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Review

Global Perspectives on and Research Challenges for Electric Vehicles

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Abstract: This paper describes the characteristics of worldwide scientific contributions to the field of electric vehicles (EVs) from 1955 to 2021. For this purpose, a search within the Scopus database was conducted using "Electric Vehicle" as the keyword. As a result, 50,195 documents were obtained through analytical and bibliometric techniques and classified into six communities according to the subject studied and the collaborative relationships between the authors. The most relevant publications within each group, i.e., those related to the most publications, were analyzed. The result shows 104,344 authors researching on EVs in 149 different countries with 225,445 relations among them. Furthermore, the most frequent language in which these publications were written as well as the h-index values of their authors were analyzed. This paper also highlights the wide variety of areas involved in EV development. Finally, the paper raises numerous issues to consider in order to broaden knowledge about EVs, their efficiency, and their applications in the near future for the development of sustainable cities and societies.

Keywords: Electric Vehicles; Hybrid Electric Vehicle; Battery Electric Vehicle; Scopus

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1. Introduction

Since the Scottish businessman Robert Anderson invented the first electric vehicle (EV), it has been modified and adapted to the continuing needs of society. Originally, vehicles were used only by the wealthy classes but gradually evolved into a basic and necessary asset in all citizens' personal and professional development. The first contributions to the EV involved rechargeable energy accumulators from the French plant of Gaston in 1865 and Camille Faure in 1881 [1]. At that time, these vehicles were competing with fossil fuel and steam vehicles. The first EVs with commercial functions were cabs in New York City in the late 19th century [2]. Early users of electric cars outnumbered users of internal combustion engines [3]. These vehicles evolved into hybrids to adapt to the locomotion of large heavy vehicles for both passenger transport (buses) and goods transport (trucks) where electric vehicles had insufficient locomotive power. In 1899, Ferdinand Porsche designed the first hybrid electric vehicle (HEV) with an electric and gasoline engine [4] and a range of 64 km. Its design consisted of a gasoline engine that worked at a constant speed feeding a dynamo that charged the electric batteries [5]. Internal combustion engines began to be dynamo-started, and the excess energy was used for different purposes [6].

At the beginning of the 20th century, EV production powered by rechargeable batteries was a reality, and different companies competed on the basis of the type of batteries [7]. This resulted in a change in the locomotion trend with the Ford Model T and cheap oil leaving electric locomotion in oblivion and giving way to fossil fuel combustion [8]. During the 1960s, some models of electric vehicles appeared again in the industrial sector to promote research into electric mobility due to the oil crisis [9]. In 1990, General Motors raised awareness on the environmental impact of vehicles at the Los Angeles Auto Show, and some legislative policies appeared in order to lower emissions [10,11]. This situation, together with lithium battery technology and the rising cost of fossil fuels, encouraged large automotive companies to research electric vehicles [12]. In the 21st century, citizens show their concern for nature by using ecological and sustainable systems. This favors an adequate environment for the commercialization of HEVs and EVs [13,14].

The automotive industry has been immersed in society's demands for adapting their vehicles to modern times, incorporating new technologies and new advances in electronics which increase effectiveness in the transfer of power to the electric traction system and improve the efficiency of battery charging, etc. [15,16]. Citizens are increasingly aware of the problems of environmental pollution and the need to save energy. The transportation industry contributes about a quarter of all greenhouse gas emissions in the USA and globally [17]. This information can lead to the replacement of your combustion vehicle with a more environmentally friendly one [18].

Within the category of EVs, we must differentiate between HEVs and fully electric ones [19]. The most important brands in the automotive sector are making a significant effort to develop efficient and environmentally friendly vehicles, but most of these vehicles are hybrids, that is, they use electric automotive systems for low speeds (30–60 km/h) and fossil fuel systems for high speeds in order to reduce carbon emissions into the environment [20]. Plug-in HEV systems are an alternative to HEVs [4]. These systems incorporate a charger next to the battery as well as powertrain management strategies to further improve vehicle performance. It allows the driver to configure the battery power consumption and replace fossil fuel consumption [21].

The development of an EV has several difficulties, the main one being the autonomy. Such autonomy depends on the batteries; they contribute a great part of the vehicle's cost and limit the maximum distance that can be covered without recharging [22]. In Spain, a vehicle travels an average of 80 km per trip [23], but this is not a limitation since the average autonomy of these vehicles is around 250 km. New policies are required for charging in public spaces and within areas of collective use such as parking areas and residential areas [24].

Among these EVs are those that run on batteries and those that run on fuel cells. Fuel cell EVs are based on hydrogen to produce electricity, with a grid connection for recharging and as an emergency power backup. These vehicles have the unique feature of being almost emission-free. There are a variety of fuel cells, such as direct methanol fuel cells (DMFC) [25], proton exchange membrane fuel cells (PEMFC) [26], alkaline electrolyte fuel cells (AFC) [27], phosphoric acid fuel cells (PAFC) [28], molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC) [29]. They are based on hydrogen production and storage, and the technical limitations of fuel cells include safety due to high voltage and electromagnetic interference caused by high-frequency and high-current switching in the electric propulsion system. For these reasons, these systems are not available to the public, although they seem to be an interesting option for minimum CO2 emissions [30]. Although hydrogen storage technology no longer presents safety problems, efficient production is still pending [31].

Researchers are studying different options for storage and green generation suitable for EVs. Research on battery-based EVs advances the use of ecological batteries [32], promoting the idea of green energy [33], a pillar of this type of vehicle. There is a wide variety of batteries on the market which aim to replace the non-ecological lead-acid batteries used by conventional internal combustion vehicles, which are the cheapest and most widespread [34]. The battery for the EV must be emission-free (zero emissions) and not use polluting elements, and it must have high capacity (Ampere-hours, Ah), high stored energy (Watt-hours, Wh), a usable state of charge (SoC), high life cycle, and maximum discharge current capacity, etc. The most common batteries are those based on nickel as nickel–metal hydride (Ni-MH), which are environmentally friendly [35], but their life cycles are short and they have the problem of a high rate of self-discharge [36]. The lithium battery has great advantages for this use such as a light weight, high energy, and specific power or high energy density [37]. Their main disadvantage is their high production cost compared to Ni-MH. At this time, work is ongoing on other lithium combinations such as lithium–sulfur, which has a higher energy capacity at low weight but a low life cycle [38]. Another combination is lithium iron phosphate, which has superior thermal and chemical stability as well as better safety characteristics than lithium-ion batteries [39]. Another energy storage option is the ultracapacitor (UC): double-layer electric capacitors, pseudocapacitors, and hybrid capacitors [40]. The structure of these devices is like that of a capacitor but with high capacitance [41]. They do not require maintenance, have a long service life, and are not affected by room temperature. Flywheel energy storage (FES) is also being explored. It is a device that stores/maintains kinetic energy through the rotation of the rotor/flywheel [42]. This mechanism has disadvantages such as safety issues and gyroscopic force. Another alternative for the capture of energy is the use of photovoltaic panels on the roofs of vehicles. Despite their low generation, they can reduce the generation of electricity by other techniques. The use of an automotive thermoelectric generator (ATEG), which converts thermal energy into electricity, must also be considered [43]. It has a lifetime of 10 to 20 years and requires no maintenance. Regenerative braking has been incorporated into the EVs [44] which makes it possible to generate electricity through its kinetic energy.

The grid connection infrastructure for the loading/unloading of EVs is an unresolved issue [45]. The scientific community introduced the vehicle-to-grid system (V2G) which is the inverse activity of charging the vehicle, exporting energy back to the grid during the peak energy demand or saving it as backup energy [46]. There are studies that suggest the use of renewable energy generation systems as an alternative to a grid connection and as a way of avoiding the production of non-ecological energy.

Research on EVs is ongoing. New storage systems that are more ecological and have a longer life are incorporated considering the equilibrium of the power market exposed to marginal prices [47]. Improved battery management and monitoring algorithms and new strategies for powertrain management have been considered [48], as well as new grid connection infrastructures for recharging/discharging, etc. [49].

All the advances are focused on improving the efficiency of EVs in order to make them competitive in the automotive market, with several scientific communities making continuous contributions in different areas. These contributions are doubled per decade which involves the processing of an enormous number of documents. These documents are distributed in communities according to the subject matter. Collaborations between the different communities and authors make the innovation of the locomotion systems more efficient as there are also relationships between institutions that support their laboratories to conduct the necessary tests. In this paper, the different communities that have been consolidated in this subject and their relationships over time were studied.

The following sections are structured as follows: Section 2 explains the methodology followed and the extraction of the document analyses using bibliometric techniques. These techniques were used to group the documents according to both their subthemes and relationships. Section 3 is divided into three subsections. Section 3.1. considers the different themes and independently analyses key concepts of each theme. Section 3.2. analyses the global growth of the subject matter according to its geographical distribution, the authors with the highest h-index in the subject matter, and the language of the documents. Section 3.3 sets out future challenges for each of the communities, which emerge from their analysis. The last section provides the overall conclusions and identifies the general challenges for the growth of the EV in its different varieties.

2. Materials and Methods

A bibliometric method was used in this review. It was a rapid method to identify scientific collaborations worldwide using the Scopus database. This research studied global scientific publications indexed in the Scopus database whose subject matter was related to EVs. There are several search engines based on scientometric indicators on the web, but the results considered neither collaborations between authors nor the possibility of establishing different research communities on the same subject [50]. Elsevier's Scopus was selected among the existing databases [51]. An API rasNetBot interface developed by the research group of the Department of Electrical Engineering of the University of Almeria (Spain) [52] was used.

Figure 1 shows a flowchart of the automatic information extraction script of the Scopus database, named Research Network Bot (ResNetBOT). The method used rasNetBot, with the search criterion, "TITLE-ABS-KEY"; in its download phase, it downloads all the publications that meet this criterion, obtaining as a result the metadata of the publications. Then, in phase 2, the system downloads the extended information for each of the publications, obtaining as a result a file for each publication. Once this download is finished the system launches the search algorithms. First, it obtains the data of each of the works: for example, keys, authors, year of publication, etc. Further, it obtains the references among the papers that meet the search criteria, for example, if a paper is cited by many others. However, the papers that cite it were not included in the search; these references were discarded because they were not important for the studied set since the community does not consider them adequate.

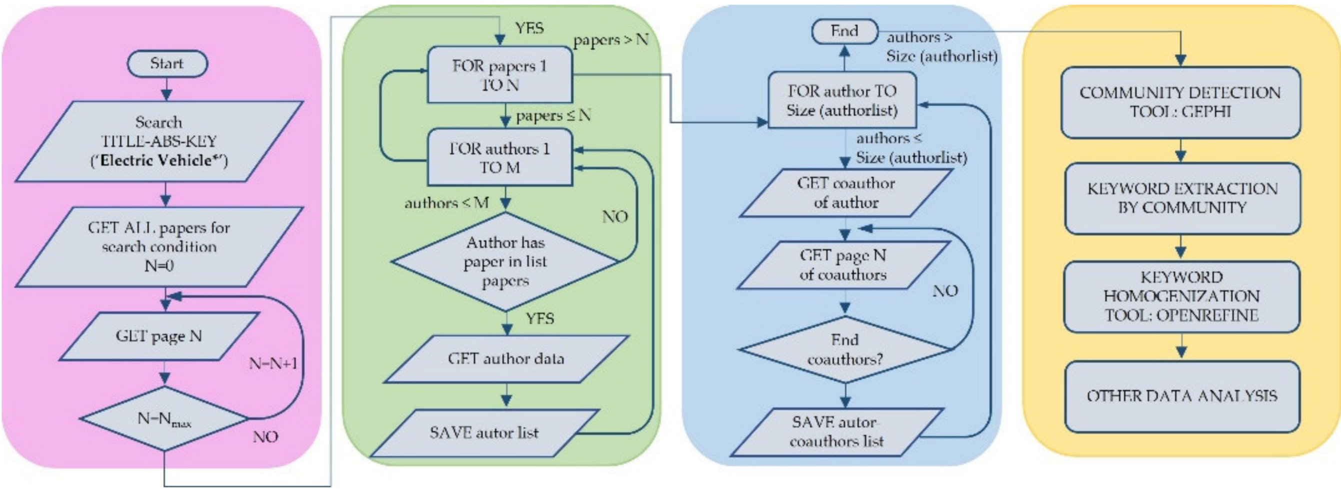


Figure 1. Flowchart for ResNetBOT automated script.

