the production of electric vehicles, and the use of new technologies as well as their sales. Similarly, the research efforts have also increased, which has caused a significant increase of new jobs and proposals that are related to electric vehicles. Within this section, a short compilation of the most relevant topics related to EVs, which have been addressed by previously available works in the literature, are introduced. In addition, the more notable differences with this survey are highlighted.

Some of the studies published to date deal with general aspects, such as the evolution of electrical vehicles throughout history, give diverse classifications according to the manner in which they have been designed and the characteristics of their engines, or analyze their impact on the electrical infrastructure. For instance, Yong et al. [9] review the history of EVs from their creation, in the middle of the nineteenth century, until present. Additionally, they carry out a classification of the vehicles according to their powertrain settings. Finally, their work analyzes the impact of charging electric vehicles on the electric grid. Likewise, Richardson [10] studies the effects that EVs can produce in the required productivity, efficiency, and capacity of the electric grid. Furthermore, he reviews the economical and environmental impact of electric vehicles. Habib et al. [11] present a review of charging methods for electric vehicles and analyze their impact in the power distribution systems. Additionally, the authors carry out an analysis of coordinated and non-coordinated charging methods, delayed loading, and intelligent planning of charges. Finally, they study the economic benefits of the vehicle-to-grid (V2G) technology according to the charging methods.

Another aspect also dealt with in diverse works has been the use of renewable energy sources (i.e., wind power, solar, and biomass) and their incorporation in the electric vehicles field. Liu et al. [12] present a general vision about electric vehicles and renewable energy sources. They specifically focus on solar and wind power, and present a set of works that are classified into three categories: (i) those works which study the interaction between EVs and the renewable energy sources for reducing the energy cost, (ii) those works focused on improving the energy efficiency, and (iii) the proposals that are mainly seeking to reduce emissions. On the other hand, Hawkins et al. [13] analyze the existing studies about the environmental impact of the Hybrid Electric Vehicles (HEVs) and the Battery Electric Vehicles (BEVs). For that purpose, they present a study of 51 environmental evaluations during the life span of the two kinds of vehicles (i.e., BEVs and HEVs). In their work, the authors take aspects, such as greenhouse gas emissions, the production, transmission, and distribution of electricity, as well as the production of vehicles, batteries, and their life span, into account. Vasant et al. [14] analyze the daily usage of PHEVs, and state that the appropriate deployment of daytime charging stations along with suitable charging control and management of this infrastructure can lead to a wider deployment of PHEVs.

Unlike the previous works, Shuai et al. [15] provide a general vision of the new economic model that is present in electric vehicles, bearing in mind the unidirectional and bidirectional flows of energy (in which the EVs themselves are capable of providing energy to the electric grid). To do this, they analyze different charging facilities for EVs, as well as different methods for unidirectional charging and bidirectional energy commercialization. Finally, they study the use of these vehicles as a feasible storage for the energy that is generated from renewable sources.

Other authors have focused on the different strategies that have been proposed for charging EVs. Tan et al. [16] revise the benefits and challenges of vehicle technology to the grid (V2G), in both the unidirectional and bidirectional charging. Besides advantages, they analyze the challenges, such as the battery deterioration and the high investment cost. Lastly, they complete a compilation of strategies for optimizing V2G, by grouping them according to the technique employed (e.g., genetic algorithms (GAs) and Particle Swarm Optimization (PSO)), as well as according to the objectives: (i) operation costs, (ii) carbon dioxide emissions, (iii) profit, (iv) support for renewable energy generation, (v) load curve, and (vi) power loss. Similar to the previous work, Hu et al. [17] present a revision and classification of methods for the intelligent charging of electric vehicles, but, in this case, focused on the fleet operators. In particular, they present works regarding battery modeling, charging and communications standards, as well as driving patterns. Lastly, they showcase a set of different control strategies to manage EV fleets, as well as mathematical algorithms for its modeling. Rahman et al. [18], present a set of employed methods for solving different problems that are related with the charging infrastructure of PHEVs and BEVs. Additionally, they assess the different charging systems in different environments, such as domestic garages, apartment complexes, and shopping centers.

Because the massive EV deployment will introduce negative impacts on the existing power grid, some works review the different issues and the potential opportunities that EV integration in the smart grid can bring. Yong et al. [9] study the impact of EV deployment from the perspective of vehicle-to-grid technology, and especially for mitigating the renewable energies intermittency. Mahmud et al. [19] discuss all of the aspects related to EV charging, energy transfer, and grid integration with distributed energy resources in the Internet of Energy (IoE). More recently, Das et al. [20] present an evaluation on how future connected EVs and autonomous driving would affect EV charging and grid integration.

Other important EV charging issues are those that are related to battery management, as well as battery health and lifetime estimations, since they are key factors in increasing the battery lifetime. Li et al. [21] review recent advancements in Big Data analytics to allow for data-driven battery health estimation. More specifically, they classify them in terms of feasibility and cost-effectiveness, and discuss their advantages and limitations. Liu et al. [22] go one step further and propose a machine learning-enabled system that is based on Gaussian process regression (GPR) to predict lithium-ion batteries aging. Finally, other approaches instead explore advanced fault diagnosis techniques, since battery faults can potentially cause performance degradation [23].

As previously shown, in general, most of the studies that deal with EVs have focused on: (i) the impact of EV charging in the electric demand, (ii) the use of renewable energy sources in the charging process, and (iii) the proposal of new methods for optimizing the charge of electric vehicles, including grid solutions. However, in this paper, we present the current situation of the market of electric vehicles, the main characteristics of the batteries, their technologies, and charging processes.

In particular, besides carrying out a comparison between the different standards, we display the different charging methods that are defined by these standards, and the connectors used by each of them. Finally, we also discuss the challenges that EVs have to face, and the research lines that we consider are left to explore yet.

3. Electric Vehicles

In this section, we present a classification of the different types of electric vehicles, commenting on their main characteristics. We also discuss the current market situation, analyzing the sales data of this kind of vehicles and sales forecast in different countries in the world.

3.1. Electric VEHICLES Taxonomy

Nowadays, we can encounter different types of EVs, according to their engines technology. In general, they are sorted in five types (See Figure 3):

- Battery Electric Vehicles (BEVs): vehicles 100% are propelled by electric power. BEVs do not have an internal combustion engine and they do not use any kind of liquid fuel. BEVs normally use large packs of batteries in order to give the vehicle an acceptable autonomy. A typical BEV will reach from 160 to 250 km, although some of them can travel as far as 500 km with just one charge. An example of this type of vehicle is the Nissan Leaf [24], which is 100% electric and it currently provides a 62 kWh battery that allows users to have an autonomy of 360 km.
- Plug-In Hybrid Electric Vehicles (PHEVs): hybrid vehicles are propelled by a conventional combustible engine and an electric engine charged by a pluggable external electric source. PHEVs can store enough electricity from the grid to significantly reduce their fuel consumption in regular driving conditions. The Mitsubishi Outlander PHEV [25] provides a 12 kWh battery, which allows it to drive around 50 km just with the electric engine. However, it is also noteworthy that PHEVs fuel consumption is higher than indicated by car manufacturers [26].
- Hybrid Electric Vehicles (HEVs): hybrid vehicles are propelled by a combination of a conventional internal combustion engine and an electric engine. The difference with regard to PHEVs is that HEVs cannot be plugged to the grid. In fact, the battery that provides energy to the electric engine is charged thanks to the power generated by the vehicle's combustion engine. In modern models, the batteries can also be charged thanks to the energy generated during braking, turning the kinetic energy into electric energy. The Toyota Prius, in its hybrid model (4th generation), provided a 1.3 kWh battery that theoretically allowed it an autonomy as far as 25 km in its all-electric mode [27].
- Fuel Cell Electric Vehicles (FCEVs): these vehicles are provided with an electric engine that uses a mix of compressed hydrogen and oxygen obtained from the air, having water as the only waste resulting from this process. Although these kinds of vehicles are considered to present "zero emissions", it is worth highlighting that, although there is green hydrogen, most of the used hydrogen is extracted from natural gas. The Hyundai Nexo FCEV [28] is an example of this type of vehicles, being able to travel 650 km without refueling.
- Extended-range EVs (ER-EVs): these vehicles are very similar to those ones in the BEV category. However, the ER-EVs are also provided with a supplementary combustion engine, which charges the batteries of the vehicle if needed. This type of engine, unlike those provided by PHEVs and HEVs, is only used for charging, so that it is not connected to the wheels of the vehicle. An example of this type of vehicles is the BMW i3 [29], which has a 42.2 kWh battery that results in a 260 km autonomy in electric mode, and users can benefit an additional 130 km from the extended-range mode.

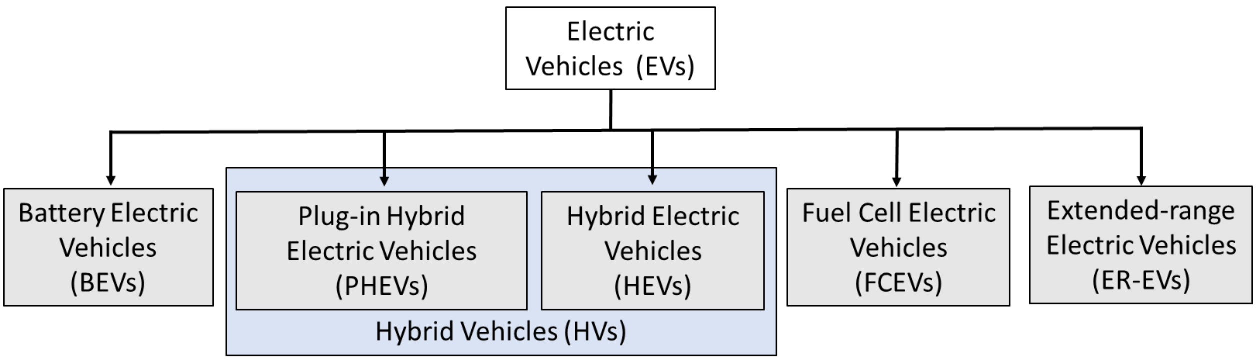


Figure 3. Electric vehicles classification according to their engine technologies and settings.

