A REVIEW ON ELECTRIC VEHICLES: TECHNOLOGIES AND CHALLENGES

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Abstract: The popularity of Electric Vehicles (EVs) is witnessing a notable surge due to several factors, including reduced costs and an increased awareness of climate and environmental issues. This manuscript provides a thorough analysis of the progress in EVs, focusing on trends in battery technology, charging methods, and the emerging research challenges and opportunities. Specifically, it evaluates the global market landscape for EVs and their potential future. Given that the battery is a crucial component of EVs, this paper presents a detailed review of battery technologies, from Lead-acid batteries to Lithium-ion. Additionally, we examine the various standards governing the EV charging process, along with proposals concerning power control and battery energy management. In conclusion, we outline our viewpoint on the expected advancements in this field in the near future, as well as the research opportunities that remain available for both industry and academia.

Keywords: Electric Cars; Plug-In Hybrid Electric Cars; battery recharging; battery technology; charging options; EV connectors

1. Introduction

The automotive sector has emerged as one of the most significant global industries, impacting not only the economy but also the realms of research and development. There is a growing incorporation of technological advancements in vehicles aimed at enhancing the safety of both passengers and pedestrians. Furthermore, the increasing number of vehicles on the roads facilitates swift and comfortable transportation. Nevertheless, this surge has resulted in a substantial rise in air pollution levels within urban areas (i.e., pollutants such as PM, nitrogen oxides (NOX), CO, sulfur dioxide (SO2), etc.).

Moreover, according to a report from the European Union, the transportation sector accounts for nearly 28% of total carbon dioxide (CO2) emissions, with road transport responsible for over 70% of emissions within this sector [1]. Consequently, authorities in most developed nations are advocating for the adoption of Electric Vehicles (EVs) to mitigate the accumulation of air pollutants, CO2, and other greenhouse gases. Specifically, they are promoting sustainable and efficient mobility through various initiatives, primarily through tax incentives, purchase assistance, or other special measures such as complimentary public parking or free access to motorways Electric vehicles offer numerous benefits over traditional cars:

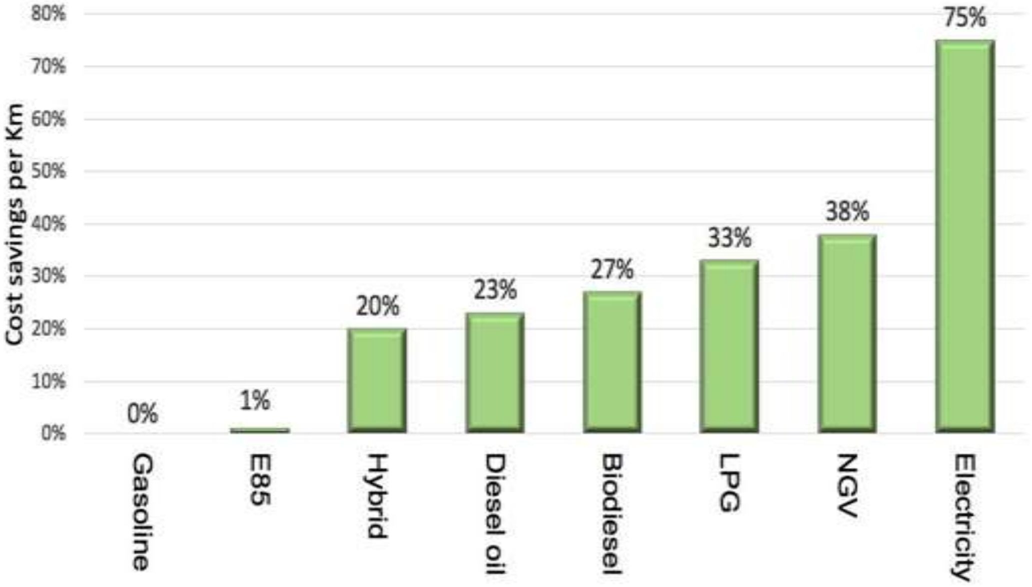
Zero emissions: these vehicles do not emit tailpipe pollutants, CO2, or nitrogen dioxide (NO2). Additionally, their manufacturing processes are generally more environmentally friendly, although the production of batteries can negatively impact the carbon footprint.

Simplicity: Electric Vehicle (EV) engines consist of fewer components, resulting in significantly lower maintenance costs. These engines are more straightforward and compact, eliminating the need for a cooling system, as well as the requirement for gear shifts, clutches, or components that minimize engine noise.

- Reliability: the presence of fewer and simpler components in this category of vehicles results in a reduced frequency of breakdowns. Furthermore, electric vehicles (EVs) are not subjected to the typical wear and tear associated with engine explosions, vibrations, or fuel corrosion.
- Cost: the expenses related to vehicle maintenance and the electricity needed for operation are considerably lower when compared to the maintenance and fuel expenses of conventional combustion

vehicles. The energy cost per kilometer in EVs is markedly less than that of traditional vehicles, as illustrated in Figure 1.

- Comfort: riding in EVs offers enhanced comfort due to the lack of vibrations and engine noise [2].
- Efficiency: electric vehicles demonstrate greater efficiency than their traditional counterparts. However, the total well-to-wheel (WTW) efficiency is also affected by the efficiency of the power plant. For instance, the overall WTW efficiency for gasoline vehicles fluctuates between 11% and 27%, whereas diesel vehicles fall within the range of 25% to 37% [3].In contrast, EVs powered by a natural gas power plant exhibit a WTW efficiency between 13% and 31%, whereas those powered by renewable energy can achieve an overall efficiency of up to 70%.
- Accessibility: this category of vehicles provides access to urban areas that are restricted for other combustion vehicles (e.g., low emissions zones). EVs are not subject to the same traffic limitations in major cities, particularly during periods of high pollution levels. Notably, a recent OECD study indicates that, at least regarding Particulate Matter (PM) emissions, EVs may not significantly enhance air quality [4].



A comparative study of the cost savings per kilometer offered by vehicles that use Gasoline, Ethanol (E85), Hybrid technology, Diesel fuel, Biodiesel, Liquefied Petroleum Gas (LPG), Natural Gas Vehicles (NGV), and Electric power [5]. Conversely, electric vehicles (EVs) encounter notable challenges related to their batteries:

- Driving range: the range is generally restricted to between 200 and 350 km on a full charge, although advancements are being made in this area. For instance, the Nissan Leaf boasts a maximum driving range of 364 km [6], while the Tesla Model S can exceed 500 km [7].
- Charging time: fully charging the battery pack may require between 4 to 8 hours. Even a "fast charge" to reach 80% capacity can take approximately 30 minutes. For example, Tesla superchargers can charge the Model S to 50% in just 20 minutes, or to 80% in 30 minutes [7].
- Battery cost: the expense associated with large battery packs is significant.
- Bulk and weight: battery packs are substantial in weight and occupy a considerable amount of space within the vehicle. It is estimated that the batteries in such vehicles weigh around 200 kg [8], although this can vary based on the battery's capacity.

In the forthcoming years, electric vehicles (EVs) will play a crucial role in the development of smart cities, alongside shared mobility and public transportation, among other elements. Consequently, there is a pressing need for enhanced efforts to streamline the charging process and to advance battery technologies. The primary limitation of EVs lies in their range. Nevertheless, researchers are actively engaged in developing superior battery technologies aimed at extending driving range while reducing charging time, weight, and cost. These components will ultimately define the future environment of electric vehicles.

In this paper, we provide a detailed survey of the key components of EV technologies, charging methodologies, and the research conducted by various teams and laboratories. Figure 2 illustrates the principal topics discussed in this paper. In summary, the insights and contributions of our research are as follows: (i) we offer an analysis of existing surveys within the literature, highlighting the necessity of our work, as we address certain aspects that have not been previously explored and encompass the most recent studies available, (ii) we evaluate the current global market status of EVs and their future outlook, (iii) we conduct a comprehensive review of battery technologies—from lead-acid to lithium-ion, including cutting-edge technologies such as graphene, (iv) we examine the various standards established for EV charging, along with the types of connectors defined by these standards, (v) we present significant research related to Battery Management Systems (BMSs), thermal management, and power electronics, and (vi) we conclude our study by discussing anticipated developments in this field, as well as the research areas that, in our view, remain open for exploration by both industry and the academic community.

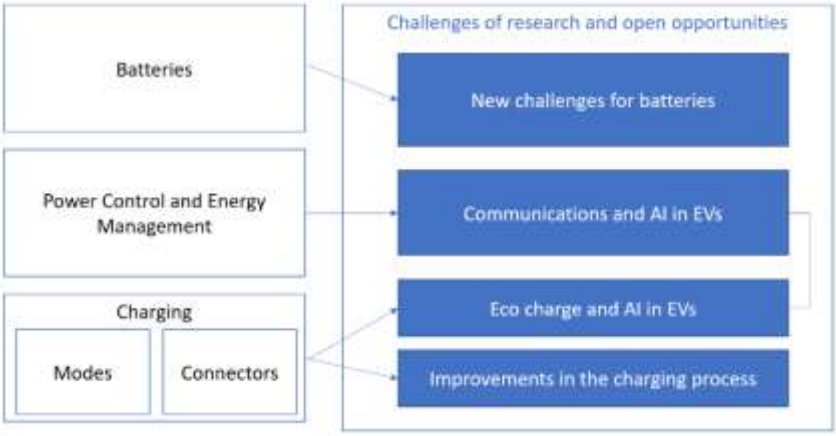


Figure 2. Topics included in our work.

The remainder of the paper is organized as follows: Section 2 reviews the most pertinent surveys found in the literature and underscores the necessity of our research. Section 3 provides a comprehensive overview of the market, emphasizing a classification of the various types of electric vehicles (EVs), the trends in EV sales, and the current state of the market. In Section 4, we examine the most significant characteristics of batteries and categorize the different types of batteries based on their technology. Section 5 outlines the various existing standards for charging EVs, detailing the different charging modes associated with each standard, as well as the types of connectors they define. Section 6 investigates energy management in EVs, with a particular emphasis on Battery Management Systems (BMSs), thermal management, and power electronics. In Section 7, we address topics related to EVs that, in our view, warrant further exploration, require enhancements, or present significant challenges and opportunities for the scientific community. Finally, Section 8 summarizes the key conclusions drawn from the execution of this work.