The keyword used in the search was "Electric Vehicle" in the TITLE field and in the OR AUTH KEY field. Documents and relationships between them were analyzed by means of community detection algorithms and plotted graphically using the open source program "Gephi" [53]. The size of the nodes related to each publication is proportional to the h-index. An author may have a highly referenced document, but if working alone that publication will have a smaller node than other papers less referenced but with more collaborations with other documents. In the graph, lines between two nodes indicate that they are cited, and its length shows the importance of their collaboration.

Figure 2 shows the result of the search: 50,195 documents were obtained with 225,445 relations developed between 1955 and the beginning of 2021. This information went through a process of data cleansing which allowed the disposal of documents that were not related to other communities. After this debugging process, 48,536 publications that did not show connections with the main collaboration nuclei were eliminated and the 96.69% of the total relations remained. Figure 2 shows 6 communities, but it was difficult to mark out their area because of their low density and small size. The "Battery Charges" community is mixed with the "Vehicle to Grid Power" community as well as with the "HEV Control Strategies" community. On the other hand, the "EV Market Study" community is widely related to the "EV Battery Management" and "Vehicle to Grid Power" communities. The "HEV Control Strategies" community is the biggest one and presents relations with the rest of the communities. Its relations with the "EV Battery Management" and "EV Market

Study" communities create regions in which the nodes of both communities cannot be easily distinguished.

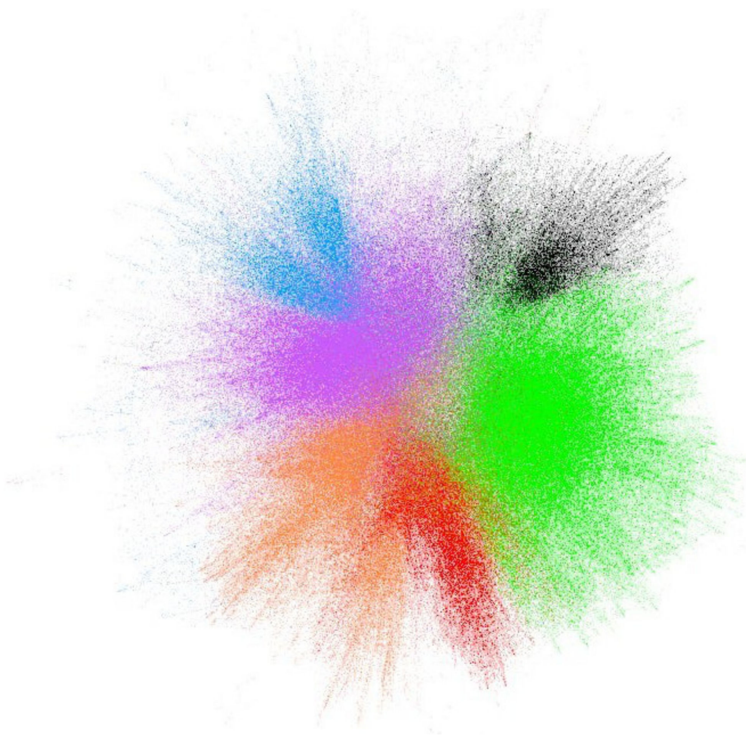


Figure 2. Representation of the communities that investigate EVs after debugging.

Figure 3 shows the number of documents that make up each community to establish their size. There are two communities that stand out for their size. The "HEV Control Strategies" community is the largest one with 29.25% of the total work, followed by the "Vehicle to Grid Power" community with 23.50%. The "EV efficiency community" (15.61%) is the next by size and is made up of half of the documents that form the largest community. It should be noted that the "Battery chargers" community is very small compared to the rest. It is made up of 5.94% of the documents and can be considered negligible compared to the rest.

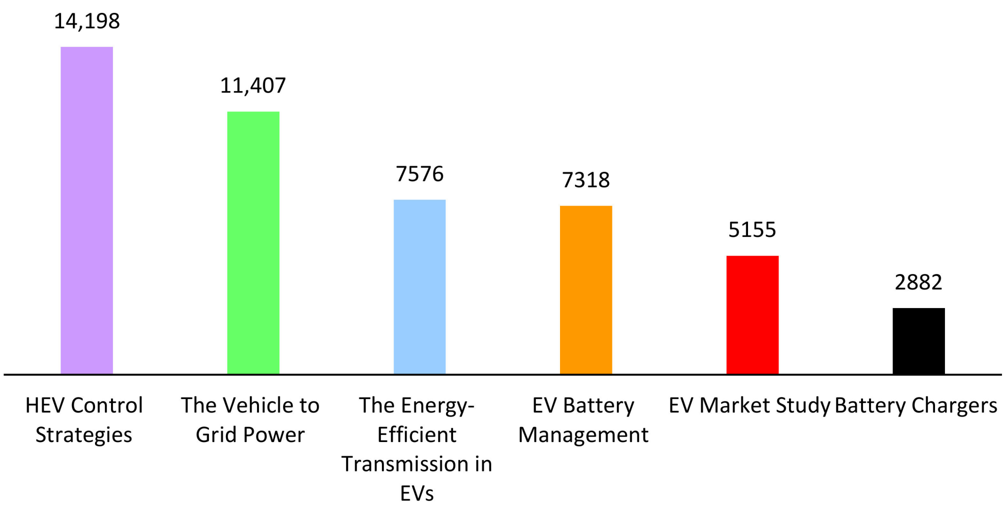


Figure 3. Representation of work distribution in each of the communities.

Figure 4 shows the keywords used in the documents studied, which reveals the great diversity of communities that study EV-related topics. In this figure, the acronyms have been eliminated and replaced by their equivalent to really see the number of repetitions and their relevance. This substitution was necessary because there are many concepts with the same acronyms and different meanings depending on the subject matter. For this reason, it is becoming less and less frequent to use acronyms in the keywords of an article. After the substitution of these acronyms, 30.36% of the total number of keywords were eliminated. The size of these words depends on its number of repetitions. The keyword “Electric Vehicle” has the largest size because it is the one that appears most frequently, in almost all communities. Other words considered to be of a general nature are “Hybrid Electric Vehicle” and “Battery”, which appear in most of the communities studied.

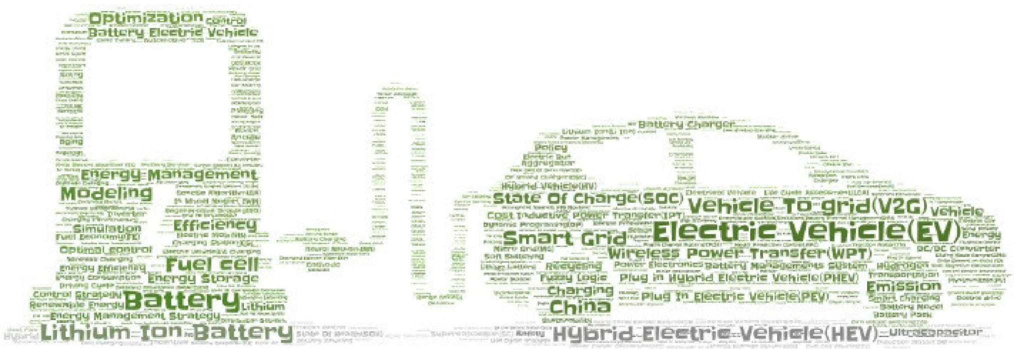


Figure 4. Representation of the global keywords of all communities.

Figure 5 shows the number of repetitions of the 20 most common keywords. “Electric vehicle” is the most repeated, with a value which is five times higher than “Hybrid electric vehicle”. This keyword is among the top 10 most repeated words in all communities and is the most repeated in 4 of them. Other words such as “Lithium-Ion Battery”, “Vehicle to Grid (V2G)”, and “Battery” have more than 300 repetitions and tend to be in almost all the communities, but in a different order according to their subject.