3.2. Subsidies and Market Position

Despite the fact that the purchase price of electric vehicles is higher, when considering the internal combustion engine edition of the same vehicle model, the EV sales volume has experienced a significant growth, especially in the last years [30]. Additionally, many countries are preparing the mobility transition, discouraging the use of fossil fuel based cars, and stimulating electric mobility. Evidence of this is the fact that, after the Paris Agreement [31], there has been an increase of the public aids to this kind of vehicles.

In fact, practically all of the governments of the developed countries are continuously applying new support and fostering policies for the use of electric vehicles in order to promote sustainable and environment-friendly mobility.

Based on the report from [32–34], for instance, Belgium offers 4000 € of purchase aid, and these types of vehicles pay a road tax of only 74 €, instead of the 1900 € that traditional vehicles pay. In France, the users who purchase an EV receive a bonus of between 4000 € and 6000 € in the case of BEVs, and of 3500 € in the case of purchasing an PHEV. A discount between 50% and 100% is also offered in the registration fee. In the United Kingdom, an incentive of a maximum of £4500 will be offered with the purchase of an EV and, if its worth is less than £40,000, the vehicle is exempted of circulation taxes. In Germany, buyers receive a bonus of 4000 € to purchase a BEV, and of 3000 € in the case of PHEVs. Additionally, BEVs do not pay property taxes, while PHEVs have a reduction of 50%. In the case of Spain, an aid of between 1300 € and 5500 € is offered to purchase BEVs and HEVs, according to their autonomy. In Norway, the property tax for BEVs and PHEVs is of 47 €, while, for petrol-driven cars, such tax varies from 290 € to 340 €. In addition, BEVs do not pay circulation fees or tolls, and they do not pay for parking in the preferred parking areas. Finally, in the USA, the federal government provides $2500 for purchasing electric vehicles and an additional $417 for every kWh of their batteries from 4 kWh, to a maximum of $7500.

All of these subsidies and policies (e.g., car purchasing tax exemption, VAT exemption, reduced license tax, tolls exemption, and free parking) are causing a noteworthy increase of the number of sales every year (especially in the last two years), as can be appreciated in Figure 4 and Table 1. As we can observe, China and USA are, by far, the countries that have the most EV sales, although Norway stands out as the country in the world, in which EVs have a higher market share as almost three out of four vehicles sold in 2020 are electric.

Table 1. Electric Vehicle (EV) market share of total new car sales between 2013 and 2020 [35–41].

Country	2013	2014	2015	2016	2017	2018	2019	2020
Norway	6.10%	13.84%	22.39%	27.40%	29.00%	39.20%	49.10%	55.90%
Iceland	0.94%	2.71%	3.98%	6.28%	8.70%	19.00%	22.60%	45.00%
Sweden	0.71%	1.53%	2.52%	3.20%	3.40%	6.30%	11.40%	32.20%
The Netherlands	5.55%	3.87%	9.74%	6.70%	2.60%	5.40%	14.90%	24.60%
China	0.08%	0.23%	0.84%	1.31%	2.10%	4.20%	4.90%	5.40%
Canada	0.18%	0.28%	0.35%	0.58%	0.92%	2.16%	3.00%	3.30%
France	0.83%	0.70%	1.19%	1.45%	1.98%	2.11%	2.80%	11.20%
Denmark	0.29%	0.88%	2.29%	0.63%	0.40%	2.00%	4.20%	16.40%
USA	0.62%	0.75%	0.66%	0.90%	1.16%	1.93%	2.00%	1.90%
United Kingdom	0.16%	0.59%	1.07%	1.25%	1.40%	1.90%	22.60%	45.00%
Japan	0.91%	1.06%	0.68%	0.59%	1.10%	1.00%	0.90%	0.77%

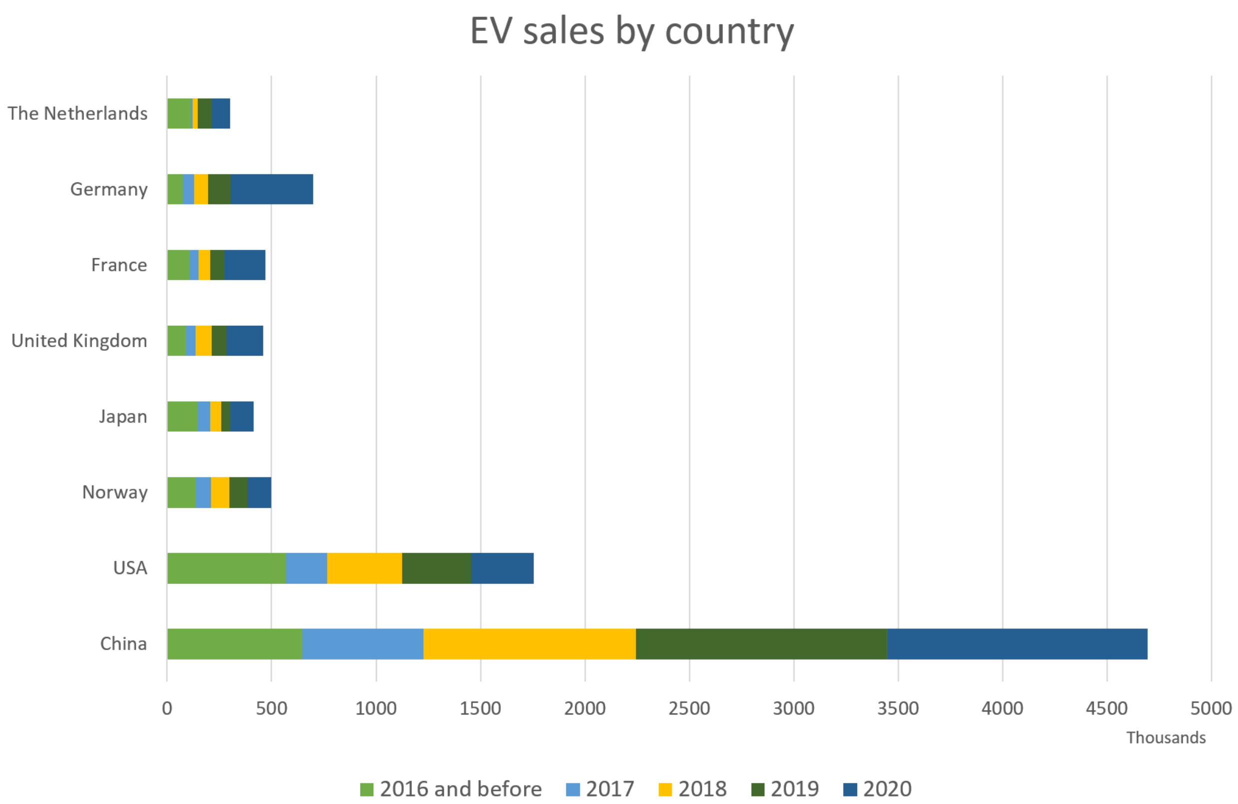


Figure 4. Evolution of the number of electric vehicle sales worldwide [35–41].

According to [42–48], these numbers are expected to keep increasing within the next years, since several countries have expressed their desire to ban internal combustion engine vehicles in the near future. An example of this is Norway, which has announced that all the cars and vans sold in 2025 should be zero-emissions. For their part, India, Israel, and The Netherlands have announced that all of the vehicles sold in 2030 will be electric. Germany and United Kingdom delay this date to 2040, the same year in which combustion vehicles will also be banned in the state of California. In a more restrictive way, in Germany they are considering banning the circulation of diesel vehicles in the cities, and Paris has announced that they will forbid diesel vehicles to circulate in the city from 2024 and those of internal combustion from 2030. Rome will ban the circulation of diesel vehicles from 2024, whereas Madrid, Athens, and Mexico city will do it from 2025.

However, besides the positive data of sales registered worldwide, it is also noteworthy that 95% of the electric vehicles were sold in only 10 countries (i.e., China, USA, Japan, Canada, Norway, United Kingdom, France, Germany, The Netherlands, and Sweden).

Finally, it should also be emphasized that there are currently several models of BEVs and PHEVs for sale. Regarding the most sold models, the Tesla Model 3 (BEV), Toyota Prius Prime (PHEV), Chevrolet Volt, Nissan Leaf (BEV), Tesla model S (BEV), Ford Fusion Energi (PHEV), and BMW i3 (BEV) stand out [30,49].

4. Batteries

In this section, interesting facts that are related to batteries are presented, such as the worldwide production increase, cost reduction, main characteristics, as well as the different existent technologies in the manufacturing process. In the last years, there have been great advancements in the development of batteries. In addition, the worldwide production of batteries for EVs has increased 66% [50], which is undoubtedly directly related to the rise of number of sales of the vehicles, with the forecast predicting the demand of batteries keeps growing. In fact, it is predicted that the offer and the demand of EVs will be even bigger in the coming years.