2. Existing EV-Related Surveys

In the last ten years, significant progress has been made in various aspects related to the production of electric vehicles, along with the introduction of new technologies and their associated market performance. At the same time, there has been a marked increase in research initiatives, leading to a considerable rise in job opportunities and proposals linked to electric vehicles. This section offers a brief overview of the most relevant topics regarding electric vehicles (EVs), as outlined by existing academic literature. Additionally, the unique features of this survey in relation to earlier studies are highlighted. Numerous scholarly articles published to date tackle broad themes, such as the historical development of electric vehicles, provide various classifications based on design approaches and engine specifications, or assess their effects on electrical infrastructure. For instance, Yong et al. [9] present a detailed review of the historical evolution of electric vehicles, tracing their origins from the mid-nineteenth century to modern advancements. Furthermore, they categorize vehicles based on their powertrain configurations. Ultimately, their research evaluates the effects of electric vehicle charging on the electrical grid In a similar vein, Richardson [10] examines the possible impacts of electric vehicles on the required productivity, efficiency, and capacity of the electrical grid. He also investigates the economic and environmental impacts associated with electric vehicles. Habib et al. [11] provide a comprehensive review of charging methods for electric vehicles and analyze their implications for power distribution systems. Moreover, the authors compare coordinated and non-coordinated charging techniques, delayed loading, and the intelligent scheduling of charging activities. Ultimately, they evaluate the results of these approaches. Another aspect that has been examined in numerous academic studies relates to the use of renewable energy sources (such as wind energy, solar energy, and biomass) and their incorporation into the field of electric vehicles. Liu et al. [12] offer a thorough overview of the relationship between electric vehicles and renewable energy sources. Their study particularly highlights solar and wind energy, organizing the existing literature into three separate categories: (i) research that explores the interaction between electric vehicles and renewable energy sources aimed at reducing energy costs, (ii) studies focused on improving energy efficiency, and (iii) proposals primarily directed towards reducing emissions. In contrast, Hawkins et al. [13] perform a critical review of the current literature regarding the environmental impacts of Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs). They provide an analysis that includes 51 environmental assessments throughout the life cycle of these two types of vehicles (i.e., BEVs and HEVs). In their academic work, the authors take into account factors such as greenhouse gas emissions, the production, transmission, and distribution of electrical energy, as well as the manufacturing of vehicles, batteries, and their operational lifespan. Vasant et al. [14] examine the everyday use of Plug-in Hybrid Electric Vehicles (PHEVs), arguing that the strategic placement of daytime charging stations, along with effective charging regulation and infrastructure management, can promote the wider adoption of PHEVs. Unlike the aforementioned studies, Shuai et al. [15] present a broad perspective on the new economic model associated with electric vehicles, considering both unidirectional and bidirectional energy flows (wherein the EVs themselves can supply energy back to the electric grid). To achieve this, they examine various charging infrastructures for electric vehicles (EVs), along with distinct approaches for unidirectional charging and bidirectional energy commercialization. Ultimately, they investigate the potential of these vehicles as viable storage solutions for energy produced from renewable sources.

Other researchers have concentrated on the various strategies proposed for charging EVs. Tan et al. [16] evaluate the advantages and challenges associated with vehicle-to-grid (V2G) technology, considering both unidirectional and bidirectional charging. In addition to the benefits, they scrutinize the challenges, including battery degradation and substantial investment costs. Finally, they compile a range of strategies for optimizing V2G, categorizing them based on the techniques used (e.g., genetic algorithms (GAs) and Particle Swarm Optimization (PSO)), as well as the objectives: (i) operational costs, (ii) carbon dioxide emissions, (iii) profitability, (iv) support for renewable energy generation, (v) load curve, and (vi) power loss. In a manner similar to the aforementioned study, Hu et al. [17] provide a review and classification of methods for the intelligent charging of electric vehicles, specifically targeting fleet operators. They particularly highlight research related to battery modeling, charging and communication standards, and driving patterns. Lastly, they present a variety of control strategies for managing EV fleets, along with mathematical algorithms for their modeling. Rahman et al. [18] introduce a collection of methods employed to address various issues related to the charging infrastructure of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). Furthermore, they evaluate different charging systems across various settings, including residential garages, apartment complexes, and shopping centers. The extensive deployment of electric vehicles (EVs) is anticipated to have adverse effects on the current power grid. Consequently, several studies examine the various challenges and potential benefits that the integration of EVs into the smart grid may offer. Yong et al. [9] investigate the implications of EV deployment through the lens of vehicle-to-grid technology, particularly in relation to alleviating the intermittency of renewable energy sources. Mahmud et al. [19] address all facets associated with EV charging, energy transfer, and the integration of distributed energy resources within the framework of the Internet of Energy (IoE). More recently, Das et al. [20] provide an assessment of how the advent of connected EVs and autonomous driving technologies will influence EV charging and grid integration.

Additionally, significant issues concerning EV charging pertain to battery management, as well as the estimation of battery health and lifespan, which are crucial for enhancing battery longevity. Li et al. [21] review the latest developments in Big Data analytics aimed at facilitating data-driven assessments of battery health. They categorize these advancements based on their feasibility and cost-effectiveness, while also discussing their respective advantages and limitations. Liu et al. [22] advance this field by proposing a machine learning-based system utilizing Gaussian process regression (GPR) to forecast the aging of lithium-ion batteries. Lastly, other methodologies investigate sophisticated fault diagnosis techniques, given that battery malfunctions can lead to performance deterioration [23].

As previously indicated, the majority of research concerning EVs has predominantly concentrated on: (i) the effects of EV charging on electric demand, (ii) the incorporation of renewable energy sources in the charging process, and (iii) the development of innovative strategies for optimizing electric vehicle charging, including grid solutions. Nevertheless, this paper aims to elucidate the current state of the electric vehicle market, the primary characteristics of batteries, their underlying technologies, and the associated charging processes.

Specifically, in addition to conducting a comparison of the various standards, we present the distinct charging methods outlined by these standards, along with the connectors associated with each. Ultimately, we also address the challenges that electric vehicles (EVs) encounter, as well as the research avenues that we believe remain to be investigated.

3. Electric Vehicles

In this section, we provide a classification of the various types of electric vehicles, highlighting their key characteristics. Additionally, we examine the current market landscape, analyzing sales data for these vehicles and forecasting sales across different countries worldwide.

3.1. Electric VEHICLES Taxonomy

Currently, various categories of electric vehicles (EVs) can be observed, classified based on their engine technology. Broadly, they are divided into five distinct types (Refer to Figure 3):

- Battery Electric Vehicles (BEVs): These vehicles are entirely powered by electric energy. BEVs lack an internal combustion engine and do not utilize any form of liquid fuel. Typically, they are equipped with large battery packs to ensure adequate range. A typical Battery Electric Vehicle (BEV) can cover a range of 160 to 250 kilometers, while certain models have the ability to reach distances of up to 500 kilometers on one charge.A notable example is the Nissan Leaf [24], which operates solely on electricity and features a 62 kWh battery, enabling a range of 360 km.
- Plug-In Hybrid Electric Vehicles (PHEVs): These hybrid vehicles are driven by both a traditional combustion engine and an electric motor that is charged via an external electric source. PHEVs can accumulate sufficient electricity from the grid to considerably lower their fuel consumption during typical driving scenarios. The Mitsubishi Outlander PHEV [25] is equipped with a 12 kWh battery, allowing it to operate approximately 50 km solely on electric power. However, it is important to note that the actual fuel consumption of PHEVs often exceeds the figures provided by manufacturers [26].
- Hybrid Electric Vehicles (HEVs): These vehicles utilize a combination of a conventional internal combustion engine and an electric motor. Unlike PHEVs, HEVs cannot be connected to the grid for

charging. Instead, the battery that powers the electric motor is recharged through the energy produced by the vehicle's combustion engine. In contemporary models, batteries can also be charged through regenerative braking, converting kinetic energy into electrical energy. The fourth-generation hybrid model of the Toyota Prius was equipped with a 1.3 kWh battery, which theoretically enabled a range of up to 25 km in all-electric mode [27].

- Fuel Cell Electric Vehicles (FCEVs): these vehicles are equipped with an electric motor that utilizes a combination of compressed hydrogen and oxygen sourced from the atmosphere, producing water as the sole byproduct of this process. While these vehicles are often regarded as having "zero emissions," it is important to note that, despite the existence of green hydrogen, the majority of hydrogen utilized is derived from natural gas. The Hyundai Nexo FCEV [28] serves as a prime example of this type of vehicle, able to cover a distance of 650 km without requiring refueling.
- Extended-range EVs (ER-EVs): these vehicles closely resemble those in the Battery Electric Vehicle (BEV) category. However, ER-EVs are additionally equipped with a supplementary combustion engine that charges the vehicle's batteries when necessary. This type of engine, in contrast to those found in Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs), is solely employed for charging purposes and is not connected to the vehicle's wheels A representative instance of this category is the BMW i3 [29], equipped with a 42.2 kWh battery that offers a range of 260 km in electric mode, while users can achieve an extra 130 km by utilizing the extended-range mode.