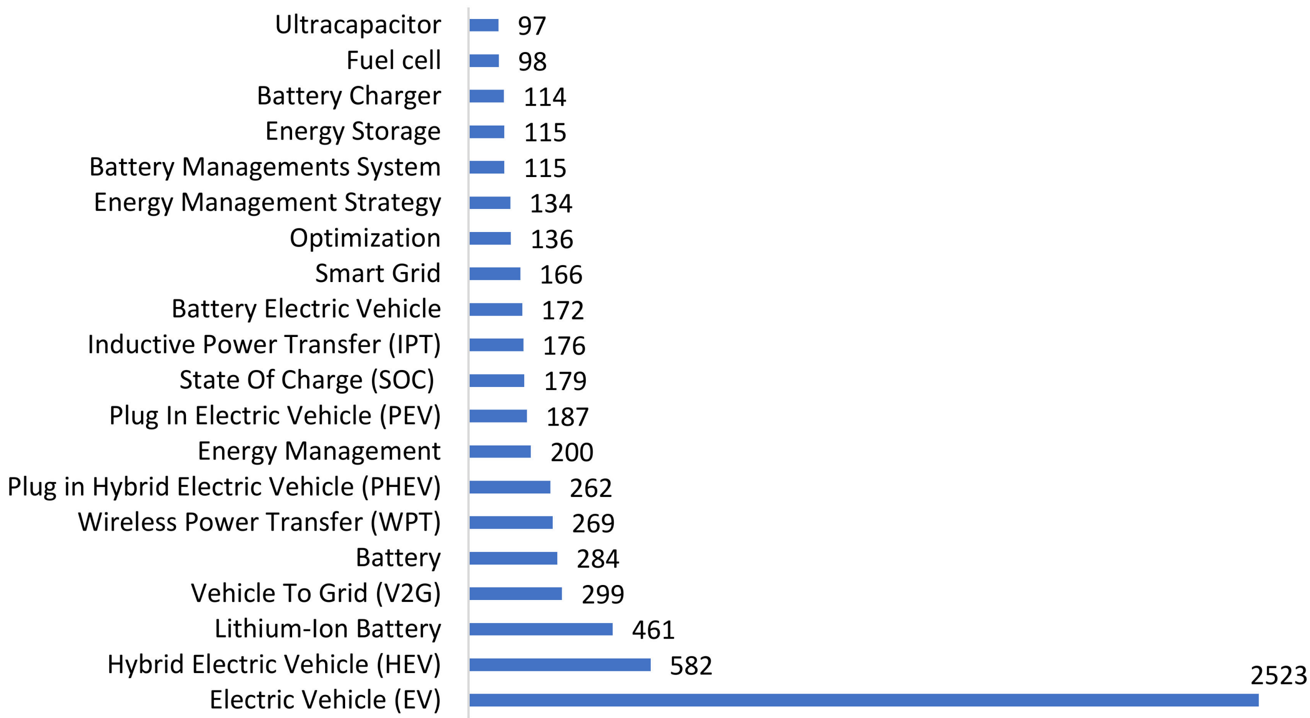


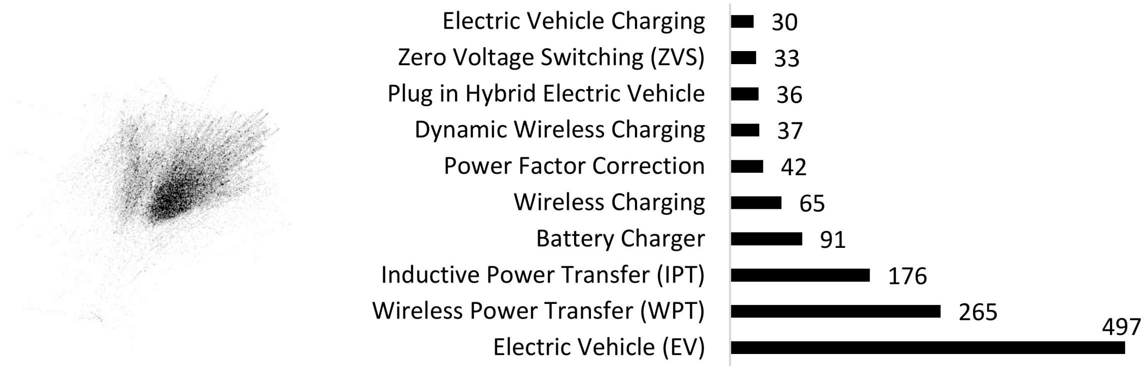
Figure 5. Representation of the 20 most repeated keywords.

3. Results and Discussion

3.1. Analysis of the Communities

This section is divided by subheadings. It provides a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn. Each community has a common theme. The main nodes of each community and their most significant contributions have been analyzed. The number of references of the three most important papers of each community have been determined according to their size.

The Battery Chargers community focuses on the various advances in technologies that improve energy efficiency in the transfer of energy in the charging of the batteries of electric vehicles. The distribution of this community is shown in Figure 6a. It is a relatively small community (5.94%), with a small central nucleus where most of the studies are concentrated. A high number of documents are located outside the community. Despite the small concentration of this community compared to others, its distribution is large because the articles are strongly dispersed, and they relate to many other communities. The three main nodes are [54] with 1236 citations, [55] with 1259 citations, and [56] with 863 citations.



(**a**) (**b**)

Figure 6. Representation of the Battery Chargers community: (**a**) Isolated distribution of publications; (**b**) Keywords.

Figure 6b shows the 10 most repeated keywords in the community. "Electric Vehicle (EV)" is the most repeated keyword with almost twice as many repetitions as the next most repeated keyword, "Wireless Power Transfer (WPT)". Keywords such as "Inductive Power Transfer (IPT)" and "Battery Charger" are among the top 20 most repeated keywords globally. The remaining keywords are related to the EV efficiency process such as "Wireless charging", with a similar number of repetitions.

Plug-in electric vehicles (PEVs) differ from HEVs because they incorporate a higher capacity battery and power converters. Batteries are charged during low-power periods and discharged during high power demand, providing an energy boost.

Advances in power electronics are present in EVs, both in the power transfer and battery charging system [57]. Charging systems use two implementation-based approaches, capacitor-based and contactless coil-based systems, which are called conductive and inductive, respectively. Charging batteries via a grid connection has disadvantages such as the gauge of the connection cable or the necessary infrastructure, among others. To overcome this, research has been carried out on wireless power transfer (WPT) or inductive power transfer (IPT), the main advantages of which are safety, convenience, and a fully automated charging process [58,59]. Wireless power transfer systems (WPTS) can be classified as inductive power transfer systems (IPTS), coupled magnetic resonance systems (CMRS), like IPTS with an extremely high-quality factor (Q), and capacitive power transfer systems (CPTS). CMRS present difficulties in maintaining resonance conditions due to their Q and are bulky, making them unlikely to be a reliable candidate for future EVs. The most likely implementation for EVs is IPTS and CPTS.

Battery chargers can also be classified according to their location as external chargers (the charger is mounted on the charging station and is independent) and internal or integrated unidirectional and bidirectional chargers (the charger is mounted on the EV) [58]. EV on-board chargers have been designed with light weight, small size, high performance, and simplicity of control as desirable features [60]. Battery charging can be performed in different modes of operation and sometimes allows interaction between them [61]:

- Grid-to-vehicle (G2V) is used in internal chargers.
- Vehicle-to-everything (V2X) uses bidirectional integrated chargers and allows distributed energy control to share stored energy. However, V2X is vulnerable to cyber–physical attacks and instability caused by time delay. There are proposals to solve this by using cyber resilience techniques, authentication protocols, and delay-tolerant techniques, through which the resilience of the V2X system to cyber–physical attacks and time delays can be increased.
- Vehicle-to-grid (V2G) uses the energy stored in the battery for the grid connection to provide services to the grid (active power demand regulation, reactive power compensation, peak shaving and valley filling of load demand, frequency and voltage regulation, harmonic compensation of grid current, improved reliability, and stability and efficiency of the system, among others).
- Vehicle-for-grid (V4G) is a special case of the V2G mode of operation to compensate harmonics in the line current and inject reactive power to improve the voltage profile of the system; it allows the G2V/V2G mode, and the remaining energy not used in this mode can only be used for reactive and harmonic power compensation during the V4G mode.
- Vehicle-to-vehicle (V2V) is used to exchange charging energy between EVs, where EV owners can sell their surplus energy to other EV owners. This functionality can also be realized by V2V for EVs connected to smart homes and car parks.
- Vehicle-to-home (V2H) implements the V2G modes to provide a backup supply for connected loads in the home (connected appliances in a smart home) and V2V.
- Vehicle-to-load (V2L) is used to ensure a continuous supply to critical loads that cannot be left without power in case of main grid failure such as military sites, hospitals, data centers, etc. It is implemented as a special case of the V2H and V2V modes of operation for electric vehicle chargers.

The battery charger is one of the main elements that define EV technology and is implemented in the charge control algorithm and charge converter topologies. Among its characteristics, it must optimize efficiency (energy density, cost, and the size and health of the battery) and be reliable and affordable. Different charging techniques based on topologies and their electrical models are presented in [58].

There are different proposals to modify the basic scheme, such as using a bidirectional DC/DC converter for regenerative loads in case of braking, etc. [61]. Inductive charging does not use a cable connection between the supply and the power system for loading. These systems are a safe and robust bet for high-power applications (>50 kW). Inductive charging is based on the AC/DC/AC conversion from the supply network and an AC/DC rectifier for the battery connection; a resonant circuit (L and C) is usually used to adapt the energy to the conditions of maximum energy efficiency. For the magnetic coupling, different forms of cores are used (U, E, I, or W), and for the resonant circuits, depending on the arrangement of the passive elements, different resonant topologies are obtained. These systems allow energy supply without contact, using galvanic isolation between the primary source and the load, with efficiencies of around 90%. The batteries used in these vehicles have a high storage capacity. The performance of the magnetic coupler limits the energy transfer and the viability of the system. Inductively coupled power transfer (ICPT) systems have been extensively studied since their invention in 1995 [62]. The literature includes many studies on the behavior of circular power pads [63], but there are other proposals with the aim of minimizing losses in EV charging [64].

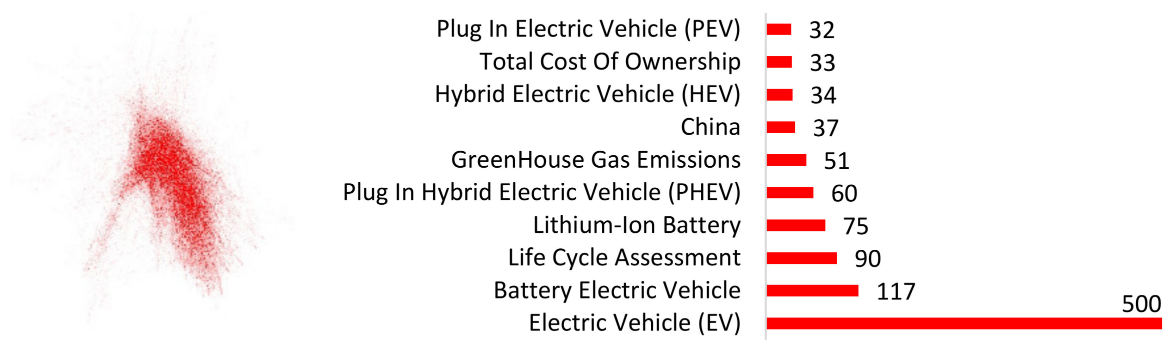
Other authors propose a theoretical inductively coupled ICPT using a variable frequency controller for EV battery charging to deliver 30 kW through a 45 mm air gap at a nominal frequency of 20 kHz and a primary current of 150 A [54]. Researchers developed a design factor called Kre for the selection of the optimal number of coils, appropriate section, compensation capacitors, and resonance frequency of an ICPT system for four basic topologies [65]. Choosing the operating frequency is essential for maximum power transfer to the load. If the frequency is not appropriate, it can cause stability and control deficiency. The results show the dependence of the quality factor of the secondary resonant circuit on the topology of the primary and secondary circuits, with parallel compensation less critical in series connection.

Researchers have proposed the design of an integrated bidirectional AC/DC charger and DC/DC converter for PHEV and hybrid/plug-in-hybrid conversions. The system allows adapting an HEV to a PHEV and uses the AC/DC converter to charge the battery with power factor correction and a DC/DC converter to transfer the energy of the battery [66]. This system adds an additional high-energy battery to the HEV system that receives or supplies power to the bidirectional DC/DC converter, which is connected to the traction and regenerative load recovery in the braking. Achieving a low-cost, highly efficient, and flexible EV charging and discharging system is an ongoing development, involving both the industrial and academic communities to make it viable and environmentally friendly. Other proposals analyze a mathematical model based on a phase and/or voltage magnitude modulator for a 1.5 kW inductive power transfer under various operating conditions [67]. Other research proposes an online electric vehicle (OLEV) center, and it has been commercialized in the Seoul Grand Park [61]. This proposal includes a wireless 100 kW power transfer system for the OLEV system obtaining a power transfer efficiency of 80% for an air space of 26 cm, and there are currently upgraded versions such as OLEV 6G [68]. Reviews on the wireless charging of electric vehicles have also been carried out, in which the benefits of the introduction of electric roads with wireless charging capacity are discussed [55].

The V2V mode of operation requires communication models to make use of applications based on the internet of things (IoT) and intelligent transport systems (ITS). Major electric vehicle companies such as Audi (Germany), General Motors (USA), BMW (Germany), Volvo Cars (Sweden), Daimler AG (Germany), Toyota Motor Corporation (Japan), Qualcomm Technologies, Inc. (USA), Volkswagen (Germany), and AutoTalks Ltd. (Israel) are developing applications that support V2V communication [60].

This kind of system will encourage using these vehicles since the charge will not depend on the type of battery, although wireless charging needs further research to make it economically viable and safe for citizens.