4.1. Characteristics of the Batteries

Concerning the main characteristics of batteries, we can highlight the following:

- Capacity. The storage difficulty and cost is one of the main problems of electric power. Currently, this results in the allocation of great amounts of money in the development of new batteries with higher efficiency and reliability, thus improving batteries' storage capacity.
  The battery capacity represents the maximum amount of energy that can be extracted from the battery under certain specified conditions. This unit can be expressed in ampere hour (Ah) or in watt hour (Wh), although the latter one is more commonly used by electric vehicles. When considering that, in EVs, the capacity of their batteries is a critical aspect, since it has a direct impact in the vehicles' autonomy, the emergence of new technologies that enables the storage of a greater energy quantity in the shortest possible time will be a decisive factor in the success of this kind of vehicles. Table 2 shows data that are related to the battery capacities of EVs. As shown, the capacity of batteries is continuously growing and vehicles with more that 100 kWh batteries are expected very soon.
- Charge state. Refers to the battery level with regard to its 100% capacity.
- Energy Density. Obtaining the highest energy density possible is another important aspect in the development of batteries, in other words, that with equal size and weight a battery is able to accumulate a higher energy quantity. The energy density of batteries is measured as the energy that a battery is able to supply per unit volume (Wh/L).
- Specific energy. The energy that a battery is able to provide per unit mass (Wh/kg). Some authors also refer to this feature as energy density, and it can be specified in Wh/L or Wh/kg.
- Specific power. The power that a battery can supply per unit of weight (W/kg).
- Charge cycles. A load cycle is completed when the battery has been used or loaded 100%.
- Lifespan. Another aspect to consider is the batteries lifespan, which is measured in the number of charging cycles that a battery can hold. The goal is to obtain batteries that can endure a greater number of loading and unloading cycles.
- Internal resistance. The components of the batteries are not 100% perfect conductors, which means that they offer a certain resistance to the transmission of electricity. During the charging process, some energy is dispelled in the form of heat (namely, thermal loss). The generated heat per unit of time is equal to the lost power in the resistance, so the internal resistance will have a greater impact in high power charges [51]. Thus, more energy will be lost during quick charging processes when compared to slow ones.
  Therefore, it is highly important that batteries can support quick charging and higher temperatures induced due to the internal resistance. In addition, the decrease of this resistance can reduce the charging time that is required, which is one of the most important drawbacks of this type of vehicles today.
- Efficacy. It is the percentage of power that is offered by the battery in relation to the energy charged.

Table 2. Battery capacities of different electric vehicles [35–41].

Vehicle	Year	Capacity (kWh)
Audi duo	1983	8
Volkswagen Jetta citySTROMer	1985	17.3
Volkswagen Golf	1987	8
Škoda Favorit	1988	10
Fiat Panda Elettra	1990	9
General Motors EV1	1996	16.5
Audi duo	1997	10
General Motors EV1	1999	18.7
General Motors EV1	2000	26.4
Tesla Roadster	2006	53
Smart ed	2007	13.2
Tesla Roadster	2007	53
BYD e6	2009	72
Mitsubishi i-MiEV	2009	16
Nissan Leaf	2009	24
Smart ed	2009	16.5
Tesla Roadster	2009	53
BYD e6	2010	48
Mercedes-Benz SLS AMG E-Drive	2010	60
Tata Indica Vista EV	2010	26.5
Tesla Roadster	2010	53
Volvo C30 EV	2010	24
Volvo V70 PHEV	2010	11.3
BMW ActiveE	2011	32
BMW i3	2011	16
BYD e6	2011	60
Ford Focus Electric	2011	23
Mia electric	2011	8, 12
Mitsubishi i-MiEV	2011	10.5
Renault Fluence Z.E	2011	22
Chevrolet Spark EV	2012	21.3
Ford Focus Electric	2012	23
Renault Zoe	2012	22
Tesla Model S	2012	40, 60, 85
BMW i3	2013	22
BYD e6	2013	64
Smart ed	2013	17.6
Volkswagen e-Golf	2013	26.5
Renault Fluence Z.E	2014	22
Tesla Roadster	2014	80
Chevrolet Spark EV	2015	19
Mercedes Clase B ED	2015	28
Tesla Model S	2015	70, 90
BYD e6	2016	82
Chevrolet Volt	2016	18.4
Kia Soul EV	2016	27
Nissan Leaf	2016	30
Renault Zoe	2016	41
Tesla Model 3	2016	50, 75
Tesla Model X	2016	90, 100
BMW i3	2017	33
Ford Focus Electric	2017	33.5
Honda Clarity EV	2017	25.5

Table 2. *Cont.*

Vehicle	Year	Capacity (kWh)
Jaguar I-Pace	2017	90
Nissan Leaf	2017	40
Tesla Model S	2017	75, 100
Volkswagen e-Golf	2017	35.8
Audi e-tron	2018	95
Kia Soul EV	2018	30
Nissan Leaf	2018	60
Renault ZOE 2	2018	60
Renault ZOE 2 rs	2018	100
Tesla Model 3	2018	70, 90
Mercedes-Benz EQ	2019	70
Nissan Leaf	2019	60
Volvo 40 series	2019	100
Audi e-tron	2020	95
BMW i3	2020	42
Hyundai Kona e	2020	64
Mercedes EQC	2020	93
Mini Cooper SE	2020	32.6
Peugeot e-208	2020	50
Volkswagen ID.3	2021	77
Ford Mustang Mach-E	2021	99
Tesla Roaster	2022	200

4.2. The Cornerstones: Cost, Capacity, and Charging Time

Currently, the batteries are the main obstacle to EV wider adoption. The development of better, cheaper, and higher capacity batteries will extend vehicles autonomy, and the users view them as a true alternative to the internal combustion engine vehicles.

In fact, batteries are a key component in EVs and therefore, there are increasing manufacturers (e.g., LG, Panasonic, Samsung, Sony, and Bosch) that invest to develop improved and cheaper batteries.

The most expensive component, in any EV, is the battery pack [52]. For instance, lithium-ion batteries of the Nissan LEAF initially represented a third of the cost of the whole vehicle. However, it is expected that this cost will be progressively reduced; at the end of 2013, the battery pack costs around $500 per kWh (up to half the price per kWh it cost in 2009); currently, the price per kWh is of $200, and it is expected to fall around $100 in 2025. Another fact that reinforces the battery cost reduction trend is that Tesla Motors is building a "Gigafactory" in order to cut down on the production costs and raise the manufacturing of batteries. The Gigafactory is designed to produce more lithium-ion batteries annually than the produced worldwide in 2013 [53]. The lower battery cost would have an obviously direct impact on EV price drop, which makes them more competitive with regard to traditional vehicles.

Regarding the capacity, Figure 5 shows the capacity of the batteries of different EVs from 1983, the date on which the Audi Duo was marketed with an 8 kWh battery until 2022, the date on which Tesla announced that will market a Tesla Roadster with a 200 kWh battery [54].

When traveling with an EV, the key factor is the autonomy, but another limiting factor is the time that is required for charging the batteries. The standard power outlets provide around 3 kW power, which would imply a 10 h load on average for charging a maximum of 30 kWh energy in a battery [55]. Even in the case of using fast charging systems, charging a vehicle may require between 1 and 3 h. In order to solve this problem, an alternative is the creation of Battery Exchange Stations (BESs), which are also known as Battery Swap Stations (BSSs), where batteries are exchanged by similar ones already charged. Israel initially located 33 BESs [56], although Better Place (the company that developed battery-switching services for EVs) filed for bankruptcy in May 2013. However, this approach was extended to the city of Nanjing in 2015 [57], a city of eight million people, which has thousands of electric buses operating. BESs were also tested by taxi vehicles in Tokyo in 2010 [58]. Thinking about this strategy, Tesla created a system in their Model S, in which batteries can be exchanged in only 90 s [59]. Denmark is studying the possibility of creating a sufficient number of BESs with the purpose of providing an infrastructure with 900 charging points and charging batteries stations that are operated by robots [60].

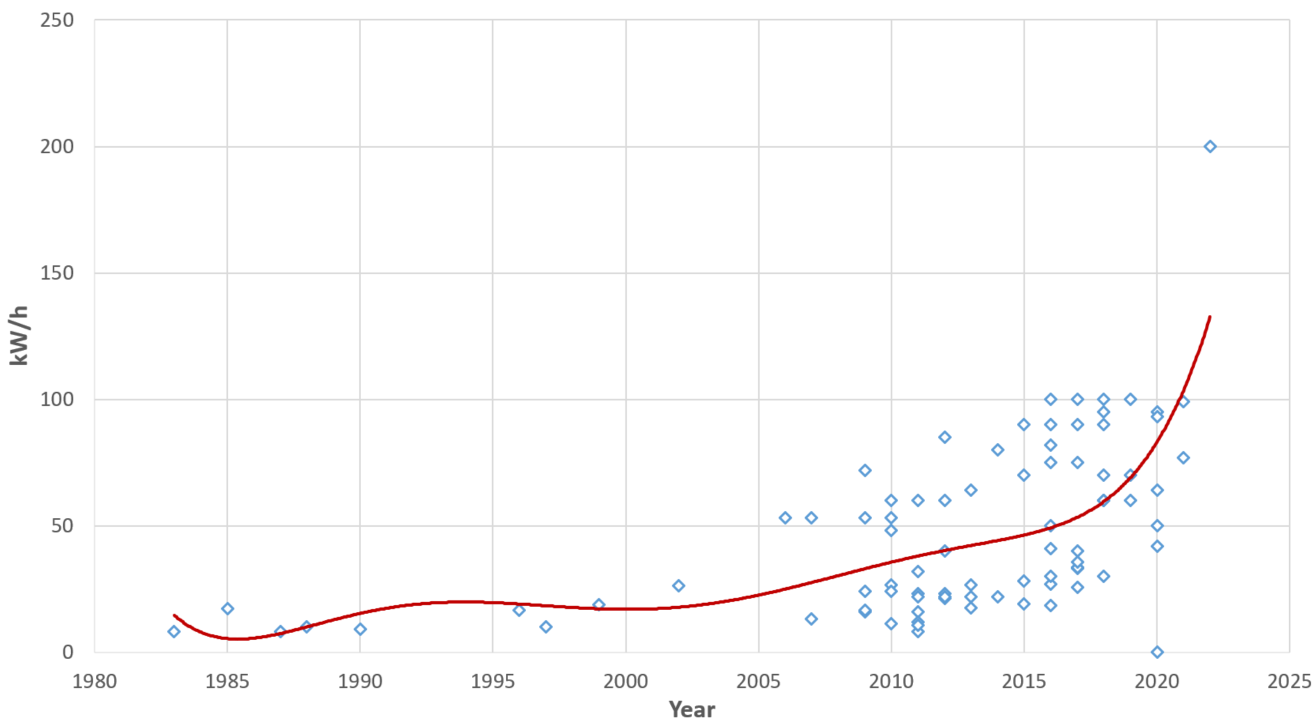


Figure 5. Evolution of the battery capacity since the mid 80s until now.