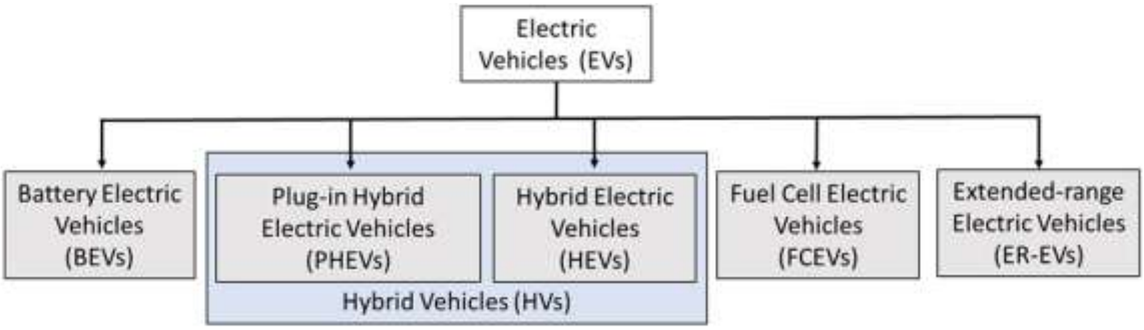


Figure 3. Classification of electric vehicles based on their engine technologies and configurations

3.2. Subsidies and Market Position

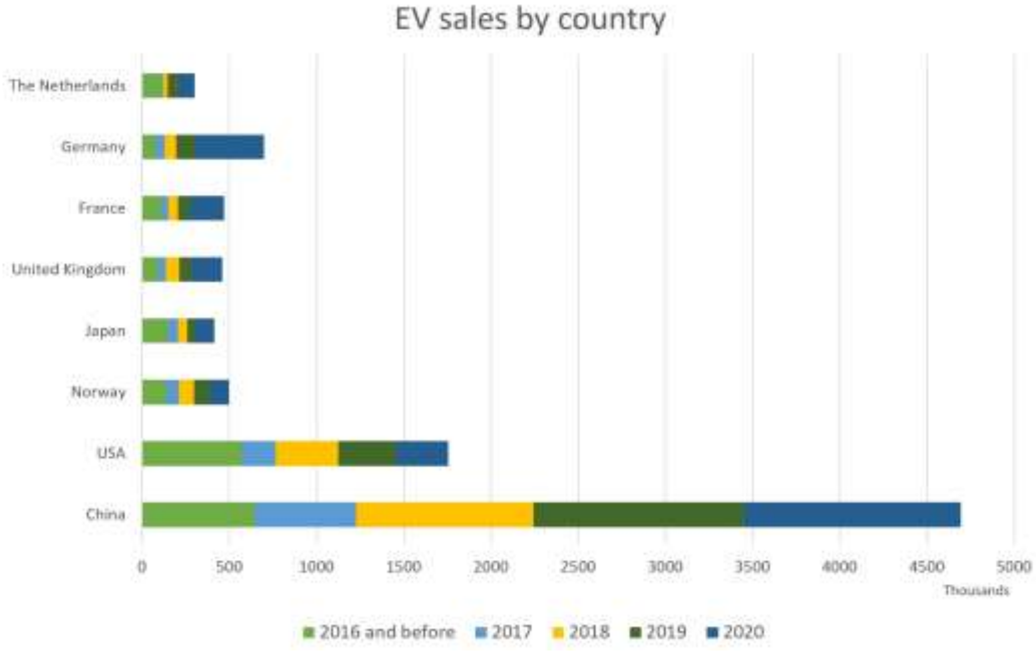
Although the initial cost of electric vehicles is greater compared to their internal combustion engine counterparts, the sales figures for EVs have seen remarkable growth, particularly in recent years [30]. Furthermore, numerous nations are gearing up for a transition in mobility, actively discouraging the use of fossil fuel-powered vehicles while promoting electric mobility. This is evidenced by the increase in public subsidies for such vehicles following the Paris Agreement [31].

Indeed, nearly all governments in developed nations are consistently implementing new support measures and policies to encourage the adoption of electric vehicles, aiming to foster sustainable and environmentally friendly transportation.

According to reports from [32–34], for example, Belgium provides a purchase subsidy of 4000 euros, and electric vehicles are subject to a road tax of only 74 euros, in contrast to the 1900 euros levied on traditional vehicles. In France, EV purchasers can receive a bonus ranging from 4000 to 6000 euros for battery electric vehicles (BEVs), and 3500 euros for plug-in hybrid electric vehicles (PHEVs). Additionally, a discount of between 50% and 100% is available on the registration fee. In the United Kingdom, buyers can benefit from an incentive of up to £4500 when purchasing an EV, and vehicles valued under £40,000 are exempt from circulation taxes. In Germany, purchasers of BEVs receive a bonus of 4000 euros, while those buying PHEVs receive 3000 euros. Moreover, BEVs are exempt from property taxes, whereas PHEVs enjoy a 50% reduction. In Spain, financial assistance ranging from 1300 to 5500 euros is available for the purchase of BEVs and HEVs, depending on their range.

In Norway, the property tax for BEVs and PHEVs is set at 47 euros, while petrol vehicles face taxes ranging from 290 to 340 euros. Additionally, BEVs are exempt from circulation fees and tolls, and they do not incur parking charges in designated areas.Ultimately, in the United States, the federal government allocates $2500 for the acquisition of electric vehicles, along with an extra $417 for each kWh of their batteries starting from 4 kWh, capped at a total of $7500.

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%



The global evolution of electric vehicle sales [35–41].

According to sources [42–48], it is expected that these numbers will keep increasing in the coming years, as many countries have expressed their plans to ban internal combustion engine vehicles in the near future. A relevant example of this movement is Norway, which has announced that all cars and vans sold by 2025 must have zero emissions. Likewise, India, Israel, and the Netherlands have stated that all vehicles sold by 2030 will be electric. Germany and the United Kingdom have extended this deadline to 2040, which aligns with the year when combustion vehicles will also be prohibited in California. In a more rigorous measure, Germany is considering a ban on diesel vehicles in urban areas, while Paris has declared a prohibition on diesel vehicles from operating in the city starting in 2024, along with a ban on internal combustion vehicles by 2030. Rome plans to enforce a prohibition on the circulation of diesel vehicles starting in 2024, whereas Madrid, Athens, and Mexico City are set to implement comparable restrictions beginning in 2025.

Nonetheless, despite the positive sales figures observed globally, it is important to recognize that 95% of electric vehicles were sold solely within just 10 countries (i.e., China, USA, Japan, Canada, Norway, United Kingdom, France, Germany, The Netherlands, and Sweden). Ultimately, it is also crucial to emphasize that there is a wide variety of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) currently available for purchase. Regarding the most popular 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) are particularly significant [30,49].

This section presents intriguing facts pertaining to batteries, including the global increase in production, reduction in costs, key characteristics, and the various technologies involved in the manufacturing process. In recent years, significant progress has been made in battery development. Furthermore, the global production of batteries for electric vehicles (EVs) has surged by 66% [50], which is undoubtedly linked to the rising sales of these vehicles, with forecasts indicating that the demand for batteries will continue to grow. Indeed, it is anticipated that both the supply and demand for EVs will expand even further in the upcoming years.

4.1. Characteristics of the Batteries

Regarding the primary features of batteries, the following points can be emphasized:

- Capacity. The challenges associated with storage and cost represent significant issues in the realm of electric power. Presently, this leads to substantial financial investments in the advancement of new batteries that offer enhanced efficiency and reliability, thereby augmenting the storage capacity of batteries.

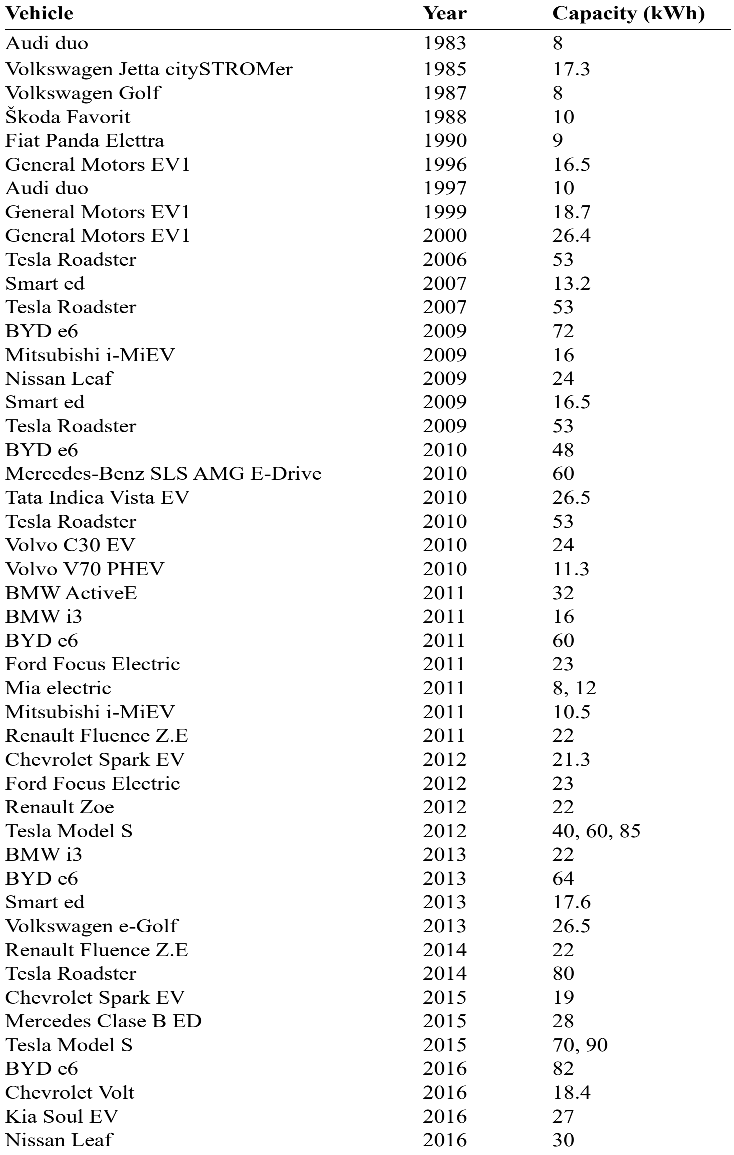
The capacity of a battery denotes the maximum quantity of energy that can be drawn from it under specific conditions. This measurement can be expressed in ampere hours (Ah) or watt hours (Wh), with the latter being more commonly used in electric vehicles.. Given that the capacity of batteries in EVs is a crucial factor, as it directly influences the autonomy of the vehicles, the development of innovative technologies that facilitate the storage of larger amounts of energy in the shortest time possible will be a pivotal element in the success of such vehicles. Table 2 presents data related to the battery capacities of electric vehicles. As illustrated, the capacity of batteries is on a continuous upward trajectory, and vehicles equipped with batteries exceeding 100 kWh are anticipated in the near future.

- Charge state. This term refers to the level of the battery in relation to its full capacity of 100%.
- Energy Density. Achieving the maximum possible energy density is a crucial factor in battery development; in other words, a battery should be capable of storing a greater amount of energy while maintaining the same size and weight. The energy density of batteries is quantified as the energy that can be delivered per unit volume (Wh/L).
- Specific energy. This is defined as the energy that a battery can deliver per unit mass (Wh/kg). Some researchers also use the term energy density to describe this characteristic, which can be expressed in either Wh/L or Wh/kg.
- Specific power. This pertains to the energy output of a battery relative to its weight (W/kg).
- Charge cycles. A charge cycle is considered complete when the battery has been fully discharged and then recharged to 100%.
- Lifespan. Another important factor to consider is the lifespan of batteries, which is determined by the number of charge cycles a battery can undergo. The objective is to develop batteries that can withstand a higher number of charge and discharge cycles.
- Internal resistance. The materials used in batteries are not perfect conductors, which results in a certain level of resistance to electrical flow. During the charging process, some energy is lost as heat (known as thermal loss). The heat generated over time corresponds to the power lost due to resistance, indicating that internal resistance significantly affects high power charging. As a result, a greater amount of energy is lost during fast charging in comparison to slower charging methods..