The EV Market Study community is formed by research about EV market trends. The characteristics of this community are shown in Figure 7a, where there are higher density areas of nodes and an external halo that relates publications within this community to others from neighboring communities. The three main nodes are [69] with 880 cites, [70] with 536 cites, and [71] with 119 cites. Figure 7b shows the 10 most repeated keywords, among which "Electric Vehicle" is the most repeated keyword, with almost five times more repetitions than the next keywords: "Battery electric vehicle", with a similar number of repetitions as the following keywords, "Life Cycle Assessment" and "Lithium-ion Battery". This indicates that the trend in this community is towards the study and improvement of electric vehicle batteries. The following words are repeated a similar number of times. Other general words such as "Plug-in hybrid electric vehicle" or "Hybrid electric vehicle" also appear. Most studies with these words focus on battery-related issues or on China, the country where the market is growing the most.



(**a**) (**b**)

Figure 7. Representation of the EV Market Study community: (**a**) isolated distribution of publications; (**b**) keywords.

Issues related to EV manufacturing pollution and green recharging are discussed in this community. In [71], a survey of 3029 people interested in purchasing a vehicle is conducted to analyze whether they prefer an internal combustion vehicle (gasoline) or the EV option. The results show that the number of potential EV consumers is higher among younger and more educated people with greener lifestyles. They also reveal that the incomes and the ownership of several cars are not relevant to drivers' decisions. Saving fuel consumption is the main motivation. Although many drivers are willing to buy an EV at a higher cost than the internal combustion ones, a price drop is required to make these vehicles competitive, mainly on the batteries [20].

Plug-in hybrid electric vehicles (PHEVs), which use electricity from the grid to power part of their drives, could contribute to the reduction in greenhouse gas (GEI) emissions from the transport sector. It would represent a 32% reduction compared to conventional vehicles and is conditional on low-carbon electricity sources. One of the conclusions established in [70] is that the electricity generation infrastructure should be long-lasting, and the next decades' technology decisions on electricity supply in the power sector would affect GEI emission reductions if PHEVs were taken into account over several decades.

Potential socio-technical barriers to EV acquisition are identified in [69]. Other research shows that the understanding of EVs differs by gender, age, and educational background, although the sample (481) may not be representative [71]. The initiative to boost the replacement of conventional vehicles is based on the potential for environmental value. There is a group of potential buyers who are very familiar with the technology, and therefore they consider these vehicles as a feasible alternative. However, others do not engage with EVs due to uncertainty about batteries and the sustainability of the power sources.

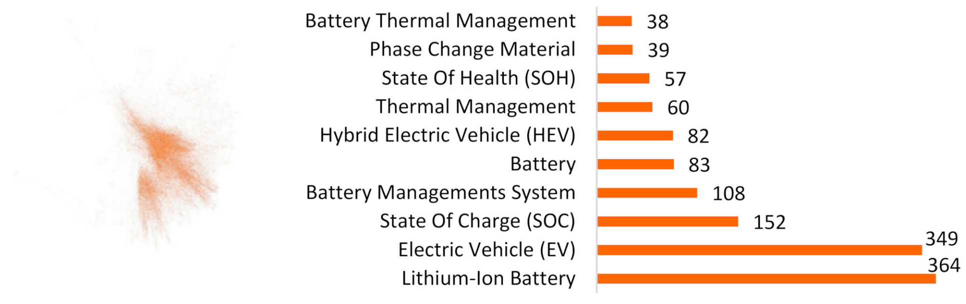
Other researchers study the relationship between environmental impacts and EVs/HEVs compared to conventional vehicles through 51 surveys. The results are not definitive and require more data. Most studies analyze fuel and electricity consumption, but there is little documentation about batteries [72]. Another study compares global warming in relation to conventional diesel and gasoline vehicles with electric ones [70]. The EV potentially produces lower emissions, and its environmental impact depends on producing electricity from renewable sources or natural gas. The production of EVs can cause higher human toxicity potential, freshwater ecotoxicity, freshwater eutrophication, and metal depletion impacts. These problems can be counteracted by making use of effective recycling programs and improving the lifetime of EVs, which decreases the negative long-term impact. This community also contemplates the advances in power electronics that are present in EVs, both in the power transfer and battery charging system [73]. Si-based devices are cheaper but less efficient compared to the generation of SiC or GaN devices (broadband switching devices), although they increase the cost of the converter.

A review of the penetration rate of HEVs and electrical PHEVs in the USA is carried out in [74]. It concludes with six recommendations related to improved surveys, inclusion of vehicle supply models and actions by automakers and state policies, the effect on automotive markets and technology competition, an improved model of market volume and vehicle ratings, and an improved sensitivity analysis that can support and verify model results and provide guidance for future model improvements. EV penetration rate was also analyzed in 30 countries, as well as its relationship to economic incentives in the policies of different countries [75]. The results consider the importance of the charging infrastructure, the economic incentives, and the presence of local production facilities with the market share of each country, although they do not guarantee a high rate of adoption of electric vehicles [75].

Other authors discuss the decrease in Li-ion battery packs' costs between 2007 and 2014 for EV manufacturers [76]. Another paper reviews the drivers and barriers to the deployment of PHEVs [73]. The study examines consumer preferences for the charging infrastructure as well as how consumers interact with and use this infrastructure. It establishes that the most important place for electric vehicle charging is at home, followed by the workplace and then public places. Studies have revealed that more effort is needed to ensure that consumers have easy access to electric vehicle charging and that charging at home, at work, or in public places should not be free of charge. Existing research on this topic is still insufficient to determine the amount of infrastructure needed to support the deployment of EVs. The relationship between policy and environmental education must be analyzed to assess the effectiveness of these policies in the adoption of EVs. Marketing plays an important role in how manufacturers want to present EVs. Although many of them focus on environmental claims, others are more oriented towards the superior performance of these vehicles [70].

The EV Battery Management community studies the autonomy of EVs since it depends largely on the battery and, therefore, the battery's SoC along with the expected battery life.

The isolated distribution of this community is shown in Figure 8a. This community consists of 14.58% of the documents and is made up of a central area as well as highly concentrated areas of nodes and papers in the outer region. The three main nodes are [77] with 3083 citations, [78] with 1128 citations, and [79] with 1349 citations.



(**a**) (**b**)

Figure 8. Representation of the EV Battery Management community: (**a**) isolated distribution of publications; (**b**) keywords.

In this community, unlike the rest, the most repeated keyword is "Lithium-Ion", with a number of repetitions similar to the most repeated keyword globally, "Electric Vehicle (EV)" (Figure 8b). The other keywords with the highest number of repetitions are "State of Charge (SOC)", "Battery Management System", and "Battery", all of which are specific to the study of batteries in EVs.

The battery in EVs must provide energy to supply enough power for a long and stable drive, as well as adequate transient power for acceleration and downhill. In addition, long cycle life, stable voltage, high energy and power density, fast response, and short recharge time are other specifications for the high-power energy storage system of an EV. EV batteries require a monitoring system (battery SoC, power fade, capacity fade, etc.) and instantaneous management of the available SoC. Good monitoring and load management can improve performance and increase battery life if charged with a proper charger and infrastructure. Conventional methods for detecting the state of the battery are easy to implement, but they do not consider aging, temperature, or external disturbances [79]. One review [80] focused on the status of lithium battery technology as the preferred energy source for the consumer electronics market. Then, a study of their characteristics was carried out, and the new existing challenges, which are aimed at achieving quantum leaps in energy and power content, were raised.

Comparing Li-ion batteries with other commonly used batteries for EVs, these batteries have high energy and power density, a long lifespan, and they are environmentally friendly, so they are suitable for EVs [77]. However, they have safety problems, and their durability, uniformity, and cost could be improved. Furthermore, there are some issues concerning battery monitoring and battery management systems (BMS), such as battery performance, the better use of battery models, the adaptive control techniques, and the expert battery management system theories.

Gregory L. Plett published a series of three papers [78] in which he proposes a method based on extended Kalman filtering (EKF) that can achieve the dynamic and instantaneous management of the SoC available in Lithium-ion polymer (LiPB) batteries in PHEVs. The Kalman filter includes a set of recurring equations that are repeatedly evaluated as a linear system or as the extended Kalman filter in the case of a non-linear system. The first paper shows the basics of BMS and the second develops the final model with dynamic requirements (open circuit voltage, ohmic loss, polarization time constants, electrochemical hysteresis, and temperature effects). The third one discusses the use of EKT for the battery management algorithm. In addition, EKF allows for dynamic power evaluations that automatically compensate for recent discharge events and provide a more accurate estimation of how much power can be consumed without exceeding voltage limits. Other researchers study battery SoC as well as HEV and EV battery state of health estimation strategies [81]. They also provide a roadmap for battery EV researchers and manufacturers. The research community is striving to develop an advanced method of SoC estimation and a Li-ion battery energy management system for future high-tech EV applications. There are frequent articles where reviews based on lithium-ion batteries are presented as a rapidly advancing field, it attracts a larger number of researchers. In [82], the authors make a battery check for EV vehicles and consider the SoC as a crucial parameter that can indicate the instantaneous energy available in a battery and inform about the charging/discharging strategies to be followed, as well as protect the battery from overcharging/over-discharging. Lithium-ion batteries are considered suitable for electric vehicles, although they present some problems due to their complex electrochemical reactions, performance degradation, and lack of accuracy in improving battery performance and lifespan. In [83], the application of artificial intelligence for battery status estimation is reviewed.

Other studies address the implementation of a dedicated battery management system which also includes Li-ion battery condition monitoring for a long-life, high-performance electric scooter prototype [84]. The results show that this system increases the reliability and autonomy. A battery's thermal energy management is an issue of concern, since good thermal management improves battery performance. Models shown in [85] respond to the thermal behavior of high-energy batteries such as Ni-MH, Li-ion, and proton exchange membrane fuel cells. Air and liquid cooling systems do not seem to be suitable for high-energy batteries, as they are greater in size and cost. Therefore, a new method which uses a pulsed heat pipe is proposed. When discharge rates and operating or ambient temperatures are high, phase-change materials are the best choice for thermal management, although this requires a study of thermomechanical behavior. They also present the possibility of heat recovering to increase energy efficiency. In [85], the effects of low temperature on batteries are explained, as well as possible different improvement strategies.

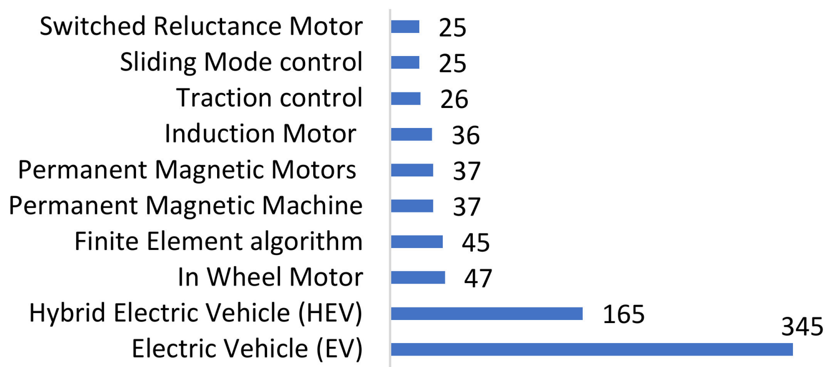
Other researchers provide a double polarization model of an equivalent circuit of a Li-ion battery for use in EVs [86]. Voltage imbalances between individual batteries are a major problem for premature cell degradation and safety risks, which leads to capacity reduction.