Concerning the approaches that are related to battery exchange proposed on a scientific level, Adler and Mirchandani [61] suggested an in-line routing method for electric vehicles that allows for changing the batteries in BEs using Markov's random decision processes. Such a method would reduce the waiting time more than 35%. Mak et al. [62] proposed robust optimization models that help the process of the battery exchange planning. The authors also analyzed the possibility of battery standardization and technological development in the optimal strategy for deploying the infrastructures. Yang et al. [63] presented a dynamic operation model of BSSs in the electric market, acquiring extra incomes when actively responding to the price fluctuation in the electricity market. Storandt and Funke [64] approached the EVs routing problem with the aim of finding out what destinations are accessible from a particular location according to the current battery level of the vehicle and the availability of charging or exchange battery stations.

4.3. Different Components and Battery Types

However, the increase of the number of EV models, as well as the different types of batteries and the lack of standardization, are not making the use of BESs a feasible process, since all of the vehicles served by BES should use identical batteries [65]. In fact, although lithium-ion batteries (Li-ion) are increasingly used in EVs, there exists a great variety of batteries, among which the following stand out:

- Lead-acid batteries (Pb-PbO_2). These batteries were invented in 1859 and are the oldest kind of rechargeable battery. Although this kind of battery is very common in conventional vehicles, it has also been used in electric vehicles. It has very low specific energy and energy density ratios. The battery is formed by a sulfuric acid deposit and a group of lead plates. During the initial loading process, the lead sulfate is reduced to metal in the negative plates, while, in the positives, lead oxide is formed (PbO_2). The GM EV1 and the Toyota RAV4 EV, are examples of vehicles that used this kind of batteries.
- Nickel-cadmium batteries (Ni-Cd). This technology was used in the 90s, as these batteries have a greater energy density [66], but they present high memory effect, low lifespan, and cadmium is a very expensive and polluting element. For these reasons, nickel-cadmium batteries are currently being substituted by nickel-metal-hydride (NiMH) batteries.
- Nickel-metal-hydride batteries (Ni-MH). In this type of batteries, an alloy that stores hydrogen is used for negative electrodes instead of cadmium (Cd) [67]. Although they present a higher level of self discharge than those of nickel-cadmium, these batteries are used by many hybrid vehicles, such as the Toyota Prius and the second version of the GM EV1. The Toyota RAV4 EV, apart from having a lead-acid version, also had another with nickel-metal-hydride.
- Zinc-bromine batteries (Zn-Br_2). These kinds of batteries use a zinc-bromine solution stored in two tanks, and in which bromide turns into bromine in the positive electrode. This technology was used by a prototype, called "T-Star", in 1993 [68].
- Sodium chloride and nickel batteries (NA-NiCl). Also being referred to as Zebra, they are very similar to sodium sulfur batteries. Their advantage is that they can offer up to 30% more energy in low temperatures, although its optimum operating range is between 260 °C and 300 °C. These kinds of batteries are ideal for its use in electric vehicles [69]. The disappeared Modec company used them in 2006.
- Sodium sulfur batteries (Na-S), which contain sodium liquid (Na) and sulfur (S). This type of battery has a high energy density, high loading and unloading efficiency (89–92%), and a long life cycle. In addition, their advantage is that these materials have a very low cost. However, they can reach functioning temperatures of between 300 and 350 °C [70]. This type of batteries is used in the Ford Ecostar, the model that was launched in 1992–1993.
- Lithium-ion batteries (Li-Ion). These batteries employ, as electrolyte, a lithium salt that provides the necessary ions for the reversible electrochemical reaction that takes place between the cathode and anode. Lithium-ion batteries have the advantages of the lightness of their components, their high loading capacity, their internal resistance, as well as their high loading and unloading cycles. In addition, they present a reduced memory effect.

Lithium-ion batteries must operate within a safe and reliable operation area, which is restricted by the temperature and voltage windows. Exceeding the restrictions of these windows will cause a quick mitigation of the battery performance and even result in a security hazard (e.g., catch fire or even explode), as from 150 °C electrolytes start to destroy themselves [71]. This type of battery is the most used today by the majority of EVs and PHEVs.

Table 3 and Figure 6 include a comparison of the most relevant characteristics of the different technologies introduced. An important aspect when comparing the different technologies is their working temperature, since it can limit their adoption. In that regard, lead-acid and lithium batteries are the best that put up with low temperatures, as they can load temperatures up to −20 °C, although, in the case of Li-Ion batteries, low temperatures seriously affect its capacity, causing self-discharge [72]. In fact, this type of battery has an optimum functioning temperature of 40 °C. As we can also observe, batteries that are formed by sodium (Na-NiCl y Na-S) have higher functioning temperatures. Regarding the specific energy and the energy density, lead-acid (Pb-PbO_2) and Nickel (Ni-Cd, Ni-MH) batteries stand out negatively, while the more valuable batteries are, by far, the lithium-ion ones.

Table 3. Characteristics of EV batteries [35–41].

	$Pb\text{-}PbO_2$	Ni-Cd	Ni-MH	$Zn\text{-}Br_2$	Na-NiCl	Na-S	Li-Ion
Working Temperature (°C)	−20–45	0–50	0–50	20–40	300–350	300–350	−20–60
Specific Energy (Wh/kg)	30–60	60–80	60–120	75–140	160	130	100–275
Energy Density (Wh/L)	60–100	60–150	100–300	60–70	110–120	120–130	200–735
Specific Power (W/kg)	75–100	120–150	250–1000	80–100	150–200	150–290	350–3000
Cell Voltage (V)	2.1	1.35	1.35	1.79	2.58	2.08	3.6
Cycle Durability	500–800	2000	500	>2000	1500–2000	2500–4500	400–3000

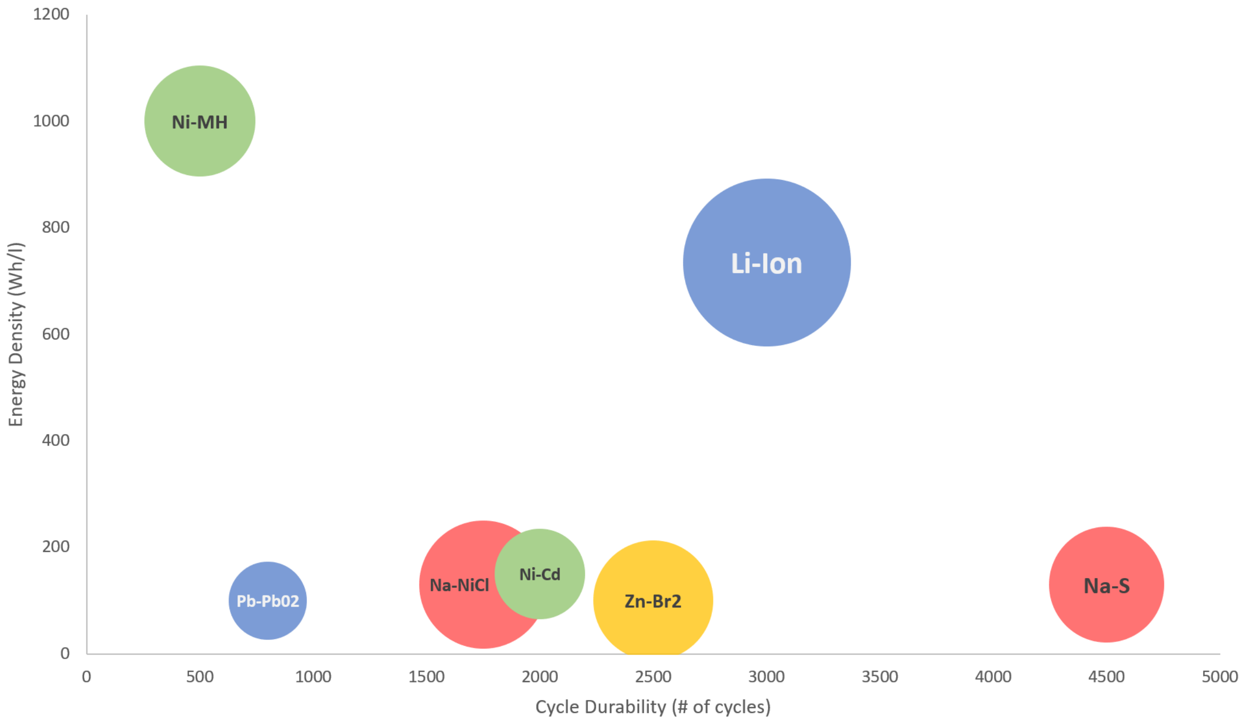


Figure 6. A comparison of battery technologies in terms of their Cycle Durability (x-axis), Energy Density (y-axis), Specific Energy (bubble size), and Working Temperature (bubble color). Note that warm colors represent higher working temperatures.

Concerning the specific power, lead and zinc batteries offer worse results (up to 100 W/kg), while the kinds of batteries with the best scores are those of Ni-MH (with a maximum of 1000 W/kg), and Li-ion, which offer up to 3000 W/kg. As far as the cells voltage, batteries that are formed by nickel and zinc are the ones with lower voltage, while sodium batteries (Na-S y Na-NiCl) and Li-ion use a higher voltage. On the other hand, with respect to the life cycles, the batteries that offer worse results are those of Ni-MH and lead-acid. Lastly, lithium batteries are able to support up to 3000 cycles, and those of Na-S are those that offer better results, supporting up to 4500 cycles.

When considering all of the above parameters, current electric vehicles rely on lithium ion technology for their batteries, as this technology presents the best performance in almost all of the analyzed characteristics.

5. Charging of Electric Vehicles

Besides the autonomy, another important aspect is the duration and the characteristics of the charging process of the batteries. In order for the EVs to definitely succeed, it will be necessary that the users can charge their vehicles in a fast and simple way. To do so, it will be fundamental to have an infrastructure deployment that allows such fast and simple charge. This implies charging at homes, and the creation of electric charging stations that provide quick charges during long commuting. Below, the different standards or rules that are created for electric vehicles charging technology are presented. In particular, we detail the different charging modes that are defined in the current standards, as well as the connectors.