Consequently, it is crucial for batteries to accommodate rapid charging and elevated temperatures resulting from internal resistance. Furthermore, a reduction in this resistance can lead to a decrease in the necessary charging time, which remains one of the significant limitations of this category of vehicles at present.

- Efficacy. This refers to the proportion of power provided by the battery compared to the energy that has been 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

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

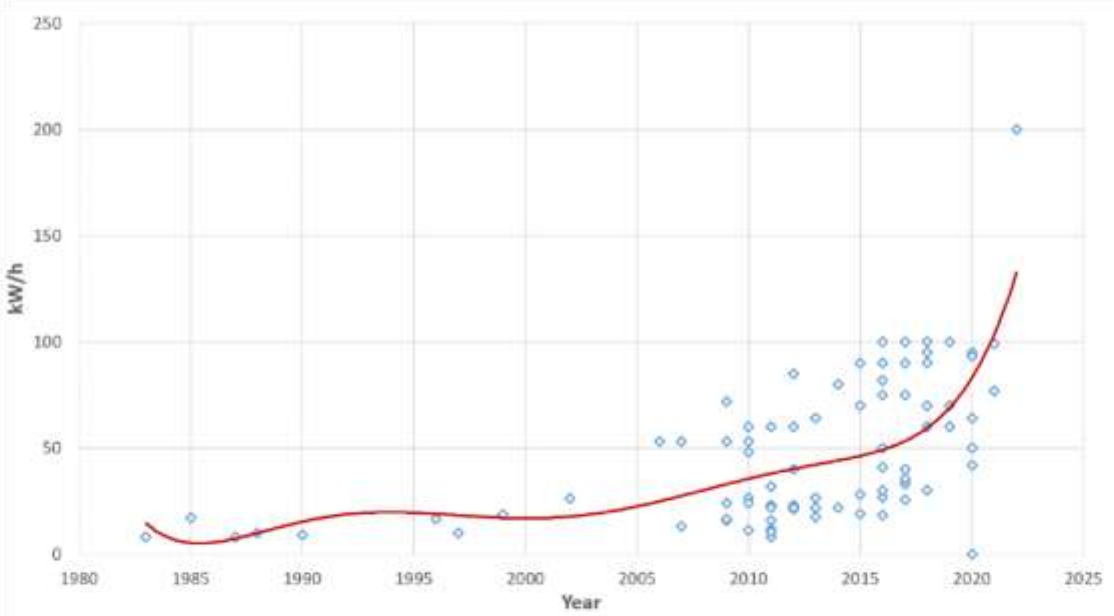
At present, the primary barrier to the broader adoption of electric vehicles (EVs) is the battery technology. Advancements in the development of more efficient, cost-effective, and higher-capacity batteries will enhance the autonomy of vehicles, allowing users to perceive them as a genuine alternative to internal combustion engine vehicles.

Indeed, batteries constitute a crucial element in EVs, prompting a growing number of manufacturers, such as LG, Panasonic, Samsung, Sony, and Bosch, to invest in the creation of enhanced and more affordable battery solutions.

The battery pack is the most costly component in any electric vehicle [52]. For example, the lithium-ion batteries used in the Nissan LEAF initially accounted for one-third of the total vehicle cost. Nevertheless, it is anticipated that this expense will gradually decrease; by the end of 2013, the cost of battery packs was approximately $500 per kWh (which is about half the price per kWh from 2009); currently, the price per kWh stands at $200, with expectations to drop to around $100 by 2025. Additionally, a significant factor supporting the trend of decreasing battery costs is Tesla Motors' initiative to construct a "Gigafactory" aimed at reducing production costs and increasing battery manufacturing. This Gigafactory aims to manufacture a greater number of lithium-ion batteries annually than the total produced worldwide in 2013 [53].The reduction in battery costs will undoubtedly have a direct effect on lowering EV prices, thereby enhancing their competitiveness against traditional vehicles.

Concerning capacity, Figure 5 illustrates the battery capacities of various electric vehicles (EVs) from 1983, when the Audi Duo was introduced with an 8 kWh battery, up to 2022, when Tesla announced its intention to market a Tesla Roadster featuring a 200 kWh battery [54].

When using an EV, autonomy is a crucial factor; however, the duration required for battery charging also poses a significant limitation. Standard power outlets deliver approximately 3 kW of power, which translates to an average charging time of 10 hours to fully charge a battery with a maximum capacity of 30 kWh [55]. Even with fast charging systems, the time needed to charge a vehicle can range from 1 to 3 hours. To address this issue, one alternative is the establishment of Battery Exchange Stations (BESs), also referred to as Battery Swap Stations (BSSs), where depleted batteries can be replaced with fully charged ones. Initially, Israel had 33 BESs [56], although Better Place, the company that pioneered battery-switching services for EVs, declared bankruptcy in May 2013. Nevertheless, this concept was later implemented in Nanjing in 2015 [57], a city with a population of eight million that operates thousands of electric buses. Additionally, BESs were trailed with taxi vehicles in Tokyo in 2010 [58].. In light of this strategy, Tesla developed a system for their Model S that allows for battery exchanges in just 90 seconds [59]. Denmark is currently exploring the feasibility of establishing a sufficient number of BESs to create an infrastructure comprising 900 charging points and battery charging stations operated by robots [60].



The evolution of battery capacity from the mid-1980s to the present.

In terms of scientific methodologies concerning battery exchange, Adler and Mirchandani [61] introduced an in-line routing method for electric vehicles that enables battery replacements in battery electric vehicles (BEs) by utilizing Markov's random decision processes**.**This technique is expected to decrease waiting times by over 35%. Additionally, Mak et al. [62] introduced robust optimization models that enhance the planning process for battery exchanges. The authors also examined the potential for battery standardization and technological advancements as part of an optimal strategy for infrastructure deployment. Furthermore, Yang et al. [63] developed a dynamic operational model for battery swapping stations (BSSs) within the electric market, enabling the generation of additional revenue by actively responding to fluctuations in electricity prices. Lastly, Storandt and Funke [64] tackled the routing challenge for electric vehicles (EVs) with the objective of determining which destinations are reachable from a specific location based on the vehicle's current battery level and the availability of charging or battery exchange stations.

4.3. Different Components and Battery Types

Nevertheless, the growing number of electric vehicle (EV) models, coupled with the various types of batteries and the absence of standardization, renders the implementation of battery exchange stations (BESs) impractical, as all vehicles utilizing BES must be equipped with identical batteries [65].

Indeed, while lithium-ion batteries (Li-ion) are becoming more prevalent in EVs, there is a significant diversity of battery types, among which the following are particularly notable:

- Lead-acid batteries (Pb-PbO2). These batteries, first developed in 1859, represent the oldest form of rechargeable battery. Although they are predominantly found in traditional vehicles, they have also been employed in electric vehicles. Their specific energy and energy density ratios are quite low. The construction of this battery consists of a sulfuric acid solution and a series of lead plates. During the initial charging phase, lead sulfate is converted to metal on the negative plates, while lead oxide (PbO2) is generated on the positive plates. The GM EV1 and the Toyota RAV4 EV serve as examples of vehicles that utilized this type of battery.
- Nickel-cadmium batteries (Ni-Cd). This technology was prevalent in the 1990s due to their higher energy density [66]. However, they are associated with significant memory effects, a limited lifespan, and the use of cadmium, which is both costly and environmentally harmful. Consequently, nickel-cadmium batteries are being replaced by nickel-metal-hydride (NiMH) batteries.
- Nickel-metal-hydride batteries (Ni-MH). These batteries utilize an alloy that stores hydrogen for the negative electrodes instead of cadmium (Cd) [67]. While they exhibit a greater self-discharge rate compared to nickel-cadmium batteries, they are widely employed in various hybrid vehicles, including the Toyota Prius and the second generation of the GM EV1. Additionally, the Toyota RAV4 EV was available in both lead-acid and nickel-metal-hydride versions.
- Zinc-bromine batteries (Zn-Br2). This type of battery employs a zinc-bromine solution contained in two separate tanks, where bromide is converted to bromine at the positive electrode. This technology was utilized in a prototype known as 'T-Star' in 1993 [68].
- Sodium chloride and nickel batteries (NA-NiCl). Commonly referred to as Zebra batteries, they closely resemble sodium-sulfur batteries. Their primary advantage lies in their ability to deliver up to 30% more energy at lower temperatures, although their optimal operating range is between 260 ◦C and 300 ◦C. These batteries are particularly well-suited for electric vehicle applications [69]. The now-defunct Modec company implemented them in 2006.
- Sodium sulfur batteries (Na-S) consist of liquid sodium (Na) and sulfur (S). This battery type is characterized by a high energy density and efficient charging and discharging capabilities.

(89–92%), and they possess a prolonged life cycle. Furthermore, a significant advantage of these materials is their remarkably low cost. Nevertheless, they can operate at temperatures ranging from 300 to 350 ◦C [70]. This category of batteries is utilized in the Ford Ecostar, which was introduced in 1992–1993.

- Lithium-ion batteries (Li-Ion). These batteries utilize a lithium salt as the electrolyte, which supplies the essential ions for the reversible electrochemical reaction occurring between the cathode and anode. Lithium-ion batteries are characterized by the lightweight nature of their components, their substantial loading capacity, their internal resistance, and their ability to undergo numerous loading and unloading cycles. Additionally, they exhibit a minimized memory effect.

Lithium-ion batteries are required to function within a designated safe and reliable operational range, which is constrained by specific temperature and voltage limits. Surpassing these limits can lead to a rapid decline in battery performance and may even pose safety risks, such as the potential for fire or explosion, particularly since electrolytes begin to decompose at temperatures exceeding 150 ◦C [71]. Currently, this type of battery is predominantly utilized in most electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs).

