Original Research

The Impacts of Electric Vehicle Scale-up Development on Emission Reduction: Mapping the Field and Providing a Research Agenda

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Abstract

Research on the emission reduction potential of electric vehicles (EVs) offers significant insights for the transportation sector to mitigate the effects of human-induced climate change. Despite the growing interest in topic, a comprehensive literature compilation remains unavailable. To better understand the research progress and evolution of EVs' emission reduction, we analyzed 1,984 articles published between 1993 and 2023. These articles, sourced from the Web of Science core collection, focus on the themes of "electric vehicle" and "emission reduction". Visualization tools such as CiteSpace, VOS viewer, and R-studio-based Bibliometrix were employed for a detailed bibliometric and thematic analysis. This paper presents the development trends of international publications, the key collaborations between international authors and institutions, a map of leading research centers on the topic, and a visualization of applied disciplines involved in this field. Building on the visualization analysis results, this paper further explores the emission reduction of EVs in various application scenarios, and examines the impacts of EV incentive policies on emission reduction.

Introduction

In recent years, the continuous increase in carbon emissions has significantly contributed to global climate change [1]. The latest International Energy Agency (IEA) statistic shows that global CO_2 emissions in 2021 were 36,257 Mt, more than three times higher than in 1960. To address the problem of global climate degradation, countries have begun actively developing decarbonization measures [2]. With the increasing number of motor vehicles, approximately a quarter of global carbon emissions come from the transportation sector, making it a primary focus for reducing carbon emissions [3, 4]. Thus, a sustainable low-carbon transportation system is required [5], and EVs are garnering attention from various societal sectors [6].

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Compared to conventional fuel vehicles (CFVs), EVs offer substantial advantages in replacing fossil energy consumption and reducing carbon emissions [7]. Consequently, the development of EVs has become a strategic consensus among nations to achieve energy-saving and emission-reduction targets in the transportation sector [8].

In 2012, only 120,000 EVs were sold worldwide, representing a negligible share of the overall automotive market. To promote large-scale EV development, many countries such as China and the USA have introduced various policies and measures, such as purchase subsidies, tax exemptions, exemptions from registration, and driving restrictions [9]. Furthermore, with advances in technology, significant reductions in battery costs, and improvements in battery capacity, EVs are becoming more competitive in terms of price and range compared to CFVs [10]. As a result, EVs are gaining acceptance among more consumers, and their share of the automotive market is growing. With global ownership of 16.5 million EVs, global sales in 2022 reached a new record high of 7.8 million (five times the sales in 2019), and the global electric car market share surpassed 10% for the first time, surpassing 8.3% in 2021. The IEA predicts that global EV sales increase to 43 million by the end of 2030 (about 30% of total vehicle sales, excluding two- and three-wheelers) to meet the Paris Agreement's goal of limiting global warming to 2ºC. With the large-scale promotion of EVs, massive electricity demand will change the spatial pattern of energy use and carbon emissions in various countries. Numerous studies have been conducted to analyze the entire life cycle of vehicles to understand the energy savings and emission reductions achieved by EVs. Due to differences in EV technology levels, resource endowment, infrastructure, user travel patterns, inconsistent model settings, and system boundaries across different studies, the conclusions of extant studies are not uniform. There is an urgent need for a systematic review of the existing research results and gaps, which will help researchers understand the current research status and future priorities in this field.

Scholars typically extract relevant papers based on specific topics and further describe the analysis in the traditional literature review writing process [11]. In contrast to traditional approaches, this paper employs the scientometric visual analysis method proposed by Chen et al. [12], which combines the research method of scientometrics with in-depth thematic analysis. This study offers three marginal contributions: first, we organize and present a comprehensive overview of available research. Second, we describe research hotspots and identify gaps. Finally, we further analyze research directions and make recommendations for the development of EV emission reduction.

Material and Methods

Method

For this paper, we used CiteSpace, VOSviewer, and the R-studio-based Bibliometrix toolkit for visual analysis. As popular and practical visualization tools, the analytical perspectives of CiteSpace and VOSviewer are similar, encompassing authors, institutions, countries, keywords, and literature co-citation. Compared to VOSviewer, CiteSpace can further extend the analysis of each node's attributes, making it more convenient for researchers to gain in-depth understanding. Additionally, the analysis perspective of the R-Studio-based Bibliometrix toolkit is more comprehensive. Combining these tools can make the literature review more rigorous and reliable, helping scholars identify the research focus and future research trends.

First, we used the R-studio-based Bibliometrix toolkit to sort out the timeline of publications; Second, VOSviewer and R-studio-based Bibliometrix were employed to visually analyze the publications of authors, institutions, and countries. Third, CiteSpace, VOSviewer, and R-studio-based Bibliometrix toolkit were combined to analyze the keywords of the collected literature from multiple angles. Finally, we summarized the published and cited journals using R-studio-based Bibliometrix, and outlined the disciplines to which the journals belong by utilizing CiteSpace's dual-map overlay function. Based on the visualization, a thematic analysis was conducted in conjunction with highly cited literature. This analysis includes an in-depth discussion of the current status of EV emission reduction, an examination of EV application fields, and an evaluation of the emission reduction effects of EV incentive policies.