When charging electric vehicles, we can find different standards, which are determined, mainly, by the region in which they are being used or applied. More specifically, in North America, and in the Pacific zone, the SAE-J1772 standard for loading electric vehicles is used. However, in China, the GB/T 20234 standard is used, whereas, in Europe, the IEC-62196 standard was introduced. The main difference between these three standards is that while the two former ones classify the charging modes according to the power type (DC or AC power), the latter one classifies such modes by the charging power involved.

The SAE-J1772 [73] mode is a North American standard of electric connectors for electric vehicles created in 1996, and supported by SAE International. This standard is common in USA and Japan, and it establishes the following charging modes (see Table 4):

- AC Level 1. Standard electrical outlet that provides voltage in AC of 120 V offering a maximum intensity of 16 A, which serves a maximum power of 1.9 kW.
- AC Level 2. Standard electrical outlet with 240 V AC and a maximum intensity of 80 A, so it offers a maximum power of 19.2 kW.
- DC Level 1. External charger that by inserting a maximum voltage of 500 V DC with a maximum intensity of 80 A, it provides a maximum power of 40 kW.
- DC Level 2. External charger that, by inserting a maximum voltage of 500 V DC with a maximum intensity of 200 A, provides a maximum power of 100 kW.

Table 4. Charge ratings of the SAE-J1772 [73].

Charge Method	Volts	Maximum Current (Amps-Continuous)	Maximum Power
AC Level 1	120 V AC	16 A	1.9 kW
AC Level 2	240 V AC	80 A	19.2 kW
DC Level 1	200 to 500 V DC maximum	80 A	40 kW
DC Level 2	200 to 500 V DC maximum	200 A	100 kW

5.1. Charging Modes

The IEC-62196 standard [74] is an international standard created by the International Electrotechnical Commission (IEC) in 2001 for charging electrical vehicles in Europe and China. The IEC-62196 establishes the general characteristics of the charging process, as well as the way in which the energy is supplied. This norm derives from the IEC-61851 and it provides a first classification of the charging type according to its nominal power and, thus, of the charging time [74,75]. Users are provided with four modes in order to charge the vehicles (see Table 5).

- Mode 1 (Slow charging). It is defined as a domestic charging mode, with a maximum intensity of 16 A, and it uses a standard single-phase or three-phase power outlet with phase(s), neutral, and protective earth conductors. This mode is the most used in our homes.
- Mode 2 (Semi-fast charging). This mode can be used at home or in public areas, its defined maximum intensity is of 32 A, and, similar to the previous mode, it uses standardized power outlets with phase(s), neutral, and protective earth conductors.
- Mode 3 (Fast charging). It provides an intensity between 32 and 250 A. This charging mode requires the use of an EV Supply Equipment (EVSE), a specific power supply for charging electric vehicles. This device (i.e., the EVSE) provides communication with the vehicles, monitors the charging process, incorporates protection systems, and stops the energy flow when the connection to the vehicle is not detected.

- Mode 4 (Ultra-fast charging). Published in the IEC-62196-3, it defines a direct connection of the EV to the DC supply network with a power intensity of up to 400 A and a maximum voltage of 1000 V, which provides a maximum charging power up to 400 kW. These modes also require an external charger that provides communication between the vehicle and the charging point, as well as protection and control.

Table 5. Charge ratings of the IEC-62196 [74].

Charge Method	Phase	Maximum Current	Voltage (max)	Maximum Power	Specific Connector
Mode 1	AC Single AC Three	16 A	230–240 V 480 V	3.8 kW 7.6 kW	No
Mode 2	AC Single AC Three	32 A	230–240 V 480 V	7.6 kW 15.3 kW	No
Mode 3	AC Single AC Three	32–250 A	230–240 V 480 V	60 kW 120 kW	Yes
Mode 4	DC	250–400 A	600–1000 V	400 kW	Yes

Guobiao Standards (GB) created the GB/T-20234 standard for charging infrastructures of electric vehicles in China. Although China initially adopted the European standard IEC-62196, the use of their own standard, such as the GB/T-20234, is being promoted. This standard classifies the charging modes between AC and DC, as shown in Table 6.

Based on the survey performed, the SAE-J1772 standard is the only one that includes a 120 V charging mode (see Table 4). The rest of standards, even in their lowest charging modes, work at a higher voltages. As for their most powerful modes, the SAE-J1772 is also the standard that offers a lower voltage (i.e., 500 V) when compared to the 1000 V offered by both the IEC-62196 and the GB/T-20234.

Regarding the amperage, the standard that offers a lower current intensity is the GB/T-20234 with 10 A against the 16 A offered by the other two standards. However, in their most powerful modes, the SAE-J1772 only supports a 200 A maximum intensity, as compared to 250 A of the GB/T-20234 and 400 A of the IEC-62196.

Concerning the charging modes that are based on AC power, the standard that offers a lower power load is the SAE-J1772 with 1.9 kWh when compared to the 2.5 kWh of the GB/T-20234 and the 3.8 kWh supported by the IEC-62196. The standard that offers higher power is the IEC-62196 with 120 kWh, against the 27.7 kWh of the GB/T-20234 and the 19.2 kWh of the SAE-J1772. Something similar occurs in the loading modes based on DC power, in which the IEC-62196 is the standard that offers higher power with 400 kWh, against the 250 kWh of the GB/T-20234 and the 100 kWh offered by the SAE-J1772.

It is also worth noting the case of Tesla Company, which, although it is not an international standard itself, it has its own fast charging points, called Supercharger Stations. Tesla's superchargers work in DC and use their own system, whose patents have been mostly released. Although they have a maximum charging power of 145 kWh, such power is currently limited to 120 kWh, which allows for charging half of the battery of a Model S in only 20 min., or 80% in half an hour [7]. Although Tesla affirms that its superchargers are ultra-fast charging points, if we consider the IEC-62196 criterion (see Table 5), these charging points would be equal to a Mode 3 (fast charging).

Tesla's Supercharger Stations are being installed in main routes every 200 km. Currently, there are 1604 stations and a total of 14,081 superchargers around the world [7]. Additionally, the users of these vehicles have 400 kWh of free charging, which is enough for driving about 1600 km, a strategy that seeks to encourage users to purchase Tesla vehicles.

Table 6. Charging classification of the GB/T-20234 [76].

Mode	Standard	Rated Voltage	Rated Current	Maximum Power
AC Charging	GB/T-20234.2-2015	250 V	10 A 16 A 32 A	27.7 kW
		440 V	16 A 32 A 63 A	
DC Charging	GB/T-20234.3-2015	750–1000 V	80 A 125 A 200 A 250 A	250 kW

5.2. Connectors

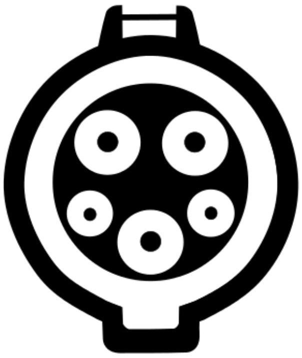
Electric vehicles have an AC/DC converter that allows charging their batteries at home through the use of traditional outlets (e.g., the Schuko in Europe). However, when requiring faster charges, Electric Vehicle Charging Stations must be used, since they can directly supply DC power to the batteries. Charging Stations can supply electricity through different connectors, depending on the standard supported, and they present the following advantages:

- They are sealed solutions (not affected by water or humidity).
- They carry a mechanic or electronic blockage.
- They enable communication with the vehicle.
- Electricity is not supplied until the blockage system is not activated.
- While the blockage system is activated, the vehicle cannot be set in motion, so that a vehicle cannot leave while plugged.
- Some connectors are able to charge in three-phase mode.

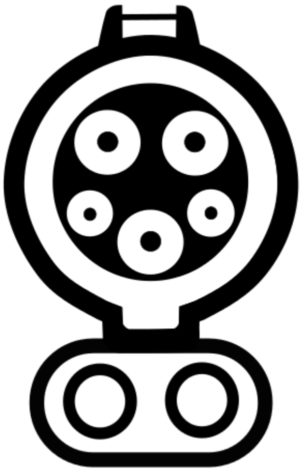
There currently exists a wide range of connectors for charging electric vehicles. These connectors are defined by the different standards: the Society of Automotive Engineers (SAE) is in charge of its normalization in the US and in part of the Pacific countries; the IEC is responsible for its standardization in a great part of the countries in the world, mainly in Europe; and, the Guobiao Standards (GB) manages the standardization in China.

J1772-2009 connectors include different protection levels, and they can even be used in rainy conditions. The AC version (see Figure 7a) was designed for single-phase electric systems with 120 V or 240 V, and they consist of five pins:

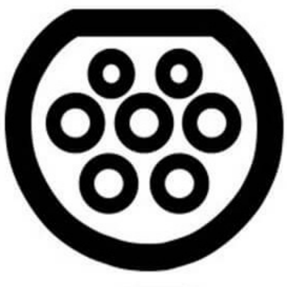
- AC pins, two pins to provide power to the vehicle (phase and neutral).
- Ground connection, a security measure, which connects the electrical system to the ground.
- Proximity detection, which avoids the vehicle to move while plugged.
- Pilot Control, which allows communication with the vehicle.