Table 3 and Figure 6 present a comparative analysis of the key characteristics of the various technologies discussed. A critical factor in evaluating these technologies is their operational temperature, as this can significantly influence their market acceptance. In this context, lead-acid and lithium batteries are the most resilient in low-temperature environments, capable of operating at temperatures as low as −20 ◦C. However, it is important to note that low temperatures can severely impact the capacity of Li-Ion batteries, leading to self-discharge [72]. The optimal operating temperature for this battery type is around 40 ◦C. Additionally, it is evident that sodium-based batteries (Na-NiCl and Na-S) can function at higher temperatures .When considering specific energy and energy density, lead-acid (Pb-PbO2) and Nickel (Ni-Cd, Ni-MH) batteries exhibit subpar performance, while lithium-ion batteries demonstrate a markedly higher value.

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

	Pb-PbO2	**Ni-Cd**	**Ni-MH**	**Zn-Br2**	**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

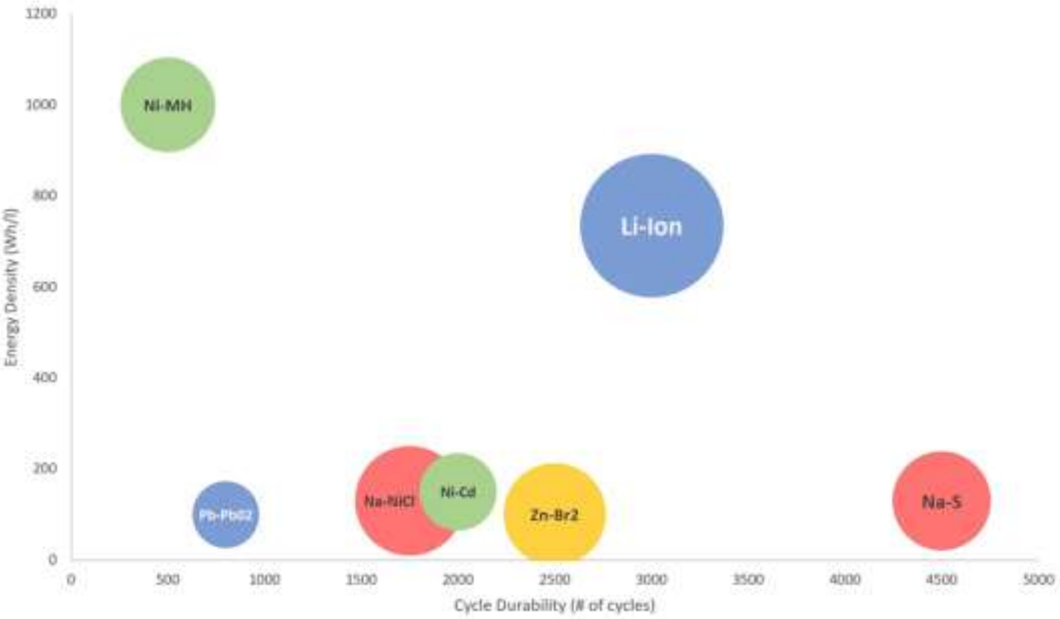


Figure 6 illustrates a comparison of various battery technologies based on their Cycle Durability (represented on the x-axis), Energy Density (depicted on the y-axis), Specific Energy (indicated by bubble size), and Working Temperature (denoted by bubble color). It is important to note that warmer colors signify higher working temperatures.

In terms of specific power, lead and zinc batteries demonstrate inferior performance, achieving a maximum of 100 W/kg. Conversely, the battery types that excel in this category are Ni-MH batteries, which can reach up to 1000 W/kg, and Li-ion batteries, which can provide up to 3000 W/kg. Regarding cell voltage, batteries composed of nickel and zinc exhibit the lowest voltage levels, while sodium batteries (Na-S and Na-NiCl) and Li-ion batteries operate at higher voltage levels. Furthermore, when considering life cycles, Ni-MH and lead-acid batteries yield the least favorable results. In contrast, lithium batteries can endure up to 3000 cycles, while Na-S batteries achieve the highest performance, supporting up to 4500 cycles.

Taking into account all the aforementioned parameters, contemporary electric vehicles depend on lithium-ion technology for their batteries, as this technology offers superior performance across nearly all of the evaluated characteristics.

5. Charging of Electric Vehicles

In addition to the element of autonomy, a crucial factor that deserves attention is the length and characteristics of the battery charging process. For electric vehicles to attain substantial success, it is essential that users possess the ability to charge their vehicles in an efficient and straightforward manner. This goal requires the creation of an infrastructure that supports such rapid and uncomplicated charging. This necessity includes the provision of home charging solutions, as well as the advancement of electric charging stations that provide fast charging options during long-distance travel. Below, we outline the various standards and regulations that govern the technology associated with electric vehicle charging. Specifically, we clarify the different charging modes defined in the current standards, along with the relevant connectors.

When analyzing the charging of electric vehicles, one encounters a range of standards, which are primarily determined by the geographical area of application. In North America and the Pacific region, the SAE-J1772 standard is specifically utilized for charging electric vehicles. Conversely, China employs the GB/T 20234 standard, whereas Europe has adopted the IEC-62196 standard.The main difference among these three standards lies in the classification of charging modes; the first two categorize them based on the type of power (DC or AC), while the the latter categorizes them based on the charging power involved..

The SAE-J1772 standard, which was established in 1996 and is endorsed by SAE International, serves as a specification for electric vehicle connectors in North America. This standard is extensively used in both the United States and Japan and outlines various charging modes (see Table 4):

- AC Level 1: This mode makes use of a conventional electrical outlet that provides 120 V AC, with a maximum current of 16 A, leading to a maximum power output of 1.9 kW.
- AC Level 2: This mode utilizes a standard electrical outlet that supplies 240 V AC and accommodates a maximum current of 80 A, resulting in a maximum power output of 19.2 kW.
- DC Level 1: This mode requires an external charger that can handle a maximum voltage of 500 V DC and a maximum current of 80 A, delivering a maximum power output of 40 kW.
- DC Level 2: This mode also employs an external charger, which is capable of accepting a maximum voltage of 500 V DC and a maximum current of 200 A, achieving a maximum power output of 100 kW.

5.1. Charging Modes

The IEC-62196 standard, created by the International Electrotechnical Commission (IEC) in 2001, serves as a global framework for charging electric vehicles in Europe and China.. This standard outlines the essential characteristics of the charging process and the methods through which energy is supplied. It is based on the IEC-61851 standard and introduces an initial classification of charging types according to their nominal power, which in turn affects the duration of the charging process. Users are offered four distinct modes for vehicle charging (see Table 5). 1. Mode 1 (Slow charging) is defined as a domestic charging option, with a maximum current of 16 A. It utilizes standard single-phase or three-phase power outlets that are equipped with phase(s), neutral, and protective earth conductors. This mode is primarily used in residential environments. 2. Mode 2 (Semi-fast charging) is suitable for both home and public settings, with a specified maximum current of 32 A. Like Mode 1, it uses standardized power outlets that include phase(s), neutral, and protective earth conductors. 3. Mode 3 (Fast charging) supports a current range of 32 to 250 A. This mode requires the use of Electric Vehicle Supply Equipment (EVSE), which is a specialized power supply intended for electric vehicle charging. The EVSE enables communication with the vehicle, manages the charging process, incorporates safety features, and halts energy flow when the vehicle connection is not detected.

- Mode 4 (Ultra-fast charging). As outlined in the IEC-62196-3, this mode specifies a direct link between the electric vehicle (EV) and the direct current (DC) supply network, allowing for a current intensity of up to 400 A and a peak voltage of 1000 V, thereby enabling a maximum charging power of 400 kW. Additionally, these modes necessitate the use of an external charger that facilitates communication between the vehicle and the charging station, along with necessary protection and control mechanisms.

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

The Guobiao Standards (GB) set forth the GB/T-20234 standard for electric vehicle charging infrastructure in China. While China initially embraced the European standard IEC-62196, there is a growing promotion of their own standard, such as GB/T-20234. This standard differentiates between AC and DC charging modes, as illustrated in Table 6.
Based on the conducted survey, the SAE-J1772 standard uniquely incorporates a 120 V charging mode (refer to Table 4). The other standards, even at their lowest charging modes, operate at higher voltages. In terms of their most powerful modes, the SAE-J1772 also presents a lower voltage (i.e., 500 V) compared to the 1000 V provided by both the IEC-62196 and the GB/T-20234.
Regarding amperage, the GB/T-20234 standard specifies a minimum current intensity of 10 A, unlike the 16 A offered by the other two standards. In their highest power modes, the SAE-J1772 supports a maximum intensity of 200 A, while the GB/T-20234 allows for 250 A and the IEC-62196 permits up to 400 A.

In terms of AC power-based charging modes, the SAE-J1772 standard has the lowest power load at 1.9 kWh, in contrast to the 2.5 kWh provided by the GB/T-20234 and the 3.8 kWh.With respect to AC power-based charging modes, the SAE-J1772 standard provides the lowest power load at 1.9 kWh, compared to the 2.5 kWh of the GB/T-20234 and the 3.8 kWh supported by the IEC-62196. The IEC-62196 standard delivers the highest power at 120 kWh, surpassing the 27.7 kWh of the GB/T-20234 and the 19.2 kWh of the SAE-J1772. A similar trend is observed in DC power-based loading modes, where the IEC-62196 stands out with the highest power at 400 kWh, compared to the 250 kWh of the GB/T-20234 and the 100 kWh provided by the SAE-J1772. Additionally, it is noteworthy to mention Tesla Company, which, despite not being an international standard itself, operates its own fast charging points known as Supercharger Stations. Tesla's superchargers function in DC and utilize their proprietary system, the patents for which have largely been released.
While Tesla claims that its superchargers represent ultra-fast charging stations, an examination of the IEC-62196 standard (refer to Table 5) indicates that these charging stations are comparable to Mode 3 (fast charging).

Tesla's Supercharger Stations are being established along major routes at intervals of 200 km. Presently, there are 1604 stations and a cumulative total of 14,081 superchargers globally [7]. Furthermore, users of these vehicles are provided with 400 kWh of complimentary charging, sufficient for approximately 1600 km of travel, a tactic aimed at incentivizing consumers to buy 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

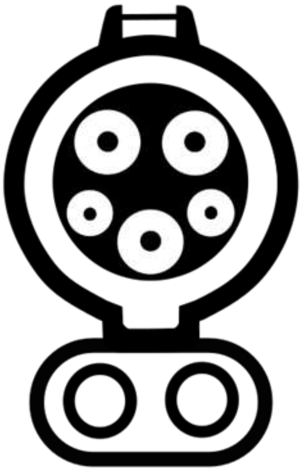
Electric vehicles are equipped with an AC/DC converter that facilitates the charging of their batteries at home via conventional outlets (for instance, the Schuko in Europe). However, for quicker charging, it is necessary to utilize Electric Vehicle Charging Stations, as these stations can provide DC power directly to the batteries. Charging Stations offer electricity through various connectors, which depend on the supported standard, and they offer several advantages:

- They are sealed solutions, rendering them impervious to water or humidity.
- They incorporate a mechanical or electronic locking mechanism.
- They allow for communication with the vehicle.
- Electricity is not delivered until the locking system is activated.
- When the locking system is engaged, the vehicle cannot be moved, ensuring that it remains stationary while connected.
- Certain connectors are capable of charging in three-phase mode.