Temporal Distribution of Publications and Spatial Analysis

The R-studio-based Bibliometrix was employed to analyze the collected literature from a time dimension to understand their trends during the past 30 years. Then, an interactive map of the country's publications was built to help understand the density of cooperation among nations and which ones have contributed substantially to this field. Simultaneously, the VOSviewer tool was used to create visual maps of authors and institutions. Each node in the maps represents an author or institution, with larger nodes reflecting more publications. Cooperative clusters are shown by nodes of the same color, with connecting lines representing author or institution collaboration. The thicker the connecting lines, the closer the cooperation.

Keyword Analysis

Keywords serve as a central summary of the literature. Visual analysis of keywords can help

researchers better understand past research results, current research status, and predict future research trends. Commonly, keywords include Keyword(Au) and Keyword-plus. The former refers to the keywords marked by the authors of the literature themselves, and the latter concerns the keywords added to the paper by the Web of Science database to increase the hit rate of the article under related topics; both are synthesized into All-keywords. This paper analyzes keywords from two angles: keyword dynamic changes and clustering. The dynamic keyword change analysis aims to clarify the key research directions at each stage from different periods. Based on the similarity of keyword attributes, the keyword clustering analysis uses the same colors to cluster keywords for easy summarization. Finally, the highest-frequency keywords are presented to help identify the research focus in this field.

Journal Analysis

Based on the R-studio-based Bibliometrix software, the journal analysis is conducted from two perspectives: published and cited journals. The most representative published and cited journals were presented in the field of EV emission reduction, which facilitated later scholars to select journals for targeted reading when studying this field.

Furthermore, this paper presents the main disciplines involved in the journals with the application of CiteSpace. This intends to help scholars discover the key applied disciplines in this field.

Data Collection

Due to varying academic expressions in different countries, the terms for the research topic are diverse. For example, the common scholarly expressions for the topic of this paper include New Energy Vehicles, Electric Vehicles, Fuel Cell Vehicles, and Plug-in Hybrid Electric Vehicles, among others. The following steps were developed to ensure a sufficient and comprehensive collection of documents. First, we reviewed many papers to compile the commonly used subject terms in

this research field and searched the Web of Science core database, which retrieved 2,040 relevant documents as of December 2, 2022. Second, the retrieved publications were refined by filtering the paper type to "Article" and "Review", and the language type to "English". Then, papers unrelated to EV emission reduction were filtered out. Finally, a total of 1,984 pieces of literature met the requirements of this article and were incorporated into the visual analysis object.

Based on the R-studio-based Bibliometrix toolkit, we present the main information concerning the collected literature (see Fig. 1). The figure provides the following information. First, the period is 1993-2023, revealing that this research field existed for 30 years. Second, the annual growth is at 3.1%. Evidently, as time progresses, more scholars devote themselves to this field, leading to increasing research outcomes. Third, the international author cooperation rate is 28.98%, and each paper has an average of four scholars actively participating in international academic cooperation. Fourth, each document references 31.8 articles on average, with a service life of 4.84 years. Fifth, there are 5,151 author keywords in the collected literature, reflecting the diversification of research content.

Results and Discussion

Temporal Analysis

The publication trend regarding the number of papers published is a quantitative indicator of scientific activity and interest in a specific topic. As shown in Fig. 2, the past three decades can be divided into four stages: low-speed development stage (1993-2009), slow growth stage (2010-2014), slight regression stage (2015-2016), and blowout growth stage (2017-2022). Before 2009, the volume of publications remained below 10 articles per year. Between 2009 and 2015, the annual publication volume ranged from 10 to 100. It underwent a decline between 2015 and 2016, but increased swiftly in 2017. The marked increase in output began in 2019, when the annual number of published papers
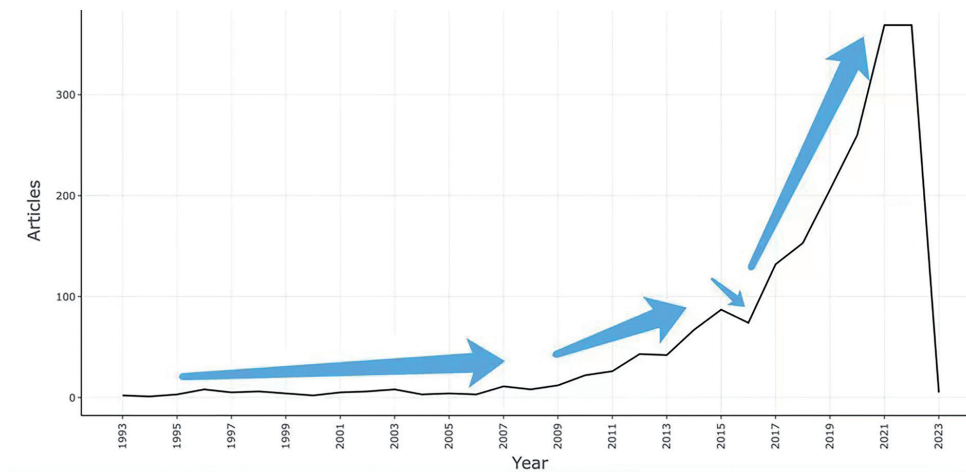

Fig. 1. Main data information.

Fig. 2. Temporal distribution of publications.

exceeded 200, reaching over 250 papers per year from 2020 onward. Finally, the publication reached its apex between 2021 and 2022. Apart from the growing interest in this field, this indicates that research on EV emission reduction has risen to a more prominent position.