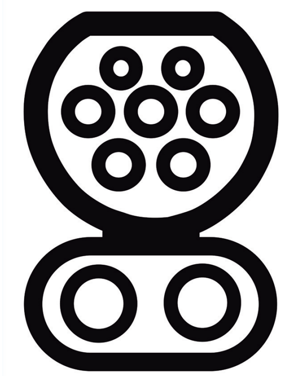
(**a**) J1772-2009 Type 1 for AC charging



(**b**) J1772-2009 Type 2 for AC/DC charging

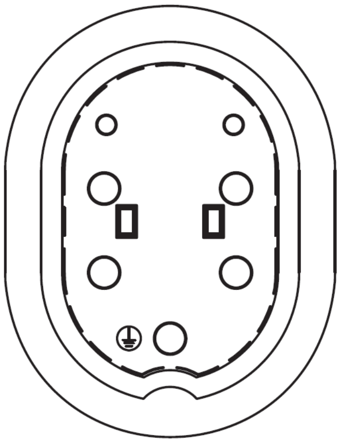


(**c**) IEC-62196 Type 2 (Mennekes)

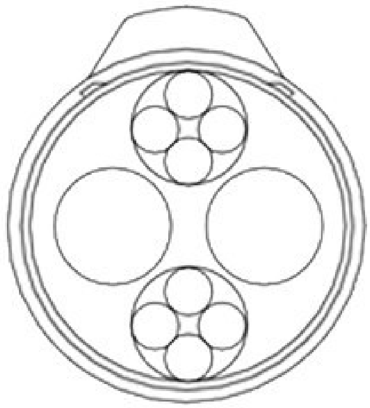


(**d**) IEC-62196 Type 2 (Mennekes CCS)

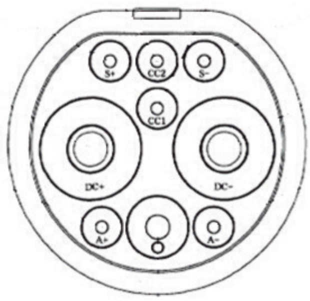
Figure 7. *Cont.*



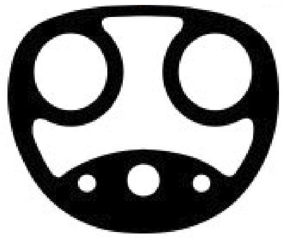
(**e**) IEC-62196 Type 3 (Scame)



(**f**) IEC-62196 Type 4 (CHAdeMO)



(**g**) GB/T 20234 fast charging connector



(**h**) Tesla connector for United States

Figure 7. EV Connectors considered by the different standards [77–79].

There exists a second version of the connector that is designed to perform a fast charge. This allows the charging time to be drastically reduced, charging the batteries of a vehicle up to the 80% in 20 min. This connector, the so-called Combined Charging System (CCS), enables AC slow charge or fast charge to DC, and its appearance is very similar to the AC version, but with two additional pins to charge in DC (see Figure 7b).

The IEC-62196 adopted the specifications of the connectors of the IEC 60309 standard, including them in its second version (IEC-62196-2), which was published by the IEC in October of 2011. More specifically, it suggests four types of plugs:

- Type 1 (SAE-J1772-2009) Yazaki. With the aim of finding a standardized connector, the Type 1 AC charging, apart from being included in the SAE-J1772 standard, was also included in the IEC-62196-2. In fact, this connector is commonly found in charging equipments for EVs in North America and Japan [80], and it is used by a great amount of vehicles, such as the Nissan Leaf, the Chevrolet Volt, the Toyota Prius Prime, the Mitsubishi i-MiEV, the Ford Focus Electric, the Tesla Roadster, and the Tesla Model S. This connector can be observed in Figure 7a.
- Type 2 (VDE-AR-E 2623-2-2) Mennekes. It was originally designed to be used in the industrial sector, so it was not specifically designed for EVs (see Figure 7c). In single-phase it is limited up to 230 V, but, in three-phase, is able to hold high voltages and intensities. This connector has 7 pins, i.e., four for the power (in three-phase mode), one ground connection, and two pins to communicate with the vehicle (blockage and communications). An example of a vehicle that uses this connector is the Renault Zoe, which can be charged with the Mennekes connector up to 43 kWh.
  Although, at first, it was not designed for fast charging, Type 2 also includes another connector, called Combined Charging System (CCS) (see Figure 7d), being essentially

an adapted Mennekes adapted to supply up to 400 A to 1000 V, which would imply a charging power up to 400 kWh [81,82].

- Type 3 (EV Plug Alliance connector) Scame. Single-phase and three-phase connector, designed by the EV Plug Alliance in 2010. It supplies 230 V/400 V and from 16 to 63 A [83]. France and Italy suggested the use of this connector for their vehicles (see Figure 7e), but, due to the poor acceptance, the production of Type 3 connectors has been finally abandoned.
- Type 4 (EVS G105-1993) CHAdeMO. Promoted by TEPCO (Tokyo Electric Power Company), it is commonly found in the EVs charging equipment in Japan, although it is also used in Europe and USA (see Figure 7f).
  CHAdeMO is designed to supply fast charges in DC. In its first versions, it held up to 400 V, starting the charge with up to 200 A. Nowadays, CHAdeMO chargers have already been designed with 150 kW power, and they aim to reach 350 kW [84]. This connector has ten pins, two for DC power supply, one for ground connection, and seven pins for communicating with the network.
  On the 8th of February of 2018, there existed 7133 CHAdeMO charging points in Japan, 6022 in Europe, and 2290 in the USA [85]. In fact, it is added to numerous vehicles, such as in the Nissan Leaf, the Nissan e-NV200, the Mitsubishi i-MiEV, and the KIA Soul EV.

Concerning the GB/T 20234 standard that is used in China, a distinguishing feature against the SAE-J1772 and IEC-62196, is that, while the latter ones use the same communication protocol between the vehicle and the charger, the Chinese standard operates with a different one, which causes the incompatibility of these charging systems [86].

The GB/T 20234 considers two kinds of connectors. The connector used for charges based on AC is physically the same used in the IEC Type 2 or the Mennekes (see Figure 7c), although they are incompatible with the European vehicles that use the same connector, as they use different protocols. The standard defines their own connector in order to carry out the DC charges (see Figure 7g).

Finally, Tesla employs two different connectors for the fast charging of their vehicles, when considering whether the vehicles are sold in Europe (see Figure 7c) or in the United States (see Figure 7h). In Europe, Tesla adopted the Mennekes connector, although slightly modified in order to perform both domestic charge (AC) and ultra-fast charges (DC) in their Superchargers. For the United States, Tesla designed their own connector.

6. Power Control and Energy Management

The energy management is a critical factor for EVs and PHEVs. Hence, the battery management system (BMS) is a key system that is designed to manage and control the battery unit in this kind of vehicle. More specifically, BMS is responsible for managing the energy that is provided by the batteries with the aim of guaranteeing their safety and reliability. Current BMSs comprise of multiple blocks, such as power delivery unity, sensors, and communication channels, integrated together.

The prime task of BMSs is to manage the power delivery trying to reduce the battery stress due to charges and discharges. BMS is the central controller preventing sudden abruption in current, and thus avoiding high discharge rates.

Cell balancing is also critical for EVs' high-powered battery packs, because a long series of individual cells is only as reliable as the weakest cell. According to this, the BMS maintains cell balancing by compensating the load of the weaker cell. In particular, it equalizes the charge on all cells in the chain to extend the overall life of the battery pack. In this way, BMS prevents individual cells from becoming overstressed.

Another important task of BMSs is measuring the state of charge and computing the driving range. Auxiliary devices, such as headlamps, the dashboard, and the cooling/heating unit, also draw power from the battery pack. However, these devices are not smart, nor do they communicate with BMS. A smarter managing of these energy demands would result in a better power delivery without reducing the power train efficiency.

Related to all of the abovementioned issues, several authors have proposed different BMS architectures. For instance, Hauser and Kuhn [87] present the requirements that a BMS should cover: (i) data acquisition, (ii) data processing and storage, (iii) electrical management, (iv) thermal management, (v) safety management, and (vi) communication. Taking all of these characteristics into account, they show a BMS schematic illustration (see Figure 8). Other authors, such as Xing et al. [88], present a review of BMS for Battery Electric (BEVs) and Hybrid Vehicles (HVs) when considering the state of charge, the state of health, and the state of life, as the key features to be considered by BMSs.

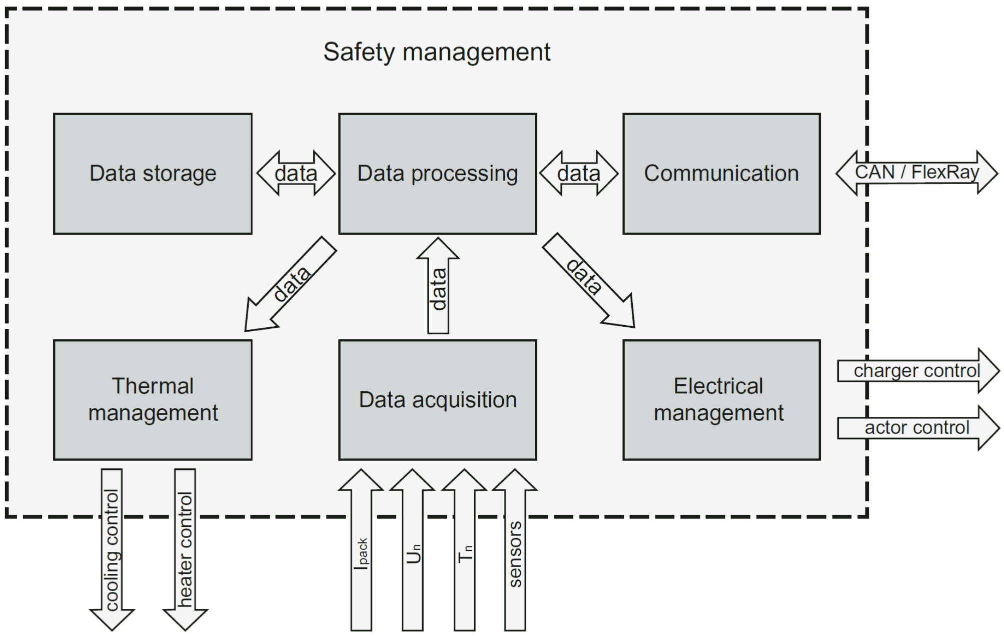


Figure 8. Main components of the Battery Management System (BMS) [87].

A more ambitious feature to be included by future BMSs was proposed by Zhang et al. [89]. Particularly, the authors simulate how to extend driving ranges, by predicting both terrain changes and preceding vehicle's movement. In their simulations, EV velocity and motor torque distribution are optimized by a nonlinear predictive controller model to reduce energy consumption.