A summary comparison and evaluation of the different methods of active battery equalization are presented according to their application, as well as the state-of-the-art energy management strategies of connected HEVs/PHEVs [84]. An overview of new strategies to address today's challenges for automotive battery systems is provided in [87]. Smart battery systems have the potential to make battery systems more efficient and future-proof for the next generations of electric vehicles. Currently, research is ongoing on the construction of high-voltage batteries as well as high-capacity batteries. Zinc batteries are seen as a promising technology for the next generation, once it overcomes insufficient energy density [88,89]. EVs with high-capacity batteries are already available. In 2022, the Tesla Roaster is the car with the highest battery capacity of 200 kWh; its predecessors such as the Tesla Model X or Tesla Model S had a capacity of up to 100 kWh. There are other brands that have models with 100 kWh capacities such as Renault (ZOE 2rs model) and Volvo (40 series model) [90].

Battery recycling presents a drawback for EV expansion. EV manufacturing uses valuable metallic materials that can be conveniently recycled. Using circular economy ideology, Roy et al. (2022) review lithium-ion battery recycling procedures and the challenges remaining to make them common practice. Most material extraction has a lower cost than the extraction of metals in nature, and some are scarce and can be used to make new batteries from the recycled materials [91].

The Energy-Efficient Transmission in EVs community focuses on the various advances in technologies that improve energy efficiency in EVs (Figure 9a). With energy prices constantly on the rise, there is a need for researchers to develop energy-efficient devices. The electric drive is the core of EVs, so its selection is a very important step that requires special attention. Torque distribution and traction control are also important parameters to consider. Other researchers are also investigating emerging technologies that improve energy consumption, such as thermoelectric heat recovery, temperature control, and regenerative braking systems. The three main nodes are [92] with 1571 citations, [93] with 1454 citations, and [94] with 871 citations. Figure 9b presents the 10 most repeated keywords in this community, with concepts such as traction control and induction motors being parameters to be considered and of special interest. The search keyword is shown as the most frequent, repeated almost three times more than the following word. Both words are the most repeated words globally, as they are the ones used in the search methodology. The following most repeated words are specifically related to the topic of this community, such as "In Wheel Motor", "Permanent Magnetic Machine", and "Induction Motor".

(**a**)



(**b**)

Figure 9. Representation of the energy-efficient transmission in EVs community: (**a**) isolated distribution of publications; (**b**) keywords.

Chau and Chan (2007) identified and discussed three emerging energy-efficient technologies: the thermoelectric waste heat recovery and temperature control systems for HEVs, the integrated starter generator for mild hybrids, and the electronic continuously variable transmission propulsion for HEVs. They pointed out that research in energy efficiency technologies will boost the HEV [12].

Chau et al. (2008) provided an overview of permanent-magnet brushless drives for EVs and HEVs, with emphasis on machine topologies, drive operations, and control strategies [93]. The magnetic-geared outer-rotor drive system for EVs, the integrated starter generator system for micro and mild HEVs, and the electric variable transmission system for full HEVs were discussed in the article. In the analysis of rule-based strategies, Chan et al. (2010) suggests that fuzzy rules as well as the neural network are better than other methods based on deterministic rules due to their robustness and capacity for effective adaptation in real time [95]. Wu and Zheng (2017) also used several control strategies, such as a dynamic programming global optimization algorithm, fuzzy control, and torque equal distribution, optimizing the motor's working point, reducing the energy consumption, and increasing efficiency by 4.7% [92]. In the same direction, various induction, switched reluctance, and permanent-magnet brushless machines have been described in Zhu and Howe (2007), highlighting the different topologies and merits [94]. They concluded that the three different technologies can meet the performance requirements of traction drives.

Zeraoulia et al., (2006) reviewed the state of the art of four electric propulsion systems: DC motors, induction motors, permanent-magnet synchronous motors, and switched reluctance [96]. They carried out a comparative study on electric motor drive selection problems for HEV propulsion systems, concluding that induction motors seem to be the most efficient candidate for the electric propulsion of urban HEVs. De Santiago et al. (2012) presented a review of drivelines in EVs, discussing the advantages and disadvantages of each electric motor type. The authors proposed the adaption of a standardized drive cycle or other standardized methods of efficiency measurement in order to make possible the comparison between EVs [97].

Ivanov et al. (2015) presented an overview of the most original and cited variants of traction control and anti-lock braking systems for full EVs [98]. They concluded that there are multiples approaches to improve the traction dynamics of vehicles, but only a few techniques had been validated and verified in conventional vehicles. The authors also encouraged the creation of objective procedures for benchmarking and comparative analysis.

Some articles analyzed the effectiveness of different technologies in prototypes. Hori (2006) analyzed the experimental prototype "UOT MARCH II" regarding the effectiveness of various control studies such as the model-following control and slip ratio control [99]. The benefits of the studies were proven to take advantage of quick, accurate, and distributed torque generation. Chen et al. (2011) analyzed the technical requirements for the design of a permanent-magnet electric variable transmission based on an analysis of the operation of the Toyota Prius II [100]. The authors chose this HEV as the reference vehicle because it is a well-known and efficient system, but it could be considered for the design and analysis of other hybrid powertrains.

The Vehicle-to-Grid Power community is formed by researchers who intend to develop systems to commercialize vehicle-to-grid power. They also investigate the impact on the connection to the electrical grid, recharge/discharge optimization strategies to reduce its impact, and how to maximize the economic performance of the system. To further minimize impacts in terms of climate change, the use of renewable energy for electric vehicles could be improved by integrating energy demand interaction models.

Figure 10a shows the distribution of this community. It is the second community in size (32.6%) and features a central zone with the greatest concentration of nodes. It is related to other communities by the outer zone. The three main nodes are [101] with 2190 citations, [102] with 1697 citations, and [103] with 1581 citations.

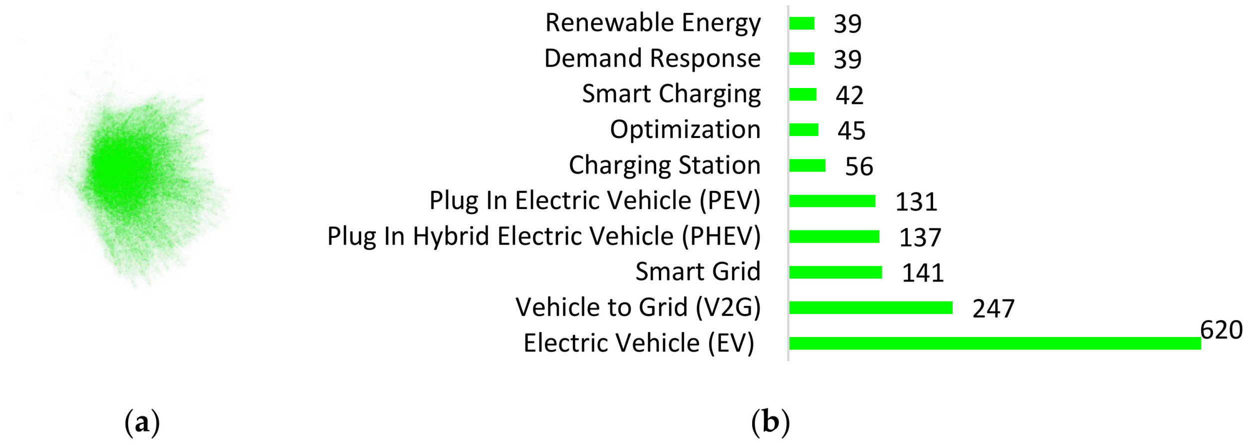


Figure 10. Representation of the vehicle-to-grid power community: (**a**) isolated distribution of publications; (**b**) keywords.

Figure 10b shows the 10 most repeated keywords in the community. The next most repeated keyword is "Vehicle to Grid (V2G)" with half as many repetitions as the previous one, marking it the main theme of this community along with specific words such as "Smart Grid", "Microgrid", and "Optimization", among others. The following words are among the top 20 most repeated words globally. Some of these words are "Plug in Hybrid Electric Vehicle" and "Plug in Electric Vehicle", which are present in almost all communities.

The distribution grid is being affected as electric vehicles expand. Among the considerations for the distribution grid are the adequacy of electricity generation (use of renewables) and energy efficiency. The greatest impact occurs at peak EV load demand hours, which requires the expansion of generation capacity. This also involves overloading the substation and service transformers, shortening their lifetime. It can cause power quality problems such as voltage sags, power imbalances, and voltage/current harmonics, among others. This community investigates alternatives to provide solutions to these considerations and their implications for the distribution network [104].

The use of EVs increases when the possibility of the commercialization of the V2G and V4G systems increases. This is the reverse activity of charging the vehicle and an alternative to export power back to the grid during peak power demand or to use it as backup power. V2G is not suitable for a base-load power distribution network (constant electricity supply throughout the day), where large generators produce higher power at lower cost. However, it does seem suitable for a fast-response and high-power services to balance constant load fluctuations and to adapt to unexpected equipment failures. In [102], it is quantitatively expressed how much EVs can become part of the electrical network, and methods are discussed to estimate expected revenues and costs. They propose using V2G when there is a capacity payment for being online and available along with an additional energy payment when the energy is sent. This results in improved reliability and reduced costs of the electrical system. Once the electric network and the EV fleet are analyzed, it is observed that they respond inversely since the electric network has high capital costs and low production costs, and for the EV fleet it is the other way around. The same happens when using electric generators for 57% compared to 4% of the vehicles. The electric grid has no storage capacity, while the car fleet must have storage to fulfil its function. In [103], strategies and business models for V2G are proposed, as well as the necessary steps for its implementation considering the comparison of the electric grid and the EV fleet. This proposal is in line with the use during peak energy demand hours or as backup energy in the short term. However, in the long term it proposes backup generation and storage for renewable energy.

Another study proposes to add an aggregator as an intermediate system to manage a vehicle's energy while regulating the energy of the distribution network [105]. The procedure for the alternative charging or discharging of the batteries of the vehicles belonging to the aggregator is established to meet the power requested by the grid operator, but it is difficult to develop an algorithm that efficiently serves vehicles with arbitrary loads. The aggregator must control the sequence, duration, and charging rate of each vehicle based on the price of electricity, which maximizes the aggregator's revenue.

PHEV batteries can be recharged either in a parking lot or at home. Recharging consumes a large amount of electrical energy, and this can lead to large and undesirable peaks in electrical consumption that can cause an impact on the distribution network. In [101], the impact on the distribution network of household recharging is studied. Intelligent recharging can be planned, where the charging is coordinated remotely to shift the demand to periods of lower PHEV recharge consumption and thus avoid higher peaks in electricity consumption. The results of this paper show that coordinated charging, using quadratic programming techniques, reduces power losses since dynamics do not improve results. In [106], the relationship between feeder losses, load factor, and load variation in coordinated PHEV loading is studied. Three optimal load algorithms are simulated to reduce the impact on the distribution network at the load connection. The results confirm the effectiveness of the study in maximizing the load factor and minimizing the load variation. Moreover, [107] addresses advanced strategies for centralized EV load control allowing the integration of a larger fleet into the system without network reinforcements. This allows the network to be operated in less extreme conditions by adopting a level of local control to operate in isolation, as the EV batteries can provide rapid compensation to the system. In [108], an analytical solution is developed to predict the charge of an EV considering the stochastic nature of the individual battery charging start time as well as the initial SoC of the battery. This method is applied to four EV charging scenarios: uncontrolled domestic charging, uncontrolled off-peak domestic charging, "smart" domestic charging, and uncontrolled public charge travelers capable of recharging at the workplace. A market EV penetration between 10% to 20% would result in a maximum daily increase in energy demand from 17.9% to 35.8% for the uncontrolled domestic charging scenario. However, off-peak domestic charging increases electricity consumption at night. The "smart" charging method is the most beneficial for both the distribution network operator and EV customers. However, if they start to charge simultaneously it will impose a new peak in the off-peak period on the distribution network. The above studies model the distribution network on a small scale, but, for a real analysis, a large-scale distribution network must be considered. In [109], two real distribution areas are studied to obtain a model for large-scale distribution planning. The results show that with smart charging strategies it is possible to decrease incremental investment by applying a decrease in simultaneous charging and off-peak scheduling of the distribution network.