Spatial Analysis

Author Analysis

Fig. 3 represents the analytical results of the 1,984 literature sources on the collaboration between authors. Due to the high number of authors, VOSviewer was employed to screen authors with more than 5 articles. A total of 65 people met the qualifications, and different color nodes identified 28 collaborative groups. For example, the authors with the surnames He, Zhang, Wu, and Hao form a small cooperative group. Furthermore, authors such as the surnames Gregory A., Hyung Chul, and Timothy J. play a mediating role, linking different

Table 1. Top 10 authors with the most publications.

Author	Documents	Citations	Total Link Strength
Keoleian, Gregory A.	25	835	33
Kim, Hyung Chul	20	295	29
Kucukvar, Murat	18	784	23
Liu, ZongWei	16	539	24
Messagie, Maarten	15	973	23
Stromman, Anders Hammer	14	2148	23
Van Mierlo, Joeri	14	1005	21
Wallington, Timothy J.	14	551	35
Wu, Ye	13	919	29
Zhao, FuQuan	13	568	25

cooperative groups, turning multiple small ones into a large network.

During the author analysis, we focused on the authors who published higher amounts of papers. Table 1 displays the names, citations, and total link strength of the top ten authors who published the most papers in EV emission reduction. It can be observed that the above-mentioned authors play mediating roles, linking different cooperative groups, are within the top ten. Additionally, the total link strength value is relatively large, indicating that the number of publications is closely related to cooperation. From another perspective, the number of citations to the author's literature does not have a strong relationship with the total number of publications. For example, Keoleian, Gregory A has the most publications. In sharp contrast to this author is Stromman, Anders Hammer, who has a total of 16 publications, two-thirds that of the former, but a total of 2,148 citations, which is approximately three times that of Keoleian.

Institution Analysis

We used the VOSviewer software to visually analyze the publishing institutions. Fig. 4 reveals that 67 institutions have a total number of documents equal to or greater than ten. However, only a few core institutions are dedicated to EV emission reduction research. A total of 168 connections represents institutional cooperation, indicating that the current institutional cooperation density is low. The top ten institutions were separately analyzed to further observe the core research institutions. Table 2 demonstrates that Tsinghua University has the largest number of publications, with 68 papers and 3,026 citations, followed by the University of Michigan and Argonne National Laboratory. Concerning literature citations, Argonne National Laboratory takes the lead, with 36 articles published on related topics having been cited 2,000 times. Comparing Argonne National Laboratory
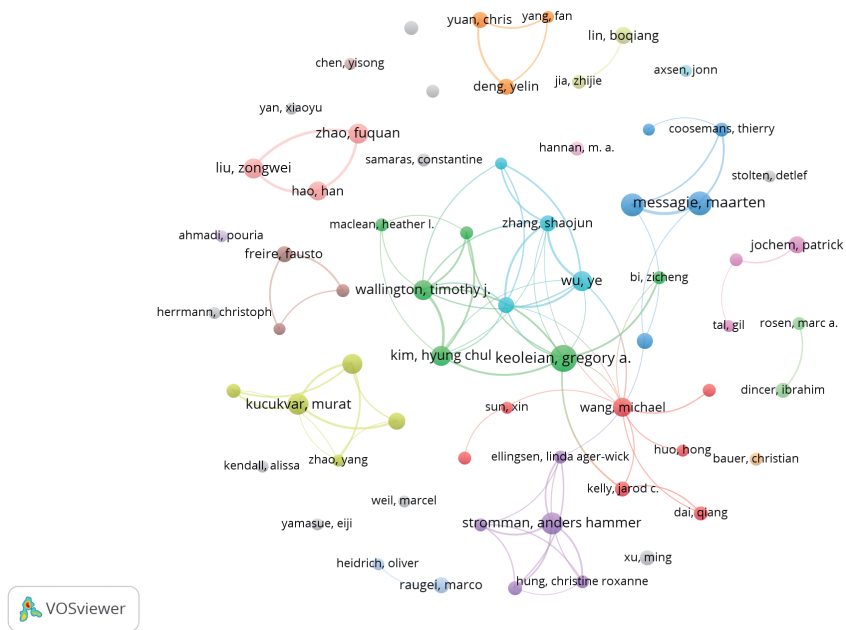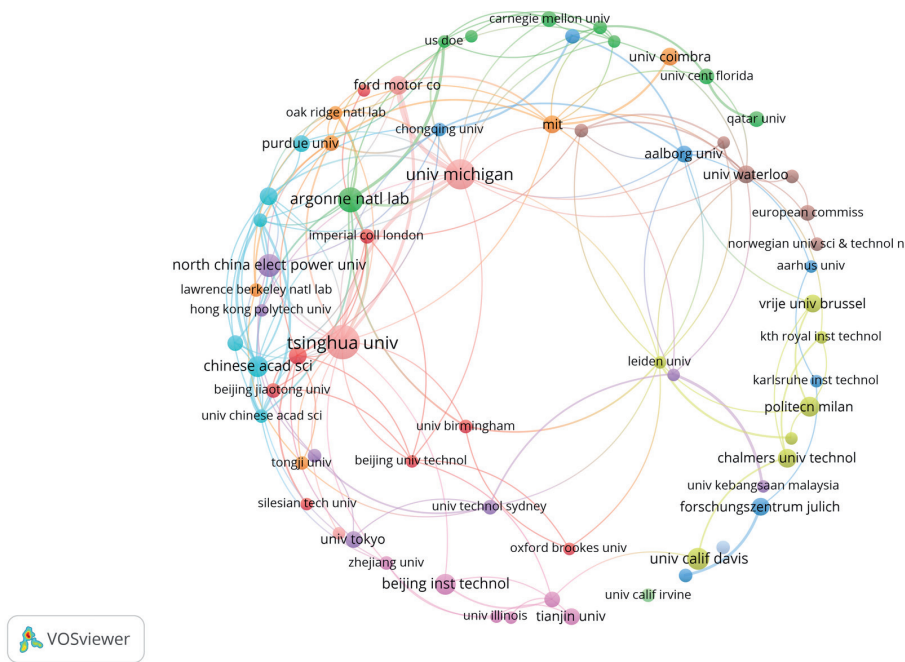
Fig. 3. Author co-occurrence map.