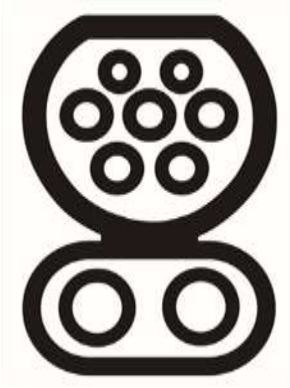
Currently, there is a diverse array of connectors available for charging electric vehicles. These connectors are categorized according to different standards: the Society of Automotive Engineers (SAE) oversees their normalization in the United States and parts of the Pacific region; the IEC is responsible for standardization in many countries worldwide, particularly in Europe; and the Guobiao Standards (GB) governs standardization in China.

The J1772-2009 connectors offer various levels of protection and are suitable for use in wet conditions. The AC variant (refer to Figure 7a) is specifically designed for single-phase electrical systems operating at 120 V or 240 V, comprising five pins:

- Two AC pins that supply power to the vehicle (phase and neutral).
- A ground connection, serving as a safety feature that links the electrical system to the ground.
- Proximity detection, which prevents the vehicle from moving while it is connected.
- Pilot Control, facilitating communication with the vehicle.

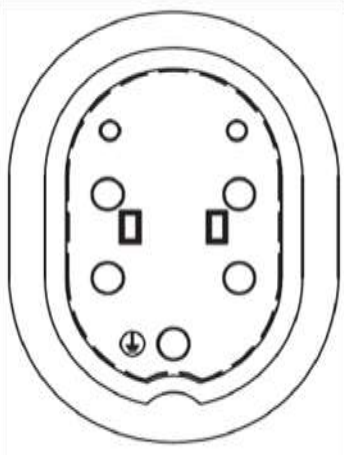


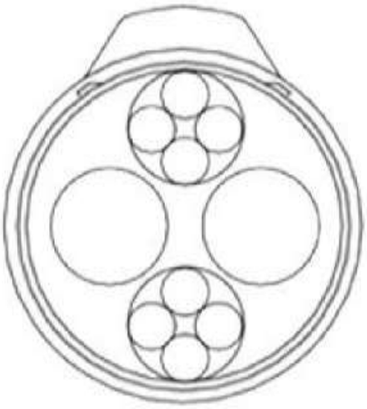
a) J1772-2009 Type 1 for AC charging
b) J1772-2009 Type 2 for AC/DC charging
c) IEC-62196 Type 2 (Mennekes)



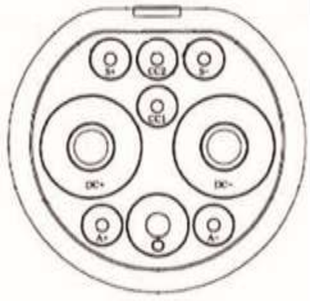
(d) IEC-62196 Type 2 (Mennekes CCS)

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

EV Connectors evaluated according to various standards [77–79].
A different version of the connector is offered, designed specifically for fast charging**.**This innovation significantly shortens the charging duration, enabling vehicle batteries to reach up to 80% capacity in just 20 minutes. This connector, referred to as the Combined Charging System (CCS), facilitates both AC slow charging and fast DC charging. Its design closely resembles that of the AC version, but it incorporates two additional pins for DC charging (refer to Figure 7b).

The IEC-62196 standard has integrated the specifications of the connectors from the IEC 60309 standard into its second version (IEC-62196-2), which was released by the IEC in October 2011. Specifically, it outlines four types of plugs:

- Type 1 (SAE-J1772-2009) Yazaki. In pursuit of a standardized connector, Type 1 AC charging has been included not only in the SAE-J1772 standard but also in the IEC-62196-2. This connector is widely utilized in electric vehicle charging equipment across North America and Japan [80], and is compatible with numerous vehicles, including the Nissan Leaf, Chevrolet Volt, Toyota Prius Prime, Mitsubishi i-MiEV, Ford Focus Electric, Tesla Roadster, and Tesla Model S. This connector is depicted in Figure 7a.
- Type 2 (VDE-AR-E 2623-2-2) Mennekes. Initially intended for industrial applications, this connector was not specifically tailored for electric vehicles (refer to Figure 7c). In single-phase configurations, it is restricted to 230 V, whereas in three-phase setups, it can accommodate higher voltages and currents. This connector comprises 7 pins: four designated for power in three-phase mode, one for ground, and two for vehicle communication (blocking and data exchange). A notable example of a vehicle utilizing this connector is the Renault Zoe, which can be charged via the Mennekes connector at a rate of up to 43 kWh. Although it was not originally designed for rapid charging, Type 2 also features an additional connector known as the Combined Charging System (CCS) (see Figure 7d), which is essentially a modified Mennekes capable of delivering up to 400 A

at 1000 V, allowing for charging power of up to 400 kWh [81,82].• Type 3 (EV Plug Alliance connector) Scame. This connector, designed by the EV Plug Alliance in 2010, supports both single-phase and three-phase configurations. It provides 230 V/400 V and current ratings ranging from 16 to 63 A [83]. France and Italy proposed the adoption of this connector for their vehicles (see Figure 7e); however, due to limited acceptance, the production of Type 3 connectors has ultimately been discontinued.

• Type 4 (EVS G105-1993) CHAdeMO. Endorsed by TEPCO (Tokyo Electric Power Company), this connector is predominantly utilized in electric vehicle charging infrastructure in Japan, although it is also employed in Europe and the USA (see Figure 7f).

CHAdeMO is engineered to provide rapid charging through direct current (DC). In its initial iterations, it supported voltages up to 400 V, initiating the charging process with currents of up to 200 A. Currently, CHAdeMO chargers have been developed to deliver 150 kW of power, with aspirations to achieve 350 kW [84]. This connector comprises ten pins: two designated for DC power supply, one for ground connection, and seven for communication with the network.

As of February 8, 2018, there were 7,133 CHAdeMO charging stations in Japan, 6,022 in Europe, and 2,290 in the United States [85]. Notably, it is integrated into various vehicles, including the Nissan Leaf, Nissan e-NV200, Mitsubishi i-MiEV, and KIA Soul EV.

Regarding the GB/T 20234 standard utilized in China, a key distinction from the SAE-J1772 and IEC-62196 standards is that, while the latter two utilize the same communication protocol between the vehicle and the charger, the Chinese standard employs a different protocol, leading to incompatibility among these charging systems [86]. The GB/T 20234 standard encompasses two types of connectors. The connector used for AC charging is physically identical to the IEC Type 2 or Mennekes connector (refer to Figure 7c); however, it is incompatible with European vehicles that utilize the same connector due to differing protocols. The standard specifies its own connector for conducting DC charging (see Figure 7g).

Lastly, Tesla utilizes two distinct connectors for the rapid charging of its vehicles, depending on whether they are marketed in Europe (see Figure 7c) or the United States (see Figure 7h). In Europe, Tesla has adopted the Mennekes connector, albeit with slight modifications to facilitate both domestic charging (AC) and ultra-fast charging (DC) through their Superchargers. For the United States market, Tesla has developed its proprietary connector.

6. Power Control and Energy Management

Energy management plays a vital role in electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Consequently, the battery management system (BMS) serves as a crucial component designed to oversee and regulate the battery unit within these vehicles. Specifically, the BMS is tasked with managing the energy supplied by the batteries to ensure their safety and reliability. Modern BMSs consist of various components, including power delivery units, sensors, and communication channels, all integrated into a cohesive system.

The primary function of BMSs is to oversee power delivery while minimizing battery stress caused by charging and discharging cycles. The BMS acts as the central controller, preventing abrupt changes in current and thereby avoiding excessive discharge rates.

Cell balancing is crucial for the high-performance battery packs used in electric vehicles (EVs), since the overall reliability of a long series of individual cells is dictated by the weakest cell.. Specifically, it equalizes the charge across all cells in the series to prolong the overall lifespan of the battery pack.In this manner, the BMS protects individual cells from becoming overstressed.

Another significant responsibility of BMSs is to measure the state of charge and calculate the driving range. Auxiliary devices, such as headlights, dashboards, and heating/cooling units, also draw power from the battery pack. However, these devices lack intelligence and do not communicate with the BMS. A more intelligent management of these energy demands could lead to improved power delivery without compromising the efficiency of the powertrain.

In relation to the aforementioned issues, various authors have suggested different architectures for BMSs. For example, Hauser and Kuhn [87] outline the essential requirements that a BMS should fulfill: (i) data acquisition, (ii) data processing and storage, (iii) electrical management, (iv) thermal management, (v) safety management, and (vi) communication. Considering all these characteristics, they present a schematic illustration of a BMS.

(refer to Figure 8). Other researchers, including Xing et al. [88], provide a comprehensive review of Battery Management Systems (BMS) for Battery Electric Vehicles (BEVs) and Hybrid Vehicles (HVs), emphasizing the importance of the state of charge, state of health, and state of life as critical factors that BMSs must take into account.