Other research proposes coordinating PHEV charging to minimize total generation costs in real time [110]. Other papers incorporate market energy prices that vary over time [103,108] and add load time zones based on priority selection (owner's choice). This allows PHEVs to start charging as soon as possible while meeting network operation criteria. The proposed algorithm reduces system overloads and global power surges without the need to over-size the power generation infrastructure to service the PHEV fleet. In addition, it relates the charging infrastructure with the PHEV charger as well as the type of battery [110]. Battery performance depends not only on type and design but also the characteristics of the charger and the charging infrastructure. Common onboard chargers restrict power to meet weight, space, and cost restrictions, except the onboard charger which has no such restrictions and supports low-cost, high-power, and rapid bidirectional charging with a unit power factor. The availability of a charging infrastructure reduces battery energy storage requirements and costs. Inductive battery charging supports wireless charging systems and were considered in the "Chargers Batteries" community, being the foundation of V2G wireless.

The HEV Control Strategies community. HEVs have two sources of energy which require optimal energy management strategies that consider fuel consumption savings and CO_2 emissions reduction.

Figure 11a shows the isolated distribution of this community. It is the largest one and it has areas of high density of nodes where it is difficult to distinguish isolated nodes. It also has a wide halo formed by documents related to other communities. The three main nodes are [111] with 1458 cites, [112] with 1162 cites, and [113] with 1098 cite.

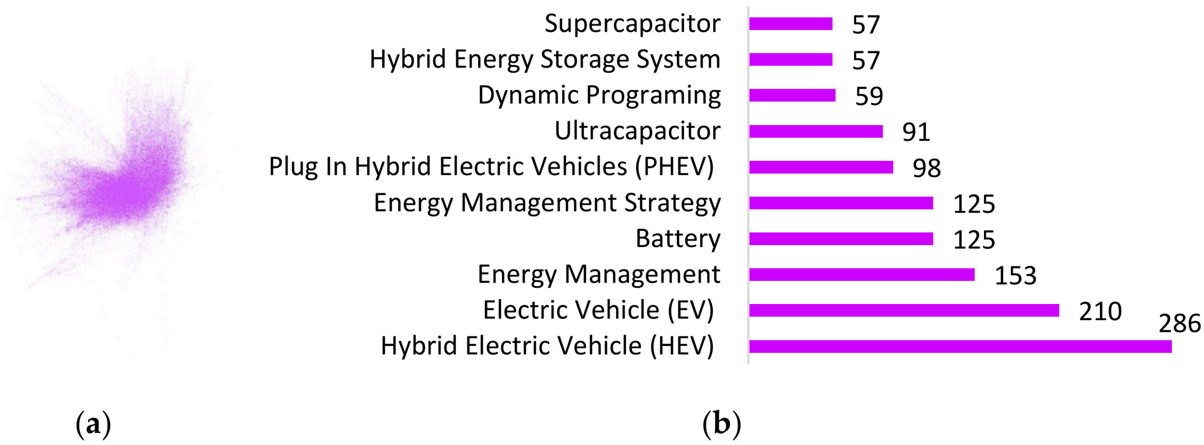


Figure 11. Representation of the HEV control strategies community: (**a**) isolated distribution of publications; (**b**) keywords.

Figure 11b shows the 10 most repeated keywords in this community. The search keyword "Electric Vehicle (EV)" has a lower number of repetitions than the keyword "Hybrid electric vehicle", a general word frequent in almost all communities and which is specific to this community. Other words specific to this community are "Energy Management", "Energy Management Strategy", and "Dynamic Programming". Among the top 10 most repeated keywords are other general keywords such as "Plug in Hybrid Electric Vehicle (PHEV)" and "Ultracapacitor".

EVs have significant advantages over internal combustion engines as they are quieter and more efficient, reliable, and durable. The EV motor controller is smaller and lighter than the current internal combustion engine as well as cheaper to maintain and manufacture [112]. EVs in general (EV, HEV, PHEV, and hydrogen cell vehicles) are more energy efficient as they are hybrids with optimal fuel consumption strategies [111,114]. For HEVs and PHEVs to be competitive with conventional vehicles, costs must be reduced, efficiency improved, and the range of electric driving increased [115]. Power conversion and rotating machines are similar in HEVs and PHEVs, as well as the problems associated with them [114]. These vehicles require an efficient energy management system to divide the energy demand between the powertrain components [116]. There are two different methods of energy management: control strategies based on a physical model of the system and optimization strategies that are usually based on simulations of the system under study [95]. The hybrid transmission train is a discrete dynamic system, which has a time-varying, multi-domain, and non-linear variable plant. In these vehicles, an intelligent control algorithm is used to improve the control of low-level components [31]. The implementation of the control strategy is carried out within the vehicle's central controller, and it is responsible for making decisions on when to activate or deactivate certain local parts of the transmission system. These strategies are based on different parameters to satisfy the driver's demand, maintain the battery charge preventing them from overloading and overdischarging, optimize the efficiency of the transmission train, minimize engine stops and restarts and idle time to avoid unnecessary fuel consumption, and to perform in its optimal operating region most of the time and reduce fuel consumption and emissions [101]. However, emission reduction and efficiency optimization are parameters in opposition, although a balance is sought between both. Global optimization techniques are not valid for real-time development using heuristic control techniques, where the static ones use the energy consumption to calculate the fuel cost and the dynamic ones optimize as a function of a time horizon rather than for an instant of time. It is required to use control strategies with a non-linear, variable-time, multi-domain system [117]. The methods are classified into two general trends: those based on rules (deterministic and fuzzy) and those based on optimization (global and real time). In [111], possible improvements on the control strategies developed up to 2007 are analyzed. An updated review of metaheuristic algorithms used for EV optimization is presented in [118].

In [113], a proposal implemented in an HEV with a dynamic strategy is presented. The rules-based proposal considers cost, minimization of fuel consumption, and emissions. The study shows that low fuel consumption could significantly reduce emissions. In [30], the authors propose a control system that looks for the instantaneous cost considering the two energy sources and the restrictions imposed by the state of the battery and the amount of fuel.

3.2. Analysis of Authors and Documents on the Topic of EVs

Research based on EVs has been widely developed in 149 countries, with 104,344 authors researching in different areas. Figure 12 shows the distribution of the researchers according to their country of origin. The darkest country is the one with the greatest number of researchers in the subject. There are scientific contributions from all the continents, highlighting European (28.6%) and Asian (48.3%) countries, the United States (14.4%), and Canada (3.3%).

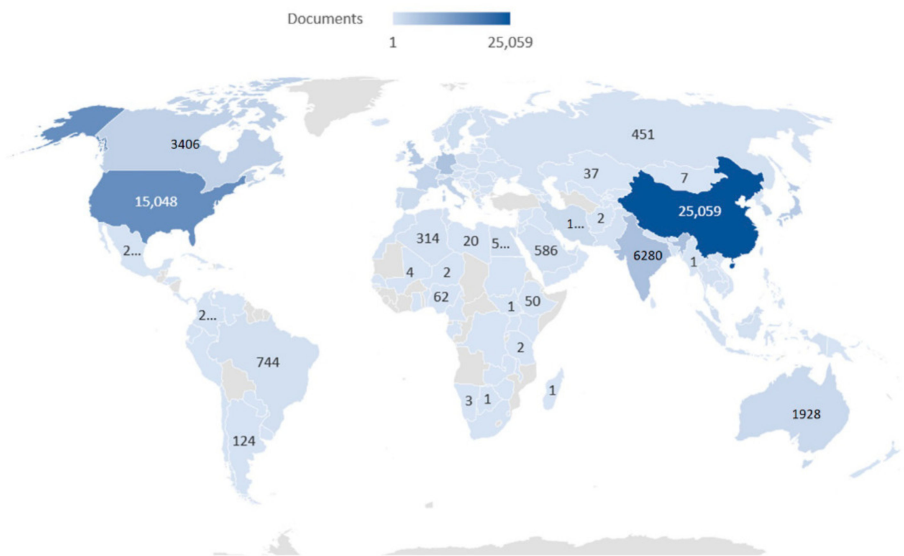


Figure 12. Distribution of authors by country.

The representation of the 20 countries with the highest number of researchers working on EVs is shown in Figure 13. China is the country with the highest contribution, with 25,059 researchers (24.02%), almost twice as high as the contribution of the following country, the USA, with 15,048 researchers (14.42%). It should be noted that the countries that have invested the most in technology are the countries of origin of the greatest number of researchers, such as China or the USA, as well as world powers such as India with 6280 researchers (6.02%), Germany with 5881 researchers (5.64%), the United Kingdom with 4577 researchers (4.39%), and Japan with 4349 authors (4.17%). It also shows the growing development in technology in other countries such as South Korea with 3758 authors (3.60%), or Canada with 3406 researchers (3,26%). Most of the countries in the European Union are among the 20 countries with the greatest contributions, such as Italy (3.12%), France (2.73%), Spain (1.58%), and Iran (1.57%). The rest have percentages close to 1%, as is the case for Taiwan (1.11%), the Netherlands (1.09%), and Sweden (1.09%), followed by Portugal with 1.05% of the total number of researchers. The sum of the contributions by authors from the rest of the countries is 19.30%.

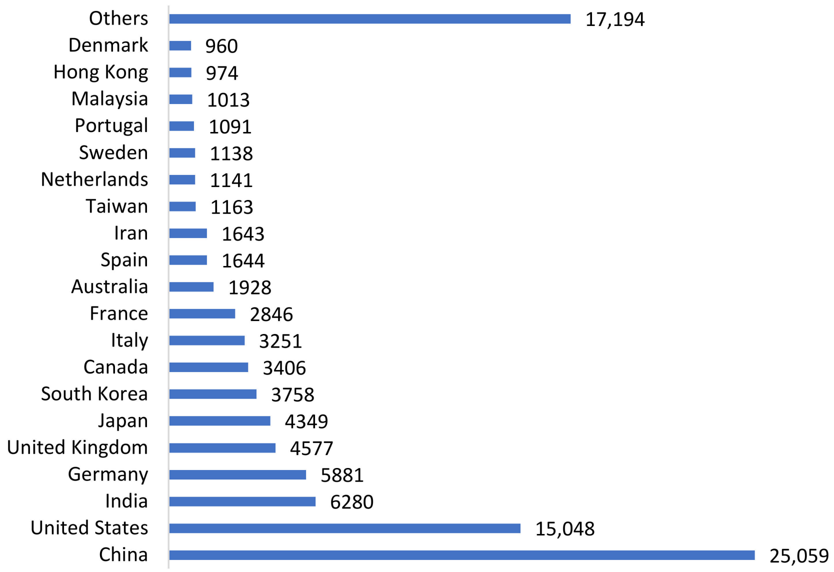


Figure 13. Representation of the 20 countries with the greatest number of authors' contributions.