Fig. 4. Institution co-occurrence map.

has about half as many papers published as Tsinghua University, but a far exceeding number of citations. This suggests that the global academic community has widely recognized and cited the published results of Argonne National Laboratory.

Country Analysis

This section presents a visual analysis from the perspective of countries. Fig. 5a) depicts a science world map analysis, where deeper colors represent more publications in a given nation. The connections show cooperation between countries, and more connections equate with closer cooperation. Scholars in most nations pay significant attention to this topic, with only African and a few Asian countries showing less notice. Fig. 5b) displays nations with more than 20 publications, focusing on comparing the volume of publications among countries. This figure contains two colors: orange (MCP) represents the number of papers

Table 2. Top 10 most published institutions.

Organization	Documents	Citations
Tsinghua University	68	3026
University of Michigan	54	2732
Argonne National Laboratory	36	3654
North China Electric Power University	31	370
University of California-Davis	29	443
Chinese Academy of Sciences	26	697
Beijing Institute of Technology	25	1181
Politecnico di Milano	23	813
Chalmers University of Technology	22	569
Ford Motor Company	22	876

published through cross-border cooperation, and green (SCP) indicates the number of documents published by scholars from their own country. This figure reflects the overall number of articles published and the proportion of cross-border cooperation from another angle. Regarding the number of publications, China and the United States greatly surpass the third and other countries, becoming the main contributors in this field. Next, Germany, Italy, and the United Kingdom have also issued more than 100 articles respectively, making significant contributions to the research of EV emission reduction.

Journal Analysis

This section analyzes the published journals, cited journals, and which journals form the core of EV emission reduction research. Fig. 6a) represents the top ten journals with the most publications in this field. The journal with the highest number of article publications is the Journal of Cleaner Production, with 178 papers, primarily involving research areas such as cleaner production, environmental science, and green sustainability. The next most published journals include Energies, which includes papers on scientific research, technology development, engineering policy, and management studies related to the energy field; Sustainability, which publishes pieces on the human environment, as well as economic, cultural, and social sustainability; Applied Energy, which provides a forum for information on energy conversion and conservation, optimal use of energy resources, analysis and optimization of energy processes, and innovation in sustainable energy systems; International Journal of Hydrogen Energy, which publishes articles on all aspects of hydrogen energy research, including production, storage, transmission, utilization, enabling technologies, and environmental impact; Transportation Research Part D-Transport and Environment, which issues papers on the environmental impact of transportation, related policies, and transportation system management. According to Bradford's law in bibliometrics, the six journals mentioned above form the core journals in EV emission reduction.Bradford's law can be considered as sorting scientific and technological journals in descending order based on the number of professional papers published in a given discipline. Journals in this discipline can be divided into core, related, and unrelated areas. The number of papers in each area is equal, and the number of periodicals in the core, related, and non-related areas is $1:n:n^2$.

From another perspective, the quality of references is one key to determining the quality of published papers. Fig. 6b) presents the top ten journals with the highest citation frequency. Evidently, the Journal of Cleaner Production is the most frequently cited in EV emission reduction, with 4,120 citations. Combining Figs 8(a-b) shows that multiple journals have both the most publications and citations. These journals include Applied Energy, Energy, International Journal of Hydrogen Energy, and Transportation Research Part D-Transport and Environment.
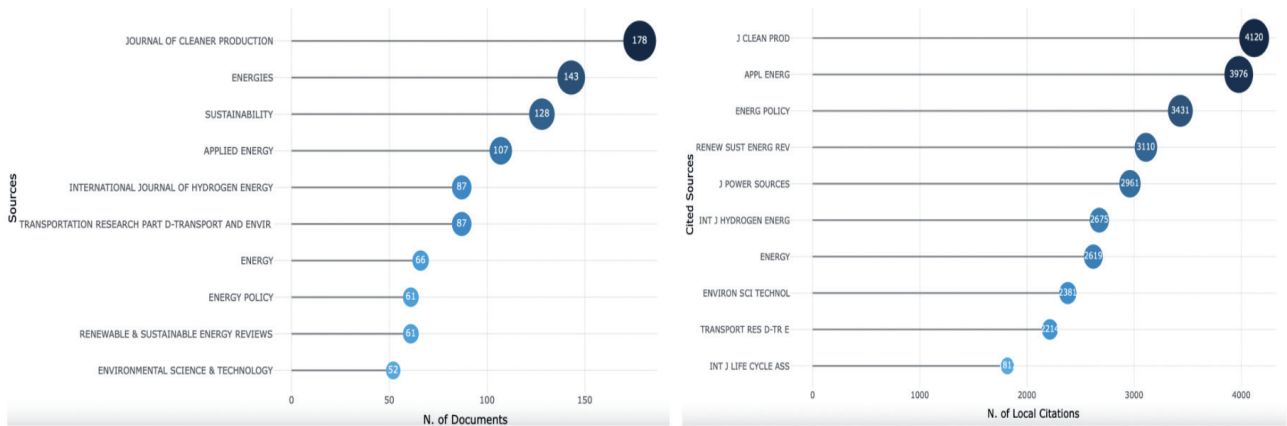