In fact, future BMSs will be smarter and faster, integrating on chip analytics capabilities to accurately estimate driving ranges and smart adapting to load changes for better power delivery. BMSs will also support: (i) different and adaptive charging protocols, (ii) any battery cell number, sizes, and configurations, and (iii) vehicle to grid capabilities, enabling charging transactions or booking charging slots.

Thermal Management and Power Electronics

One of the most important blocks in BMSs is thermal management, as can be observed in Figure 8. In particular, it can be necessary to increase batteries' temperature to improve their performance in cold weather conditions. With this aim, Shang et al. [90] proposed a high-frequency sine-wave (SW) heater that is based on resonant LC converters to self-heat the automotive batteries at low-temperatures. Their proposal is able to double the heating speed without the need of external heaters. In [91], they also proposed a compact heater, based upon resonant switched capacitors (RSCs) that are powered by the on-board battery pack, leading to an easy implementation, which is able to increase up to 2.67 °C/min. with a high efficiency (96.4%).

However, high temperature is the most common problem for EV batteries and power electronics present in EVs. In this sense, power electronics become very important. The continuous power density increase of electric motors requires higher power to be delivered by electronics, which results in a higher heat dissipation. To address this issue, Nonneman et al. [92] presented a comparison between different cooling strategies under similar conditions. Unlike other existing works, the authors accounted for other criteria, such as cost, complexity, and practical feasibility to better design inverters for EVs. In the same line, other authors, such as Mouawad et al. [93], proposed cost effective and high integration, as well as performance power electronic systems. In particular, they present a Silicon Carbide Integrated Power Module that integrates multiple functional elements (i.e., semiconductor devices, DC-link capacitors, output filters, current sensing, and gate driver), which is able to increase power density, improve electrical performance, and reduce the costs without compromising thermal performance or reliability.

7. Challenges of the Research and Open Opportunities

Although the development and evolution of the electric vehicles have undergone a great growth, especially in the last years, in this section we comment on the aspects that are still pending, or that can be interesting to explore to propose new and enhanced solutions.

We have classified these opportunities into four fields: (i) the use of new batteries technologies or manufacturing processes, (ii) the improvement and optimization of the charging process, (iii) the use of communications and Artificial Intelligence in electric vehicles for improving the mobility and for an efficient use of the charging infrastructure, and, finally, (iv) eco charge (i.e., using green energy) and sustainability issues that are related to EVs.

7.1. New Challenges and Technologies in Batteries for EVs

Batteries are one the most important components of EVs, since they are one of the most costly components of the overall cost of the vehicle, and batteries directly affect the EV performance, as we have previously discussed in the Section 4.

The improvement in terms of durability, in charging densities, and in the charge and discharge processes, have caused the use of multiple resources in the development of new technologies that are able to surpass the current lithium-ion batteries, which are the ones massively used in vehicles.

In our view, there is still work to do in this field, fundamentally due to its impact, as the improvement of batteries can accelerate EVs success and the worldwide deployment of these vehicles in a remarkable way. At present, new technologies and components are being researched. Some of them are the following:

- Lithium iron phosphate ($LiFePO_4$). This kind of battery presents an energy density of approximately 220 Wh/L, a great durability (they are able to withstand between 2000 and 10,000 cycles) and tolerate high temperatures.
  However, although this type of battery is starting to be tested in EVs [94], it still can be found in an early stage of research and development. MIT researchers have managed to reduce its weight and they have developed a prototype-cell that can be completely charged in just 10–20 s, a reduced time if we compare it with the necessary 6 min. for standard battery cells [95].
- Magnesium-ion (Mg-Ion). These batteries change the use of lithium over magnesium, succeeding in storing more than double the charge and increasing its stability. It is expected that this type of battery can have a 6.2 kWh/L energy density [96], which would imply 8.5 times more than the best lithium batteries, which are currently able to apply up to 0.735 kWh/L. Organizations, such as the Advanced Research Projects Agency-Energy (ARPA-E), Toyota, or NASA, are investigating this type of battery [97,98].

- Lithium-metal. In these batteries, graphite-anode is replaced by a fine lithium-metal layer. This kind of battery is able to store double of the power than a traditional lithium battery [99]. SolidEnergy Systems, a MIT startup, have already started to deploy this type of batteries in drones, and it is expected that they can be included in EVs [100]. Lithium-metal batteries have a high Coulombic efficiency (above 99.1%), withstanding more than 6000 charging cycles, and, after 1000 cycles they maintain an average Coulombic efficiency of 98.4% [101].
- Lithium-air (Li-air). This kind of battery needs a constant supply of oxygen to conduct the reaction with the lithium. They were initially proposed in the 70s, although it was not until recently that have started to be developed and improved. It is expected that its specific energy reaches around 12 kWh/kg (almost 45 times the current of lithium), which would imply being at the same level as the fuel [102].
- Aluminum-air. Batteries that are developed with this technology produce electricity from the reaction of oxygen with aluminum. Their main advantage is that this type of battery reaches very large energy densities, attaining 6.2 kWh/L [103], which allows obtaining a high autonomies (up to 1600 km) [104]. The price of this kind of battery is decreasing, currently positioning in 300 €/kWh [105], and their advantage is that they are recyclable.
- Sodium-air (Na_2O_2). The company BASF created a Sodium-air battery with an energy density of 4.5 kWh/L [106]. In electric vehicles, this type of battery can multiply the autonomy of the current lithium batteries at least thirteen times [107]. A great advantage of this type of batteries is that sodium is the sixth more abundant element in our planet [108].
- Graphene. Graphene is a material that is formed by pure carbon, which has a high thermal conductivity and it is extremely light (a one square meter blade weighs 0.77 mg) [109]. One of the major assets of graphene-based batteries is that they barely heat, enabling fast or ultra-fast charges without significant power losses due to heat. Graphenano, a Spanish company, has created a graphene battery that, added to a GTA Spano vehicle (900 hp), has been able to travel 800 km [110]. In a high power plug, this battery could be charged in only 5 min. This kind of battery is in an early phase of development, although there exist prototypes of graphene batteries with a specific power of 1 kWh/kg, and it is expected to reach 6.4 kWh/kg soon [111].

We consider that the technology is able to increase the autonomy of EVs and considerably reduce the time that is required for a complete charge will be the one that will finally succeed in the market.

7.2. Improvements in the Charging Process

In this section, we focus on the charging process, a key aspect regarding battery vehicles, and it also crucial in the field of electric vehicles, as it is highly important to facilitate users charging process, enabling EVs to reach longer distances.

One of the most important issues when charging an electric vehicle is the connector. The American and Japanese markets bet on the connectors that were proposed by the J1772 standard, while the European vehicles use the ones that were suggested by the IEC-62196. Although these markets are quite different and separate, this fact is not desirable and it can cause difficulties for users when charging their vehicles; purchasing adapters can be required, thereby increasing the cost of Electric Vehicles, and sometimes introducing safety risks.

This problem also occurs in fast charging points. As we have previously discussed in Section 5.2, there currently exist three types of standard connectors to conduct fast charges: (i) the CCS included in the J1772, (ii) the CHAdeMO added in the IEC-62196, and (iii) the GB/T. In addition, we should also consider the one used by Tesla in its superchargers.

Although Tesla, for instance, has bet on the fact that some of its vehicles have more than one type of connector, we consider it more important to progress in the creation of a unified standard, which would allow for charging all of the vehicles through a universal connector when considering the differences in the energy systems of the different regions. We consider that this universal connector will help EV drivers, but, especially, it will have a significant environmental impact.

Another aspect that can revolutionize the charging process is applying intelligent algorithms to optimize the charges, either reducing the cost, or improving the use of the electrical infrastructure. Currently, the charging process usually starts just in the moment in which the vehicle is connected to the charging point (as it is typically known as Plug&Charge); however, the price of electricity varies throughout the day in most countries, so the charging start could be adapted to significantly reduce the charging cost by avoiding the periods of high demand (where the economic cost is higher). The implementation of intelligent plugs could help EVs to gain more market share over the internal combustion engine vehicles. Although there are initial works and proposals in this area [112–114], we consider that there are still several open issues and potential works to be done in this field, as the use of communications between the vehicles and the electric infrastructure, as well as the new technologies based on Artificial Intelligence (e.g., Deep Learning techniques or Optimization Strategies [115]), will enable highly enhanced charging processes, as well as significantly reducing the economic cost.

As for community or public parking lots, we consider that using adaptive charging techniques can also be very useful, since the available infrastructure can be limited to simultaneously power all charging points. According to this, smart load balancing systems that are able to intelligently and efficiently manage the charging points should be proposed. The reasoning behind this is to be able to satisfy the charging needs of crowded scenarios without investing in new power infrastructure.

Finally, we must consider wireless charge, as an alternative to the conventional charging technologies, since it enables charging EVs batteries while driving. In fact, wireless power transfer (WPT) is very convenient because of its flexibility and comfort. Capacitive power transfer (CPT) and inductive power transfer (IPT) are the two wireless charge modes. However, it is important to note that IPT is the most commonly used, as it can be applied to many gap distances and power levels. By contrast, CPT, although it has been shown to be valid for kilowatt-power-level applications, it is only suitable for small gap power transfers.

In addition, there exist three different types of wireless charges when considering their context: (i) stationary charging, when the vehicle is parked, (ii) opportunistic charging, when the vehicle is stopped for a short period of time, (e.g., in a traffic light), and (iii) dynamic charging, when the vehicle is moving along a dedicated charging lane [116].

Related to wireless charging, Manshadi et al. [117] present the advantages of wireless charging stations in terms of electricity costs and congestion in the electricity network. Dai et al. [118] provide a critical comparison of IPT and CPT for small gap applications, wherein the theoretical and empirical limitations of each approach are established. In particular, they compare the two approaches in terms of power level, gap distance, operational frequency, and efficiency. Focusing only on CPT, Li et al. [119] presented a family of compensation topologies to achieve constant-voltage or constant-current output in CPT-based charges.