Of the authors who research on subjects related to EVs, 7.6% have an h-index within a range of 0 to 132. Figure 13 shows that 83.2% of these papers have an h-index between 0 and 10. The number of publications with an h-index of 1 (12,703 papers) represent 24.3%.

Figure 14 shows the number of publications in different languages. The most used language is English (93.80%). Although the country with the greatest number of researchers in this area is China, the international scientific journals prefer to use English. China is one of the few countries that publishes in its own language, at 4.74%, far more than the papers in German (0.37%) or Japanese (0.36%). The remaining languages make up 1.46% (see detail in Figure 14).

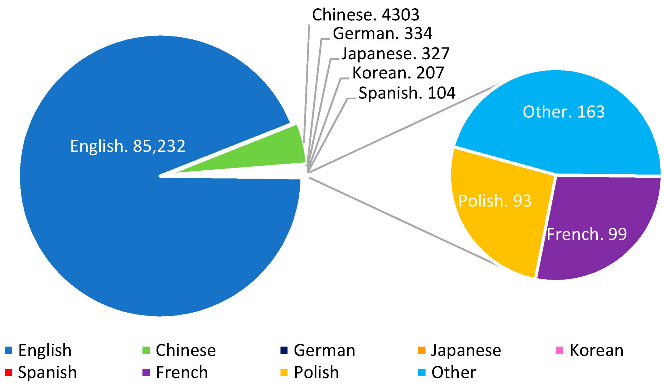


Figure 14. Representation of the languages of EV publications.

Table 1 shows a list of the 20 authors with the highest h-index. The first two authors are from the USA. The country with the largest number of researchers in this subject is China, although the first Chinese author is in the fifth position. There are no German or Japanese authors among the first 20 authors, despite these countries' positions in Figure 12. The top German author is in the 25th position, and the top Japanese author is in the 51st position. The first European authors are Blaabjerg, F., Mannucci, P., and Kuss, M. Italy's contribution is 3.1% with 3251 documents, surpassed in Europe by Germany with 5881 documents (5.6%) and the United Kingdom with 4577 (4.4%). Most of the researchers started publishing in this field in 2005. The year of highest production of documents with the keyword "electric vehicle" in Scopus is 2021 with 13,800 documents, and by September 2022 there were 9739 published documents. There has been an incremental evolution from 1969, which exceeded 100 documents, to the present day. An important milestone occurred in 2018, when more than 10,000 documents were published, which is expected to be maintained until many of the pending challenges in this subject are resolved. Until this happens, the number of publications will not decrease.

Table 1. Authors with h-index over 100 in EV research.

Indexed Name	H-Index	Citation Count	Document Count	Country	University	First Publication (Year)
Gogotsi, Y.	180	160,412	936	United States	Drexel University	2005
Dai, L.	148	86,083	662	United States	Case Western Reserve University	2006
Blaabjerg, F.	148	113,037	2912	Denmark	Aalborg Universitet	2005
Beck, H.	139	100,327	1460	Switzerland	University of Bern	2007
Liu, J.	138	80,785	496	China	Beijing Forestry University	2014
Amine, K.	136	62,151	680	United States	Stanford University	2016
Chapín, F.	135	100,129	432	United States	University of Alaska Fairbanks	2005
Chen, J.	134	63,266	583	China	Nankai University	2005
Aurbach, D.	131	71,805	738	Israel	Bar-Ilan University	2010
Poor, H.	130	78,631	2150	United States	Princeton University	2013
Liu, H.	129	64,488	1206	Australia	University of Wollongong	2005
Dou S.	128	75,307	1875	Australia	University of Wollongong	2014
Sun, Y.	127	64,493	702	South Korea	Hanyang University	2013
Liu, M.	126	54,155	732	United States	Georgia Institute of Technology	2005
Gao, H.	123	46,696	719	China	Harbin Institute of Technology	2005
Gao, F.	123	46,696	719	China	Nanjing Agricultural University	2009
Kuss, M.	116	46,395	337	Italy	Istituto Nazionale di Fisica Nucleare, Sezione di Pisa	2007
Giannakis, G.	114	52,728	1153	United States	University of Minnesota Twin Cities	2010
Cho, J.	114	48,489	389	South Korea	Ulsan National Institute of Science and Technology	2005
Wong, C.	114	52,241	1570	United States	Georgia Institute of Technology	2005

3.3. Future Perspectives and Challenges

In this paper, the key publications that have led to advances in electric vehicles have been analyzed. The bibliometric analysis of the EV has made it possible to visualize the main papers and authors that have marked the breakthrough in the papers published in the Scopus bibliographic database. Using this analysis, the research gaps and challenges can be predicted. Furthermore, the prospects of EVs can be foreseen. In the last decade, political and social awareness have been the main drivers for electric transport. Some issues, mainly related to efficiency, have been solved, and sustainability, which was initially the main driver, has been put into context. However, the market deployment of the electric vehicle as the main mode of transport requires some crucial technical issues to be resolved. The following are the main challenges extracted from the study communities.

The Battery Chargers community addresses challenges related to charging techniques and charging modes of operation, which are also addressed by the vehicle-to-grid community from the perspective of their influence on the grid. These challenges include the following:

- Optimized charging techniques are required to balance charging time and battery life and also to incorporate additional protection to balance battery temperature during the charging process in order to avoid battery degradation [58]. Battery heating is a serious problem in the case of external charging, as external charging to increase the efficiency of charging stations mainly depends on the selection of power converter topologies [119].
- The latest generation of EVs have the vehicle-to-everything (V2X) mode of operation. Extensive research in the domain of power density, power level, converter topologies, and control techniques related to the V2X system is required to expand its commercialization. The implementation of the V2X system has an important role to play in future EVs [60].
- Among the technical challenges of future EVs is the coordination between different emerging charging technologies such as V2X, V2G, and VG4 [60].

- The modes of operation between G2V and V2G must solve the following challenges: transformer ageing, battery degradation and energy loss, harmonic distortion, voltage profile deterioration, and charging curve variation [119].
- Successful communication techniques are required, in which a communication link is created between charging and EV systems. Communication vulnerability (cyber-attack) and communication delay are among their challenges. In addition, it is recommended to integrate various vehicular communication technologies such as wireless access to meet the communication needs of various use cases [120].
- The challenges facing the fast charging station are to achieve good overall efficiency, reduced harmonics, low capital operating cost, and an efficient control algorithm to control the charging current [58].
- The challenges of the wireless charging station to be solved optimally are the design of the coils, the selection of a suitable compensation network, and the ability to transfer high power over a long distance [58]. Standardized wireless charging systems across different types of charging infrastructure and different classes of electric vehicles also require technological improvements [59].
- A global standard for chargers and connectors is required to make energy transfer more efficient and to standardize the associated systems. Currently there are standards depending on the country and vehicle model; if we want to make progress with EVs we must try to homogenize the criteria for selecting associated standards. Vehicle manufacturers must also agree to use a charging connector standard, although new EVs usually come with dual-connector models depending on the charging mode of operation. The standardization of charging systems and their connectors is a gap that remains to be solved [58].
- Charging times are long, from 3 to 12 h, although 80% can be charged in 30 min when using a fast charger. Public fast chargers are still rare in many cities due to their high investment cost. By having fast charging stations along the roadside, fast charging could play an important role in expanding the range of electric vehicles [121].

The EV Market Study community studies market opportunities and consumer opinions to find thriving EV-related niche markets. EV-associated markets and their challenges include the following:

- The incorporation of autonomous driving technologies (ADT) in EVs is stimulating for the vehicle sharing industry and EV car sharing. Remaining challenges include planning the size of a fleet, vehicle relocation strategies such as mixed relocation strategies based on operators and users, vehicle route optimization, and government management policies to increase user demand such as parking fees and subsidy strategies.
- Research should be done to consider the spatial and temporal distribution of demand and the influence of dynamic demand-responsive pricing schemes for car sharing including EVs. In addition, subsidies may be the key to EV utilization for passengers with a car sharing platform, such as Uber. How to design subsidy mechanisms to promote EV sharing in a competitive environment, incorporating uncertainties in last-minute bookings, charging levels, driver choice behaviors, and energy prices in the models, are issues that need to be resolved. This topic raises many issues for future research [122].
- Regarding batteries and new charging technology, a battery exchange or leasing market has emerged. The battery leasing model may be more successful than the battery swap model during the early stages of EV adoption because the initial capital costs (land, building a facility, and maintaining a battery inventory) are much higher than the cost of installing a charging station [122]. The study of productive leasing models is based on a standardization of batteries that would limit battery stocking.
- Charging infrastructure can be a productive market, but there are investment and planning issues for charging infrastructure that need to be addressed in the face of the growing number of electric vehicles on the market [123], mainly due to the lack of

government regulations and subsidies to support these infrastructures. In addition, this business requires standardization of the infrastructures and optimal planning of their location.

- Many of the potential markets still require profitable short-term business models.
- The social and market acceptability of a different technology than the conventional one is an issue that needs to be addressed. Increased acceptance of EV technology would enable mass production and could make the technology more economically viable for the consumer [58].

The EV Battery Management community shows that most batteries used in commercial EVs are lithium-ion, although low charging temperatures must be considered, as they significantly influence the ability of Li-ion batteries to self-discharge. Research has evaluated other alternatives such as sodium-based (Na-NiCl and Na-S), lead–zinc, and Ni-MH batteries, but Li-ion has the highest capacity. Lithium-ion batteries are considered suitable for electric vehicles, although they present some problems due to their complex electrochemical reactions, performance degradation, and lack of accuracy in improving battery performance and lifespan [82], as well as the drawback of using toxic and expensive materials such as cobalt or nickel and rare earths, which makes them environmentally unfriendly. Rare earths are mainly concentrated in China, which can act geopolitically on their evolution and control the manufacture of batteries. In addition, their extraction poses risks to the ecosystem, human health, and the destruction of wildlife [124]. Rechargeable zinc batteries are seen as a promising technology for the next generation, once it overcomes insufficient energy density [59,60]. Another alternative to avoid premature battery ageing—since high-variation EV current intensifies battery ageing—is the use of a hybrid high-energy-density storage system such as batteries with ultracapacitors (UC), superconducting magnetic energy storage (SMES), and flywheels. This requires optimization strategies to manage EV energy [7]. While each of the hybrid systems theoretically have utility, none have been brought to commercialization because large-scale EV deployment is complex and time-consuming and the additional cost and complexity imposed on the vehicle is relatively greater than the economic savings due to improved battery cycle life and reduced energy losses. Mass production of batteries will have to take into consideration the following challenges:

- Research on new batteries that have higher capacity, higher energy density, better safety, more efficient battery management, longer life cycles, and that are environmentally friendly [60].
- Higher capacity batteries will encourage the adoption of faster and more powerful charging methods, as well as improved wireless charging technology.
- The energy management system needs improvements to decrease costs and increase the life cycle of batteries; the trend in recent research is hybrid energy systems, but their commercialization requires robustness, low computational complexity, real-time control, accuracy, and overall optimization of the energy management system.
- Studies initially used life cycle assessment (LCA) as a method of assessing the environmental impacts of emerging technologies such as EVs, but it is insufficient to consider the economic and social impacts. Few studies assess socio-economic indicators at the macro level, except for life cycle cost analysis. Many studies link CO2 emission reduction as a precursor to driving EV expansion, but secondary effects, macroeconomic impacts, and impacts related to the global supply chain need to be considered as a comprehensive approach to help decision making in the event of conflicts in technology deployment [124].
- Another remaining challenge is the recycling of batteries, which, as noted, have toxic materials. If batteries are not carefully designed with end-of-life management in mind, dependence will simply shift from one non-renewable source (oil) to others (rare earth metals), which is an important issue for further study for the world's green revolution [124].