(a) World map
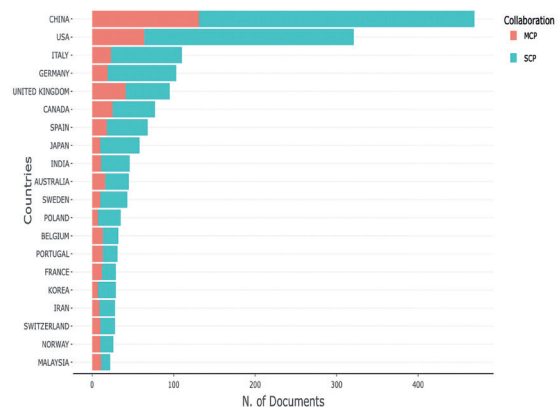
(b) Number of national publications

Fig. 5. Countries collaboration network of electric vehicle emission reduction research.

(a) most relevant sources

(b) most cited sources

Fig. 6. Most relevant and most cited sources.

Fig. 7 displays a dual-map overlay of the journal distribution of citing and cited papers. The left side of the figure shows the distribution of citing literature in journals, representing the main disciplines involved in current research on EV emission reduction. The right side illustrates the distribution of cited literature in journals, representing the most cited disciplines. The former is the application field, and the latter is the research foundation. The middle is connected with different color lines to distinguish different discipline categories. Notably, the current research cites references from #2 Environmental, Toxicology, and Nutrition, #4 Chemistry, Materials, and Physics, and #12 Economics, Economic, and Political. Meanwhile, the disciplines involved in applying literature mainly include #7 Veterinary, Animal, and Science, #1 Mathematics, Systems, and Mathematical, and #3 Ecology, Earth, and Marine.

Keywords Analysis

Keyword-Plus Dynamic Analysis

To comprehend the dynamic evolution changes of keyword-plus over the past 30 years, we generated a dynamic evolution map with R-studio-based Bibliometrix. As seen in Figure 8, early papers featured keyword-plus terms such as hydrogen production, fuel cells, air, biomass, energy, and gasoline, indicating a focus on the energy field. Researchers sought ways to alleviate the global energy scarcity crisis, particularly addressing the depletion of non-renewable energy sources like gasoline and coal. Concurrently, scholars actively explored sustainable green energy and technologies, including the combination of hydrogen energy and fuel cells. During the mid-term stage, papers primarily contained keyword-plus terms like
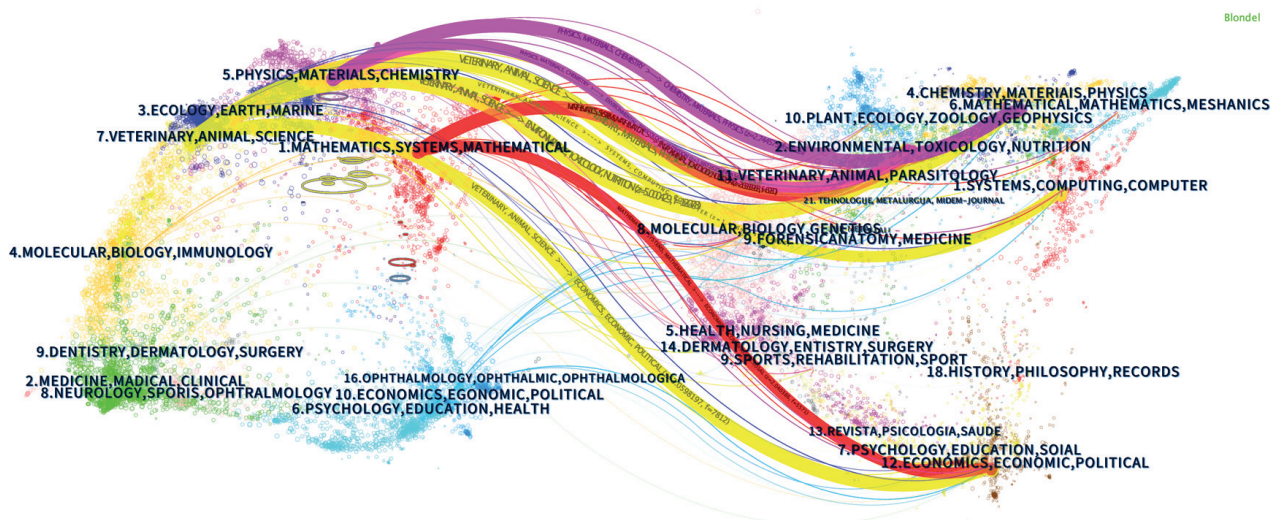