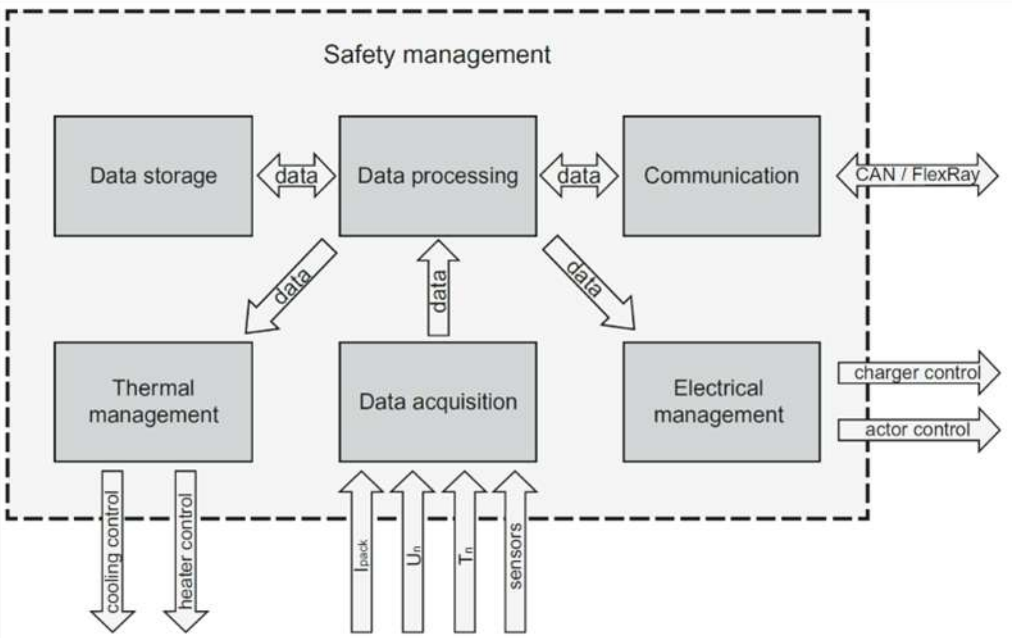


Figure 8. Key elements of the Battery Management System (BMS) [87].

A more ambitious feature proposed for future Battery Management Systems (BMSs) was introduced by Zhang et al. [89]. Specifically, the authors simulate methods to extend driving ranges by forecasting both terrain variations and the movements of preceding vehicles. In their simulations, the optimization of electric vehicle (EV) velocity and motor torque distribution is achieved through a nonlinear predictive controller model aimed at minimizing energy consumption.

Indeed, future BMSs are expected to be more intelligent and efficient, incorporating on-chip analytical capabilities to accurately assess driving ranges and adapt dynamically to load variations for enhanced power delivery. Furthermore, BMSs will accommodate: (i) various and adaptive charging protocols, (ii) any configuration of battery cell numbers and sizes, and (iii) vehicle-to-grid functionalities, facilitating charging transactions or the reservation of charging slots.

Thermal Management and Power Electronics

One of the critical components in Battery Management Systems (BMSs) is thermal management, as illustrated in Figure 8. Specifically, it may be necessary to elevate the temperature of batteries to enhance their performance in cold weather conditions. To achieve this, Shang et al. [90] introduced a high-frequency sine-wave (SW) heater that utilizes resonant LC converters to self-heat automotive batteries in low-temperature environments. Their design can double the heating rate without relying on external heaters. Furthermore, in [91], a compact heater was proposed that utilizes resonant switched capacitors (RSCs) and is powered by the on-board battery pack. This design allows for easy implementation and can achieve a temperature rise of up to 2.67 °C/min while maintaining a high efficiency of 96.4%.

Nevertheless, elevated temperatures pose a significant challenge for electric vehicle (EV) batteries and the power electronics utilized in EVs. In this context, power electronics play a crucial role. The ongoing increase in power density of electric motors necessitates greater power delivery from electronics, leading to increased heat dissipation. To tackle this challenge, Nonneman et al. [92] conducted a comparative analysis of various cooling strategies under similar conditions. In contrast to other research, the authors took into account extra elements like cost, complexity, and practical feasibility to enhance inverter designs for electric vehicles. Similarly, other researchers, including Mouawad et al. [93], proposed cost-effective and highly integrated power electronic systems that also emphasize performance. They specifically present a Silicon Carbide Integrated Power Module that consolidates multiple functional components (i.e., semiconductor devices, DC-link capacitors, output filters, current sensing, and gate driver), which enhances power density, improves electrical performance, and reduces costs without sacrificing thermal performance or reliability.

7. Challenges of the Research and Open Opportunities

Despite the significant growth in the development and evolution of electric vehicles, particularly in recent years, this section discusses the aspects that remain unresolved or present interesting avenues for exploration to propose innovative and improved solutions.

We have categorized these opportunities into four areas: (i) the adoption of new battery technologies or manufacturing methods, (ii) the enhancement and optimization of the charging process, (iii) the integration of communications and Artificial Intelligence in electric vehicles to enhance mobility and ensure efficient utilization of the charging infrastructure, and finally, (iv) eco-friendly charging (i.e., utilizing renewable energy) and sustainability concerns associated with electric vehicles.

7.1. New Challenges and Technologies in Batteries for EVs

Batteries represent one of the most crucial elements of electric vehicles (EVs), as they constitute a significant portion of the overall vehicle cost and have a direct influence on EV performance, as previously outlined in Section 4.

The advancements in durability, charging densities, and the processes of charging and discharging have led to the exploration of various resources aimed at developing new technologies that can exceed the capabilities of the lithium-ion batteries that are currently dominant in vehicles.

In our opinion, there remains considerable work to be accomplished in this domain, primarily due to its implications, as enhancements in battery technology could significantly expedite the success of EVs and facilitate the global adoption of these vehicles in a substantial manner. Currently, research is being conducted on new technologies and components, some of which include the following:

- Lithium iron phosphate ($LiFePO4$). This kind of battery shows an energy density of approximately 220 Wh/L, showcasing remarkable durability (able to withstand between 2000 and 10,000 cycles) and the capacity to endure high temperatures.

However, despite the fact that this battery type is beginning to be evaluated in electric vehicles (EVs) [94], it remains in the early phases of research and development. Researchers at MIT have successfully reduced its weight and created a prototype cell that can be fully charged in merely 10–20 seconds, a significantly shorter duration compared to the 6 minutes required for conventional battery cells [95].

- Magnesium-ion (Mg-Ion). These batteries utilize magnesium instead of lithium, achieving the capability to store more than twice the charge while enhancing stability. It is anticipated that this battery type could achieve an energy density of 6.2 kWh/L [96], which would represent 8.5 times the capacity of the best lithium batteries, which currently reach up to 0.735 kWh/L. Various organizations, including the Advanced Research Projects Agency-Energy (ARPA-E), Toyota, and NASA, are conducting research on this battery type [97,98].

- Lithium-metal. In these batteries, the graphite anode is substituted with a thin layer of lithium metal. This battery type can store double the energy of a standard lithium battery [99]. SolidEnergy Systems, a startup from MIT, has already begun deploying these batteries in drones, and they are expected to be integrated into electric vehicles [100]. Lithium-metal batteries exhibit a high Coulombic efficiency (exceeding 99.1%), enduring over 6000 charging cycles, and after 1000 cycles, they maintain an average Coulombic efficiency of 98.4% [101].
- Lithium-air (Li-air). This type of battery requires a continuous supply of oxygen to facilitate the reaction with lithium. Although initially proposed in the 1970s, significant development and enhancement have only recently commenced. It is anticipated that its specific energy will reach approximately 12 kWh/kg, which is nearly 45 times greater than that of conventional lithium batteries, thereby placing it on par with fuel sources [102].

- Aluminum-air. Batteries utilizing this technology generate electricity through the reaction of oxygen with aluminum. A primary benefit of this battery type is its ability to achieve substantial energy densities, reaching 6.2 kWh/L [103], which enables high autonomy levels (up to 1600 km) [104]. The cost of these batteries is decreasing, currently estimated at 300 e/kWh [105], and they are also recyclable.

- Sodium-air (Na2O2). BASF has developed a Sodium-air battery with an energy density of 4.5 kWh/L [106]. In the context of electric vehicles, this battery type can potentially increase the autonomy of existing lithium batteries by at least thirteen times [107]. One major benefit of these batteries is that sodium ranks as the sixth most plentiful element on Earth [108].
- Graphene. Graphene is a material composed of pure carbon, characterized by high thermal conductivity and extreme lightness (a one square meter sheet weighs only 0.77 mg) [109]. One of the key benefits of graphene-based batteries is their minimal heat generation, allowing for rapid or ultra-rapid charging without considerable power losses due to heat. Graphenano, a Spanish company, has developed a graphene battery that, when integrated into a GTA Spano vehicle (900 hp), has achieved a travel distance of 800 km [110]. This battery can be charged in just 5 minutes using a high-power plugWhile this battery type is currently in the initial phases of development, there are prototypes available that demonstrate a specific power of 1 kWh/kg, with expectations to achieve 6.4 kWh/kg in the near future [111].

It is our belief that the technology capable of enhancing the autonomy of electric vehicles (EVs) and significantly decreasing the duration needed for a full charge will ultimately prevail in the marketplace.

7.2. Improvements in the Charging Process

In this section, we examine the charging process, which is a critical element concerning battery-operated vehicles, and it is also vital in the realm of electric vehicles. It is essential to streamline the charging experience for users, enabling electric vehicles (EVs) to cover greater distances.

A significant concern when charging an electric vehicle is the type of connector used. The American and Japanese markets have adopted connectors based on the J1772 standard, whereas European vehicles utilize those recommended by the IEC-62196. Despite the distinct and separate nature of these markets, this situation is undesirable as it can lead to complications for users during the charging of their vehicles; the need to purchase adapters may arise, consequently increasing the overall cost of electric vehicles and potentially introducing safety hazards.

This issue is also prevalent at fast charging stations. As previously mentioned in Section 5.2, there are currently three standard connector types available for fast charging: (i) the CCS associated with the J1772, (ii) the CHAdeMO linked to the IEC-62196, and (iii) the GB/T. Furthermore, we must also take into account the connector utilized by Tesla in its supercharging stations.

While Tesla has opted to equip some of its vehicles with multiple connector types, we believe that advancing towards a unified standard is of greater importance. This would facilitate the charging of all vehicles through a universal connector, taking into account the variations in energy systems across different regions. We assert that such a universal connector would benefit EV drivers significantly and, more importantly, it would have a profound positive impact on the environment.

Another factor that has the potential to transform the charging process is the application of intelligent algorithms aimed at optimizing charges, which can either lower costs or enhance the utilization of electrical infrastructure. At present, the charging process typically commences at the moment the vehicle is connected to the charging station, commonly referred to as Plug&Charge. However, electricity prices fluctuate throughout the day in many countries, suggesting that the initiation of charging could be adjusted to significantly decrease costs by avoiding peak demand periods, during which economic costs are elevated. The introduction of intelligent plugs could facilitate electric vehicles (EVs) in capturing a larger market share compared to internal combustion engine vehicles. While there have been preliminary studies and proposals in this domain [112–114], we believe that numerous unresolved issues and opportunities for further research remain, particularly regarding the communication between vehicles and the electric infrastructure, as well as the incorporation of new technologies based on Artificial Intelligence (such as Deep Learning techniques or Optimization Strategies [115]), which will lead to significantly improved charging processes and a notable reduction in economic costs.