The successful and effective deployment of wireless electric vehicles charging requires the development of cost effective, high performance, and high integration power electronic systems. In that sense, Nohara et al. [120] propose a miniaturized wireless EV charger with a high power-factor drive and natural cooling structure that incorporates the simple quasi-resonant single-ended inverter. Their approach significantly reduces the weight and volume of the converter while solving the problem of power factor and cooling. Other authors aim to greatly extend the EV operating range by exploiting the wireless charge capabilities. For example, Wang et al. [121] propose a dynamic wireless charging system that is able to fully switch the vehicle's driving power to wireless charging while the vehicle is driving on the charging area. More specifically, the proposed system can dynamically adjust the voltage value of the transmitting end or the equivalent load resistance value of the electric vehicle.

Although this technology is very promising (for instance, the use of dynamic charging would increase the driving range, even reducing the size of the battery packs), current high associated costs, and the lack of a unique and universal standard make wireless charges an unfeasible alternative to traditional wired charging process in the short term.

7.3. Communications and AI in Electric Vehicles

In order for electric vehicles to completely turn into the predominant mean of transport in our cities and roads, diverse factors will necessarily have to come together, as previously examined.

Obviously, the development that is undergoing during the last years, in terms of autonomy, power, technology, and comfort, is helping buyers to consider EVs as an actual possibility when purchasing a new vehicle. Although the price is slightly higher (in some models, the difference with respect to the combustion engine version engine is notable), the purchasing aids and the reduced tax schemes are also helping to reduce the existing gap.

However, there exist other aspects that are also essential, but they still need to be improved to lead the way to electric vehicles. The worldwide deployment of EV charging stations is the first of such aspects. Up to now, in the majority of countries, the number of charging points available is rather scarce, which certainly stops buyers. We consider that greater effort is needed to improve the charging infrastructure. Additionally, the time that is necessary to completely charge the batteries of these vehicles must be considerably reduced, so that users view electric vehicles as more attractive. Fortunately, we believe that the use of vehicular communications and Artificial Intelligence (AI) can catalyze the actual implementation of the new more ecological and sustainable transport.

Wireless communication networks will allow vehicles to be provided with a communication system that enables communications capabilities among vehicles (V2V) and the infrastructure (V2I). In addition, the use of algorithms that are based on AI will provide certain intelligence to the vehicles, and it will open up to countless new opportunities that will revolutionize the future transport systems.

We can find several proposals, based on Artificial Intelligence, related to different EV areas, such as energy efficient routing, better and smarter charges, or battery thermal management. Regarding to efficient routing, Masikos et al. [122] introduce a novel machine learning-based methodology for energy efficient routing. Their approach is able to predict the energy consumption for the different road segments that constitute the actual or potential vehicle routes. Alesiani and Maslekar [123] address the problem of finding the routes for a fleet of electric vehicles. Their proposal not only considers the battery limit of the vehicle, but also the concurrent use of charging stations along the route while using an evolutionary genetic algorithm with learning strategy.

As for smarter charges, Sugii et al. [124] propose a genetic algorithm-based scheduling method for charging multiple EVs. In particular, this approach can determine the power curve and electric power load levering. Additionally, it can reduce the capacity of the charging equipment and its initial cost. Panahi et al. [125] propose the use of ANNs to forecast daily load profile of individual EVs and fleets, as user habits is one of the most important issues in EV charges. More specifically, they use historical data to predict electricity demand and better coordinate the charges.

Related to battery thermal management, Park et al. [126] propose the use of Artificial Neural Networks (ANNs) to improve the thermal management system and reduce the total energy consumption. The proposal allows for maintaining the battery temperature within an acceptable range. Karimi et al. [127] analyze the relationship between battery thermal behavior and design parameters. In particular, their numerical analysis show that a cooling strategy that is based on distributed forced convection can provide uniform temperature and voltage distributions within the battery pack at different discharge rates.

The combined use of communications and AI will promote the appearance of new solutions that: (i) facilitate the charging process of batteries (by providing an early booking of the charging point, automatic power balancing capabilities, adaptive charges that are based on the context, etc.), (ii) improve the power generation process to satisfy the great electric demand on the grid that will arise (by offering predictions of necessary power in every moment, mobility analysis of the EVs, etc.), and (iii) speed up the transition process of assisted driving, to complete autonomous driving.

Subsequently, we are very close to the advent of the Internet of EVs concept (IoEVs), which will certainly change dramatically the way in which we move, but it will also open us a new world of research possibilities, including new applications and services.

7.4. Eco Charge and Sustainability

Electric vehicles have appeared as a model of sustainability and respect to the environment, due to the fact they do not emit harmful substances to the air, unlike conventional internal combustion vehicles. Such sustainability is not only limited to the usage of hybrid or electric vehicles, but also their design, the prime materials used in the manufacturing of these vehicles, and the energy footprint during its use, as well as the subsequent recycling of their components influencing the circles of sustainability.

However, these ideas are changing due to the appearance of several studies that have questioned the sustainability and environmental impact of EVs [128–131]. In particular, three important stages should be taken into account: (i) their fabrication process, (ii) the usage throughout their lifetime, and (iii) their disposal and recycling process.

Regarding the EV production, some studies consider that it can require more than twice as much energy to produce an electric car as compared to a conventional one [128,129], especially due to the batteries production. More specifically, the mining and processing minerals required to manufacture EV batteries (e.g., lithium, copper, cobalt, manganese, and rare earths like neodymium), as well as battery manufacturing with current technology, requires from 350 to 650 Megajoules per kWh [129]. In addition, each kWh of battery capacity involves from 150 to 200 kg of CO_2 emissions. This means, for example, that producing a 22 kWh BMW i3 battery emits almost 3 tons of CO_2.

As for the usage of EVs, one key point is the high amount of electricity that is required to charge these vehicles' batteries, especially when they will be widely deployed [130]. Moreover, such power demand would indirectly harm the environment, depending on the electric power source generation. Although EVs do not emit climate-damaging greenhouse gases and NO_2, the required electricity could be produced by fossil-fuel power plants, and thus limit the supposed climate benefits. For example, almost half of the electricity generated in Germany comes from coal and gas [132]. Hence, the use of renewable energies for manufacturing and charging electric vehicles is a key aspect. Especially for charges, this kind of power (mainly the solar and wind power) could be stored to be used in high demand periods or for cheapening the charging prices [133–137].

Concerning the infrastructure that is needed for EVs deployment, and trying to propose more eco-friendly approaches, Bhatti et al. [138] summarize all of the aspects related to EVs charging focusing on the use of solar photovoltaic modules. More specifically, they analyze the requirements of grid powered photovoltaic EV charging, including its economic and environmental impact. Similarly, Calise et al. [139] present a novel paradigm for sustainable mobility that is based on EVs, photovoltaic energy, and energy storage systems, including a comparison to the conventional grid-to-vehicle approach. Particularly, they demonstrate that, during the summer, solar energy can cover an important amount of the total energy demand.

Regarding the EV disposal, once the batteries' lifetime has ended, they can be an environmental hazard, and correct recycling is essential for the successful implementation of this transportation technology. Recycling provides a good opportunity to reduce the life cycle costs, enabling the recovery of high-value materials [140].

Finally, electromobility could also present some drawbacks. The high sales of EVs, mainly in countries, such as Norway, is the result of governments' economic incentives. However, some of these incentives can have adverse effects (e.g., the exemption of toll charges has significantly reduced toll revenue [141]). Moreover, there have been 3.6% less public transportation passengers than the same quarter last year, according to the National statistical institute of Norway [142]. Although this issue might be due to several factors, we consider that these data can be directly related to impressive growth of EV sales in this country, since EV economic advantages and higher comfort can result in a reduction of public transport usage.

8. Conclusions

In this paper, we analyzed the types of EVs, the technology used, the advantages with respect to the internal combustion engine vehicles, the evolution of sales within the last years, as well as the different charging modes and future technologies. We also detailed the main research challenges and open opportunities.

Regarding EVs, batteries are a critical factor, as these will determine the vehicle's autonomy. We analyzed several kinds of batteries, according to these features. We also presented the possible technologies that can be used in the future, such as the graphene, which is expected to be a solution that enables the storage of higher amounts of power, and charge in shorter periods of time. The EV could also benefit from this type of technology, reaching higher ranges, something that could help its adoption by drivers and users.

The development of batteries with higher capacities will also favor the use of the fastest and most powerful charging modes, as well as better wireless charging technologies. The creation of a unique connector that can be globally used is another aspect that could benefit the deployment of electric vehicles. The EV will play a highly important role in the future Smart Cities, and having different charging strategies that can adapt to the users' needs will be of special relevance. Therefore, future BMS should consider the new scenarios that were introduced by new batteries and Smart Cities requirements.

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Abbreviations

The following abbreviations are used in this manuscript:

AC/DC	Alternating Current/Direct Current
Ah	ampere hour
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
BEVs	Battery Electric Vehicles
BESs	Battery Exchange Stations
BMS	Battery Management System
BSSs	Battery Swap Stations
CCS	Combined Charging System
CHAdeMO	CHArge de MOve
CO	carbon monoxide
CO_2	carbon dioxide
CPT	Capacitive Power Transfer

ER-EV	Extended-range Electric Vehicle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GAs	genetic algorithms
GB	Guobiao Standards
HEV	Hybrid Electric Vehicle
IEC	International Electrotechnical Commission
IoE	Internet of Energy
IoEVs	Internet of Electric Vehicles
IPT	Inductive Power Transfer
$LiFePO_4$	Lithium iron phosphate
Li-air	Lithium-air
Li-Ion	Lithium-ion
Mg-Ion	Magnesium-ion
NA-NiCl	Sodium chloride and nickel
Na_2O_2	Sodium-air
Na-S	Sodium sulfur
Ni-Cd	Nickel-cadmium
Ni-MH	Nickel-metal-hydride (NiMH)
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
PM	Particulate matter
$Pb\text{-}PbO_2$	Lead-acid
PHEV	Plug-In Hybrid Electric Vehicle
PSO	Particle Swarm Optimization
SAE	Society of Automotive Engineers
SO_2	Sulfur dioxide
V2G	Vehicle-to-grid
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
Wh	watt hour
WPT	Wireless Power Transfer
$Zn\text{-}Br_2$	Zinc-bromine

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