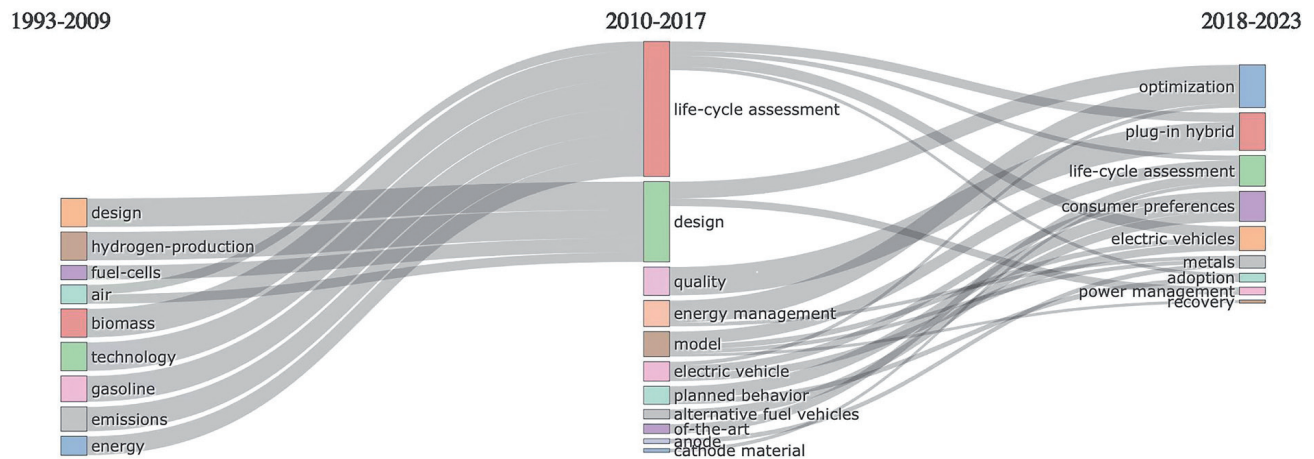Fig. 7. Discipline analysis based on dual-map overlay.

Fig. 8. Keyword-plus dynamic map.

life-cycle assessment, design, and energy management. This stage included the life cycle assessment of EV emission reduction studies and the improvement of decarbonization through model design. In the most recent papers, prevalent keyword-plus terms include optimization, consumer preferences, and recovery. At this stage, significant breakthroughs have been made in overcoming the technical barriers of EVs. Gaining insights into consumer preferences and enhancing vehicle recycling technology can further promote alternative fuel vehicles and reduce environmental pollution.

All-Keywords Clustering Analysis

Due to the enormous number of terms, the VOSviewer tool was used to screen out keywords appearing more than 15 times (see Fig. 9), and a total of 197 keywords met the requirements. Each node in the figure represents a keyword; the larger the node, the more frequently it appears, reflecting the importance of keywords in this field. The top fifteen high-frequency keywords are represented in Table 3 to help readers understand the research hotspots, with life-cycle assessment being the most frequently applied keyword. Furthermore, typical high-frequency keywords include electric vehicles, plug-in hybrid, performance, and green-gas emissions.

Fig. 9 depicts a topic cluster with keywords of the same color, representing related themes. The red cluster contains power, energy management, energy storage, wind, and renewable energy sources, indicating themes such as automotive energy and energy storage. The green cluster includes fuels biomass, alternative biomass, fuel cell vehicles, natural gas, and electricity, demonstrating a primary focus on energy consumption. The purple cluster encompasses air pollution, quality, mitigation, transport, and CO_2 emission, highlighting concerns about improving air quality and lowering CO_2 emissions from EVs. The light-yellow cluster includes

incentives, behavior, willingness-to-pay, choice, and preference, emphasizing consumer attitudes toward EVs, purchase preferences, and the price consumers are willing to pay to reduce emissions. The blue cluster features life-cycle assessment, lithium-ion batteries, recovery, industrial ecology, and circular economy; this indicates a research framework based on the life-cycle assessment method, which analyzes various stages of EV emission reduction, such as emission reduction optimization in the entire life cycle of automobile production, transmission and distribution, utilization process, and scrap recycling.

Table 3. Top 15 high-frequency keywords.