In the context of community or public parking facilities, we argue that the implementation of adaptive charging techniques could also prove beneficial, given that the existing infrastructure may be insufficient to simultaneously power all charging stations. In light of this, it is essential to propose smart load balancing systems capable of intelligently and efficiently managing the charging points. The rationale for this approach is to meet the charging demands of congested environments without necessitating investment in new power infrastructure.

Lastly, we must take into account wireless charging as an alternative to traditional charging technologies, as it allows for the charging of EV batteries while in motion. Indeed, wireless power transfer (WPT) is particularly advantageous due to its flexibility and convenience. Capacitive power transfer (CPT) and inductive power transfer (IPT) represent the two primary wireless charging methods.

In relation to wireless charging, Manshadi et al. [117] highlight the benefits of wireless charging stations concerning electricity expenses and congestion within the electricity network. Dai et al. [118] offer a critical analysis comparing IPT and CPT for applications with small gaps, where they delineate the theoretical and empirical constraints of each method. Specifically, they evaluate the two methods based on power level, gap distance, operational frequency, and efficiency. Concentrating solely on CPT, Li et al. [119] introduced a series of compensation topologies designed to achieve either constant-voltage or constant-current output in CPT-based charging systems.

The successful and efficient implementation of wireless charging for electric vehicles necessitates the creation of cost-effective, high-performance, and highly integrated power electronic systems. In this context, Nohara et al. [120] suggest a compact wireless EV charger featuring a high power-factor drive and a natural cooling structure that utilizes a straightforward quasi-resonant single-ended inverter. Their methodology significantly diminishes the weight and size of the converter while addressing issues related to power factor and cooling. Other researchers aim to substantially enhance the operational range of electric vehicles by leveraging wireless charging capabilities. For instance, Wang et al. [121] propose a dynamic wireless charging system capable of fully transferring the vehicle's driving power to wireless charging while the vehicle is in motion over the charging area. More specifically, the proposed system can dynamically modify the voltage at the transmitting end or the equivalent load resistance of the electric vehicle.

Despite the promising nature of this technology (for example, the implementation of dynamic charging could extend the driving range while also minimizing the size of battery packs), the current high costs associated with it and the absence of a singular, universal standard render wireless charging an impractical alternative to traditional wired charging methods in the near term.

7.3. Communications and AI in Electric Vehicles

For electric vehicles to become the primary mode of transportation in our cities and on our roads, various factors must converge, as previously discussed.Clearly, the advancements made in recent years regarding autonomy, power, technology, and comfort are encouraging consumers to view EVs as a viable option when considering the purchase of a new vehicle. Although the initial cost is somewhat elevated (with some models showing a significant price difference compared to their combustion engine counterparts), financial incentives and reduced tax schemes are also contributing to narrowing the existing disparity.

Nevertheless, there are additional critical factors that require enhancement to facilitate the transition to electric vehicles. The worldwide growth of electric vehicle charging stations is one contributing factor. Currently, in most countries, the availability of charging points is quite limited, which undoubtedly deters potential buyers. We believe that a concerted effort is necessary to enhance the charging infrastructure. Furthermore, the duration required to fully charge the batteries of these vehicles must be significantly decreased to make electric vehicles more appealing to users. Fortunately, we are optimistic that the integration of vehicular communications and Artificial Intelligence (AI) can accelerate the actual adoption of more ecological and sustainable transportation.Wireless communication networks will enable vehicles to be equipped with a communication system that facilitates interactions between vehicles (V2V) and the infrastructure (V2I). Additionally, the implementation of AI-based algorithms will endow vehicles with a degree of intelligence, unlocking numerous new opportunities that will transform future transportation systems.Numerous proposals leveraging Artificial Intelligence can be identified across various domains of Electric Vehicles (EVs), including energy-efficient routing, enhanced charging solutions, and battery thermal management. In the field of effective routing, Masikos et al. [122] present an innovative machine learning-based approach aimed at optimizing energy-efficient routing. This methodology is capable of forecasting energy consumption across different road segments that make up the current or potential routes for vehicles.

Alesiani and Maslekar [123] tackle the challenge of route optimization for a fleet of electric vehicles. Their solution not only takes into account the vehicle's battery limitations but also the simultaneous utilization of charging stations along the designated route, employing an evolutionary genetic algorithm integrated with a learning strategy.Concerning smarter charging solutions, Sugii et al. [124] introduce a scheduling method based on genetic algorithms for the charging of multiple EVs. This particular approach is adept at determining the power curve and managing electric power load levels. Furthermore, it contributes to minimizing the capacity requirements of the charging infrastructure and its associated initial costs. Panahi et al. [125] advocate for the application of Artificial Neural Networks (ANNs) to predict the daily load profiles of individual EVs and their fleets, emphasizing that user behavior is a critical factor in EV charging. Specifically, they utilize historical data to anticipate electricity demand and enhance the coordination of charging activities.

In the context of battery thermal management, Park et al. [126] suggest employing Artificial Neural Networks (ANNs) to optimize the thermal management systems, thereby reducing overall energy consumption. This proposal facilitates the maintenance of battery temperatures within acceptable limits. Karimi et al. [127] investigate the correlation between battery thermal behavior and design parameters. Their numerical analysis indicates that a cooling strategy based on distributed forced convection can achieve uniform temperature and voltage distributions within the battery pack across varying discharge rates.

The integration of communications and artificial intelligence is set to foster the emergence of innovative solutions that: (i) streamline the battery charging process (by enabling early reservations of charging stations, incorporating automatic power balancing features, and implementing context-based adaptive charging, among others), (ii) enhance the power generation process to meet the anticipated high electric demand on the grid (by providing real-time power necessity forecasts, conducting mobility analyses of electric vehicles, etc.), and (iii) accelerate the transition from assisted driving to fully autonomous driving.

Consequently, we are on the brink of realizing the Internet of Electric Vehicles (IoEVs) concept, which will undoubtedly transform our modes of transportation and simultaneously unveil a plethora of research opportunities, including the development of new applications and services.

7.4. Eco Charge and Sustainability

Electric vehicles have emerged as a paradigm of sustainability and environmental stewardship, primarily because they do not release harmful pollutants into the atmosphere, in contrast to traditional internal combustion vehicles. This sustainability extends beyond merely the operation of hybrid or electric vehicles; it encompasses their design, the primary materials utilized in their production, the energy consumption during their operation, and the subsequent recycling of their components, all of which contribute to sustainability cycles.

Nevertheless, these concepts are evolving in light of various studies that have raised questions regarding the sustainability and environmental ramifications of electric vehicles [128–131]. Specifically, three critical phases must be considered: (i) the manufacturing process, (ii) the usage throughout their operational lifespan, and (iii) the disposal and recycling processes.

Concerning the production of electric vehicles, some research indicates that it may require over twice the energy to manufacture an electric car compared to a conventional vehicle [128,129], particularly due to the production of batteries. More precisely, the extraction and processing of minerals necessary for the production of EV batteries (such as lithium, copper, cobalt, manganese, and rare earth elements like neodymium), along with the current technology used in battery manufacturing, demands between 350 and 650 Megajoules per kWh [129]. Furthermore, each kWh of battery capacity is associated with CO2 emissions ranging from 150 to 200 kg. For instance, the production of a 22 kWh BMW i3 battery results in the emission of nearly 3 tons of CO2.In terms of electric vehicle (EV) usage, a significant consideration is the substantial electricity required to recharge the batteries of these vehicles, particularly as they become more widely adopted [130]. Furthermore, this demand for power could have indirect negative effects on the environment, contingent upon the sources of electricity generation. While EVs do not release harmful greenhouse gases or nitrogen dioxide, the electricity necessary for their operation may be generated from fossil fuel power plants, thereby undermining the anticipated climate advantages. For instance, nearly fifty percent of the electricity produced in Germany is derived from coal and gas [132]. Consequently, the utilization of renewable energy sources for the production and charging of electric vehicles is a crucial factor. Specifically, for charging purposes, renewable energy (primarily solar and wind) can be stored for use during peak demand periods or to reduce charging costs [133–137].

With respect to the infrastructure required for the deployment of EVs and the pursuit of more environmentally friendly solutions, Bhatti et al. [138] provide a comprehensive overview of the various aspects associated with EV charging, emphasizing the role of solar photovoltaic modules. They specifically examine the prerequisites for grid-powered photovoltaic EV charging, including its economic and ecological implications. In a similar vein, Calise et al. [139] introduce an innovative framework for sustainable mobility that integrates EVs, photovoltaic energy, and energy storage systems, contrasting it with the traditional grid-to-vehicle model. They particularly illustrate that during the summer months, solar energy can significantly meet a large portion of the overall energy demand.

In terms of EV disposal, once the lifespan of the batteries concludes, they pose potential environmental risks, making proper recycling vital for the effective implementation of this transportation technology. Recycling presents a valuable opportunity to lower life cycle costs while facilitating the recovery of high-value materials [140].

8. Conclusions

In this paper, we conducted an analysis of various types of electric vehicles (EVs), the technologies employed, the benefits in comparison to internal combustion engine vehicles, the trends in sales over recent years, as well as the various charging methods and prospective technologies. Additionally, we elaborated on the primary research challenges and available opportunities.

With respect to EVs, batteries represent a crucial element, as they significantly influence the vehicle's range. We examined multiple battery types based on these characteristics. Furthermore, we introduced potential future technologies, such as graphene, which is anticipated to provide solutions for storing greater amounts of energy and enabling faster charging times. This technological advancement could enhance the EV's range, thereby facilitating its acceptance among drivers and users.

The advancement of batteries with increased capacities will also support the implementation of the fastest and most efficient charging methods, along with improved wireless charging technologies. The development of a universal connector that can be utilized globally is another factor that could enhance the proliferation of electric vehicles. The EV is poised to play a pivotal role in the forthcoming Smart Cities, and the availability of diverse charging strategies that can cater to users' requirements will be particularly significant. Consequently, future battery management systems (BMS) should take into account the new scenarios introduced by innovative batteries and the demands of Smart Cities.

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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
Na2O2	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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