The Energy-Efficient Transmission in EVs community studies the electric motor, together with power electronics and batteries, which are essential parts of the powertrain. The automotive industry has developed different alternatives such as induction, permanent-magnet, and wound-rotor motors, according to diverse concerns in motor design. Each alternative has advantages and disadvantages. For example, permanent-magnet motors are based on rare earths, which are difficult to obtain and geographically limited, mainly to China, making them limited and dependent on availability. The efficiency of the DC–DC converter will have a direct impact on the efficiency balance. Depending on whether the power flow is bidirectional or unidirectional, converters vary [121]. The remaining challenges that can be found include the following:

- One remaining challenge is the coupling of the motor and battery for driving conditions and performance requirements (cost, efficiency, driving dynamics, and driving comfort).
- The selection of a power coupling architecture, together with the optimization of both the appropriate component size according to the architecture employed and the control strategy, will be the subject of future research. Although there are many examples of energy-efficient control strategies in the literature, they should be investigated to achieve dynamic coordinated control of the mode switching process, as it has a significant impact on vehicle handling and ride comfort [125].
- Efficiency improvement of the permanent-magnet synchronous motors (PMSM). Among the losses in this class of motors are copper losses, iron losses, friction losses, and dispersion losses. Iron losses have not been considered in previous works; however, several studies have found iron loss to be an important component of the total losses [126]. Therefore, ignoring iron losses will overestimate motor efficiency. Pei et al. (2022) point that copper losses and iron losses are greatly dependent on control strategies [127], and in the near future the PMSM efficiency optimization strategy with time-varying parameters should be studied.
- Increase the power density of the motor. This can be achieved through three approaches: increasing the speed of the motor; the use of new materials in the magnetic circuit, winding insulation, etc.; or the application of new technologies to the motor production [128].
- Direct torque control (DTC) has been used traditionally, but it results in large torque fluctuation. To solve the torque ripple problem, efforts are dedicated in the literature to overcome these issues and various improved methods are being proposed. One of them is to calculate the effective voltage vector action time in real time to guarantee the minimum torque ripple for current torque error [129]. Nasr et al. (2022) proposed a DTC strategy based on an effective duty ratio regulation to improve the torque performance in terms of the steady-state error and the ripple [130].
- In general, manufacturers are further converging on permanent-magnet motor designs for their superior efficiency and power density, but the sustainability of the permanent magnets depends on the recovery and recycling methods for these magnets in the automotive error [131]. Nasr et al. (2022) proposed a DTC strategy based on an effective duty-ratio regulation to improve the torque performance in terms of the steady-state error and the ripple [132].

The Vehicle-to-Grid Power community raises outstanding challenges of implementing a standardized model that solves the interactions of charging operations with the grid to improve grid stability. Electric vehicles not only act as transport for people and goods, but they also have communication to interact with other electric vehicles and all smart devices through IoT applications, which makes them very valuable for other applications such as auxiliary backup power to the grid. There are interesting proposals addressing this issue with different methodologies such as the EV charging scheduling and the charging infrastructure planning for car sharing systems [122]. However, there is still no state-of-the-art methodology covering different levels of decision making for EV systems. More research is needed on smart dynamic fleet charging/discharging strategies, including V2G and V4G technology, to improve grid stability, as well as the implementation of V2X technologies in future EVs. These EV operating modes can earn more revenue by applying smart charging/discharging strategies during peak and off-peak hours while serving as backup storage power for grid fluctuations, especially for sensitive supplies such as the military, health, and databases, etc. In addition to these outstanding issues, this community needs to solve the following challenges:

- Interactions of EV charging operations with the grid must be considered to improve grid stability. In addition, a rigorous assessment of the environmental and economic impacts of large-scale charging infrastructure could help the development of the dynamic wireless power transfer (DWPT) [60].
- Charging infrastructure optimized according to an assumable forecast of the EV fleet and the distribution grid. Different studies have been conducted using AI-based algorithms, but decisions still need to be made not only on EV charging needs and the grid, but also considering the habits of EV users.
- The EV Market Study Community has identified several niche markets among which the optimal distribution of battery swapping stations (BSS), as well as the charging infrastructure, must consider the habits of EV users. Battery swapping is an efficient charging alternative and BSS can serve not only for battery swapping but also as an auxiliary backup supply for the distribution network.
- V2G technology has an outstanding challenge such as cyber security for smooth operation and to ensure network security. Network security and integrity for secure and seamless data transfer from electric vehicles to the grid. Another drawback is battery degradation. Although research is being done on methods to solve this such as battery swapping, which requires standardization of batteries and infrastructure for swap management [133].
- Regulatory policies on energy market prices, so that owners can consider the EV investment and its profitability by using the sale of their energy surplus to the distribution grid or planning loads in off-peak hours of the distribution grid.
- Research focused on the integration of electric vehicles (EVs) powered by renewable energy sources is currently a viable option to combat climate change and advance the energy transition [104,121].

The HEV Control Strategies community argues that for HEVs and PHEVs to be competitive with conventional vehicles, costs must be reduced, efficiency must be improved, and electric driving range must be increased [85].

Improving the control strategies that HEVs and PHEVs, currently different strategies have been exposed in this community, but there is still basis for improvement where they consider real time conditions in the efficient driving of the vehicle by operating in the optimal region of operation most of the time and reduce fuel consumption and emissions. Although reducing emissions and optimizing efficiency are opposing parameters, a balance between the two should be pursued in future HEVs and PHEVs [118].

4. Conclusions

A search has been carried out on EV research from 1955 to 2021. We worked with 50,195 documents; 104,344 authors in 149 countries are researching on EVs and English is the preferred language for scientific publication. They were classified into six communities according to the relationships between the authors. The most representative papers of these communities were analyzed according to their influence within and outside the community. The studied publications fall into the following categories: "HEV Control Strategies", "Vehicle to Grid Power", "Energy Efficient Transmission in EV", "EV Battery Management", "EV Market study", and "EV Battery Chargers".

The analysis of the h-index of the authors shows that they do not fully correspond to the distribution of authors by country. China is the country with the highest number of authors, but the first Chinese researcher on the list is in the fifth position. China is the world leader in rare earths, materials that are essential for the manufacture of electric motors and batteries needed for EV development. This implies the need to search for other materials to meet this need and avoid China's geopolitical control over EVs. There are more than 20 researchers with an h-index over 100, which indicates that it is a very productive topic with great advances.

Competitions have proven to be a good incentive for future vehicle designers, introducing equipment improvements in EVs' technological innovation. The major innovation should focus on reducing costs and improving efficiency. Some studies from the "EV Market Study" community highlight an understanding of potential consumers of EVs in general. They highlight that the difficulty in switching from conventional vehicles to EVs lies in the fact that the EV improvement is still in progress. This perception is an issue to be addressed by manufacturers and politicians if they want to change consumers' mindset towards zero-emission products. Some manufacturers already introduce their EVs as more efficient vehicles than conventional ones and not as a greener alternative. They pay attention to market studies which show that new generations see technology and fuel savings as more attractive than ecological improvements, even assuming higher costs. In addition to innovative technology, EV manufacturers must consider market demand and the infrastructure and services required. Consumers should be informed that the cost of an EV is high compared to a combustion engine vehicle, but EVs consume less fuel and have low maintenance costs compared to combustion vehicles. In addition, electric motors have higher efficiency. The average efficiency of combustion vehicles is between 15% and 18%, while the efficiency of electric vehicles is in the range of 60% to 70%.

EV manufacturing should also be studied. The main driver for EVs is the decarbonization of the transport industry, but all the factors involved, from manufacturing to powering the batteries, must be taken into consideration. Different types of energy used to generate electricity to power electric vehicles will cause different emissions. Any study assessing vehicle emissions must therefore consider the simultaneous impact of these variables to arrive at a realistic estimate of vehicle emissions. Within these factors, an outstanding challenge is the recycling of the materials involved in EVs, mainly batteries. Considering the recent crises in the automotive industry related to the shortage of semiconductor chips, automotive spare parts due to rising raw material prices and the shortage of lithium used for EV batteries, it will be crucial to consider reuse, recycling, and remanufacturing in end-of-life management. However, research into other, more environmentally friendly materials for EV battery manufacturing is still ongoing. There is a need to analyze the entire life cycle of EVs or the global warming beyond their emissions. There is also a need to provide incentives to manufacturers and governments for effective recycling policies. Another issue to consider is EVs' charges and their relationship with renewable energy systems. The emissions must be reduced, both in transport and in the charging process of EVs.

Implementing a robust system for monitoring and managing the state of the available charge is a necessary step in research on the efficient use of high-capacity batteries. There is still much research to be done to improve battery safety using materials that allow high energy storage capacity and longer lifespan to reduce pollution and battery replacement (the toxic components of the battery) and lower EVs' costs, which is one of the future goals to make them commercially competitive.

Among the challenges for their full implementation in the automotive sector is the management of the charging infrastructure and its effects on the distribution network; there are already systems that allow fast charges of 20–30 min, although this has detrimental effects on the distribution system that would be solved with a planning of the charges. There are many proposals that implement optimization algorithms to locate charging stations from the perspective of the distribution network or the charging station owner. Each algorithm selects different parameters, the most common being energy loss and the cost of energy from the network, associated with other parameters such as the use of renewable energy or network efficiency parameters such as maximum voltage deviation, etc., in the case seen from its optimization in the distribution network. Other authors consider the perspective of the EV user, considering the cost of access, the cost of travel to charge from the point of demand to the charging station, the cost of the waiting time, and the cost of charging times, among other parameters. Other research focuses on the reliability of the distribution network. The commercialization of effective V2G, V4G, and V2X services is an interesting proposition. EVs can become part of the electric grid, although accurate studies are still needed to find an effective method for estimating expected revenues and costs with arbitrary charges and within a specific time frame. In addition to overcoming economic challenges, it must overcome the social barrier, grid security, and battery life degradation. One possible solution is battery swapping, although it requires pay-as-you-go and a third party who owns the batteries while managing their charging conditions. This can be a social barrier, where EV users do not have a guarantee on the health status of the battery being swapped, plus a battery swap management infrastructure and battery standardization are required.

Having a low-cost, highly efficient, and flexible EV charging and discharging system is an ongoing research topic. For HEVs and PHEVs to be competitive with conventional vehicles, costs must be reduced, efficiency improved, and the electric driving range increased.

The global fight for sustainability in the automotive sector requires developing regions to get involved.

The conclusion of this work shows that research on this topic is still ongoing, and there are still many issues to be solved, although the regular use of EVs would lead to the establishment of sustainable cities and societies. Promoting energy policies is only possible if countries are engaged through real environmental policies.

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