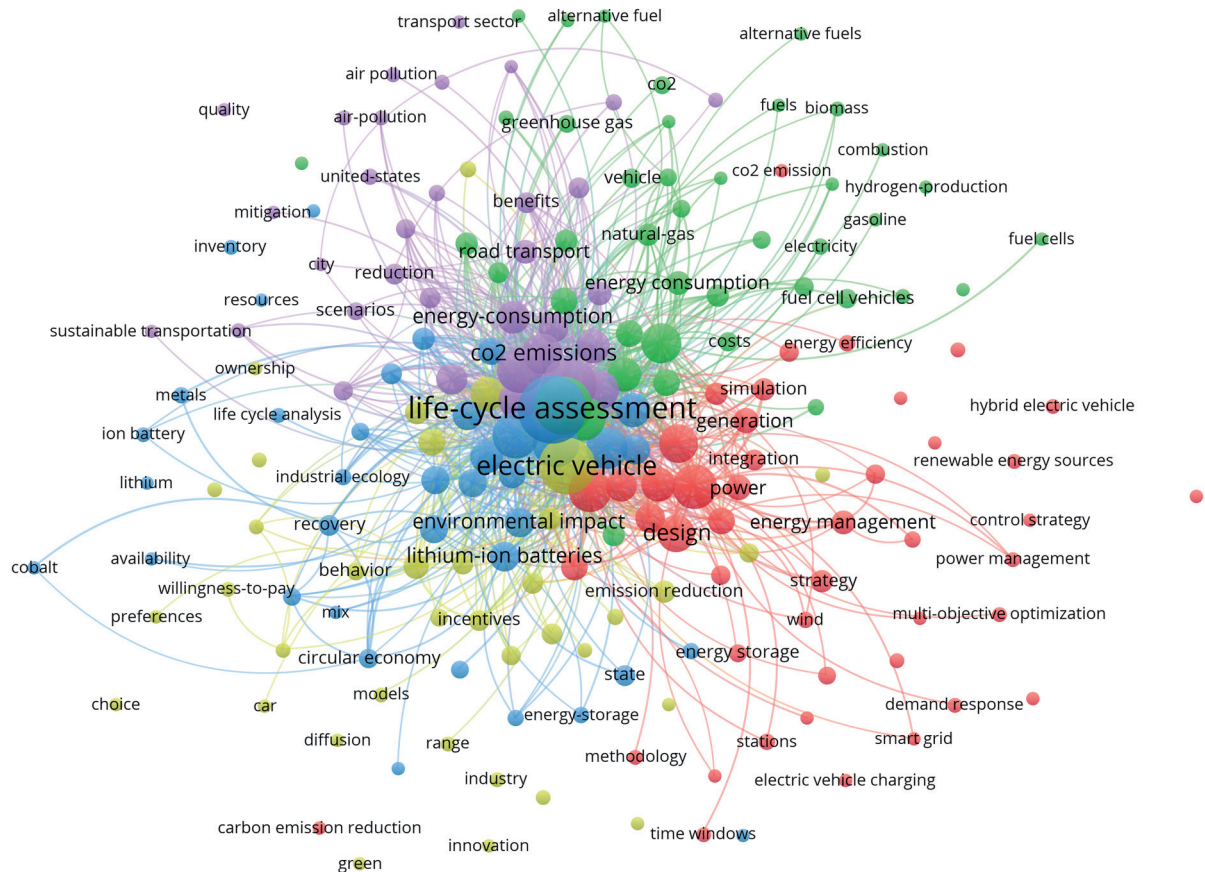| Keyword	Occurrences
Life-cycle assessment	368
Electric vehicles	323
Energy	251
Emissions	225
Plug-in hybrid	185
Greenhouse-gas emissions	178
Impact	176
Hybrid	170
Model	154
Performance	151
Optimization	138
Impacts	130
System	124
Vehicles	117
Design	115

Fig. 9. All-keywords clustering map.

Analysis of Electric Vehicle Emission Reduction Status

Compared to conventional fuel vehicles, EVs offer significant advantages in lowering carbon emissions and energy consumption [13]. However, EVs still produce certain emissions during production and use. Life-cycle assessment is a widely used analytical tool to assess EV emissions. It systematically aggregates and evaluates the energy consumption and emissions from the vehicle's production, transmission, driving, and recycling throughout its entire life cycle process; this allows for a better understanding of the vehicle's carbon emissions and targeted emission reduction studies [14]. The vehicle's entire life cycle includes the fuel cycle (Well to Wheels, or WTW) and the material cycle (Material Cycle, or Vehicle Cycle). WTW covers the extraction and transportation of energy raw materials, the production and transportation of fuel (Well to Tanks, or WTT), and fuel combustion during the vehicle driving phase (Tank to Wheel); the vehicle cycle includes raw material acquisition, parts processing, vehicle manufacturing, scrap recycling, and other processes.

According to automotive life-cycle assessments, the carbon emissions of battery electric vehicles (BEVs) mainly stem from the WTW, accounting for 60 to 70% of total life-cycle CO_2 emissions. Further analysis reveals that the power mix is the key factor influencing BEV carbon emissions during WTW. If BEVs primarily use electricity generated by fossil fuels, significant amounts of CO_2 will be emitted during power generation [15]. In contrast, when the electricity is produced by clean renewable sources such as wind or solar, less CO_2 will be produced [16]. For example, emissions from electricity generation are 180 g/km when coal is used, 151 g/km for oil, 84 g/km for natural gas, and only 8 g/km for solar photovoltaics and geothermal energy. When electricity is generated by biomass, nuclear, wind, hydro, or concentrated solar power, the emissions level is just 1-3 g/km [17]. Carbon emissions in the EV material cycle primarily arise from the raw material collection, production, and transportation processes. Lithium-ion batteries have gained considerable attention in EV applications due to their advantageous properties such as lightweight, fast charging, high energy density, low self-discharge, and long lifespan [18]. In the production process of lithium batteries, the extraction and processing of lithium ore, as well as the chemical reactions and heat treatments involved in producing battery materials, all involve carbon emissions. On average, each 1 Wh of storage capacity expansion of lithium-ion batteries is associated with a cumulative energy demand of 328 Wh and greenhouse gas emissions of 110 gCO(2)eq [19]. Similarly, lithium-ion batteries generate greenhouse gas during the recycling phase. Rajaeifar et al. (2021) analyzed the recycling

technology of lithium-ion batteries in waste EVs and concluded that, compared to other battery recycling technologies, direct current plasma technology can substantially reduce carbon emissions during the battery recycling phase [20]. Overall, replacing CFVs with BEVs offers an opportunity to reduce the CO_2 produced in the transportation sector [21].

Compared to BEVs, the emission reduction effect of plug-in hybrid electric vehicles (PHEVs) is mainly affected by the mileage of electricity coverage. When electricity is sufficient to supply driving power, PHEVs have the same effect on emission reduction as BEVs. However, PHEVs switch to internal combustion engine drive if electricity is in short supply, generating carbon emissions. PHEVs reduce greenhouse gas emissions by more than 30% compared to conventional gasoline vehicles but have a smaller reduction than conventional hybrid vehicles. In general, PHEVs have greater potential in the field of emission reduction. Improving the emission reduction effect requires completing the external charging facilities and enhancing the charging efficiency, as well as ensuring the PHEVs are always fully powered and the power source is supplied by green renewable energy as much as possible.

Fuel cell electric vehicles (FCEVs) generate power through the electrochemical reaction between oxygen and hydrogen to form water, producing electricity and heat. This process is essentially the reverse of water electrolysis. Since no carbon emissions are produced during this process, FCEVs are highly regarded for emission reduction. The current evaluation of the emission reduction effect of FCEVs focuses on the hydrogen production process. Some believe that significant carbon emissions will be generated during hydrogen manufacturing, which is not conducive to the field's focus. Others consider FCEVs the most environmentally friendly option due to their high energy density and low fuel consumption during operation [22]. Although hydrogen is zero-emission in the final application process, the cleanliness of the production path and the environmental impact of the energy used to manufacture hydrogen should always be considered [23]. With the widespread use of hydrogen fuel, hydrogen production technology has been extensively studied worldwide. The main hydrogen production pathways are categorized into four groups: electrolysis, photolysis, biolysis, and thermolysis [24]. Different hydrogen production technologies have varying effects on emission reduction. To reduce emissions, many studies focus on the development of green and clean hydrogen production technologies such as electrolytic water hydrogen production, renewable energy hydrogen production, and nuclear energy hydrogen production.

Emission Reduction of EVs in Different Application Fields

The emission reduction of EVs varies in different application scenarios. Here, we analyze three main areas: private cars, buses, and taxis. Private EVs significantly contribute to emission reduction, with the effect primarily determined by the source of power production, charging mode, and automotive operation mode. When a private EV is used frequently and powered by clean energy, it will contribute more to emission reduction [25]. Furthermore, compared to CFVs, EVs have no idle operation, making them more suitable for driving on congested urban roads. EVs currently have a relatively low share of the global private car sector, and their emission reduction effects have not yet sufficiently raised consumer awareness [26]. One group of people believes EVs are essential for decreasing emissions and is willing to pay more for this purpose. For example, high-income groups are more concerned with vehicle performance and are willing to pay higher costs for emission reduction and environmental protection [27]. People living in cities for a long time are likelier to adopt EVs. Elites with higher education, such as a bachelor's or doctoral degree, are likelier to prefer EVs from an environmental standpoint [28]. Another group is skeptical of EVs, concerned about the inadequate mileage for daily driving and the current deficient charging infrastructure [29]. Various factors prevent consumers from fully comprehending the significance of reducing EV emissions [30].

Buses are another vital application scenario for EVs. Compared to the reduction of emissions by EVs in the private sector, public transportation performs relatively well [31], because urban public buses have a more extended range and significantly reduce carbon emissions. Furthermore, the high passenger volume of urban public buses can reduce the number of private vehicles on the road, alleviate traffic congestion, and reduce carbon emissions [32]. In addition, fixed charging locations exist for buses, even for plug-in hybrid ones, which can be easily charged and improve operational efficiency. Taking the public transportation system in Liuzhou City, China, as the research object, when all diesel buses are replaced by electric buses, carbon emissions can be reduced by 23%, from 207.15 tons per day to 47.56 tons [33]. IEA data shows that every 1,000 pure electric buses on the road could save 5 million barrels of diesel while markedly decreasing airborne pollutants.

Similarly, taxis, like private cars and public buses, are an important component of urban transportation and play an essential role in reducing emissions [34]. A study based on the FREE NOW taxi fleet in Dublin discovered that by converting the entire fleet to BEVs, carbon emissions were reduced by 77%. Comparing the carbon emissions of various vehicle configurations across the entire fleet, the results revealed that pure electric taxis have the best emission reduction effect, followed by PHEVs [35]. Many countries and cities have implemented development strategies to increase the market share of EVs in the taxi sector. European cities, including London, Berlin, and Paris, have promoted electric taxis by providing subsidies, lowering taxes,

and constructing charging stations. Meanwhile, cities in China, such as Shanghai and Beijing, have largely promoted electric taxi popularity by providing EV replacement services and taxi replacement subsidies [36].

Car-sharing is a private rental service, similar to taxis, primarily used to alleviate urban congestion and pollution. It has emerged as an important segment of the global car market [37]. Sharing EVs offers apparent benefits in lowering emissions. In one regard, this movement can reduce car inventory, reducing greenhouse gas and pollutant emissions during the manufacturing process. Concurrently, the high usage rate of sharing cars can effectively reduce the vehicle's idle time. According to Li et al., the carbon density of shared autonomous EVs on the California grid is more than five times lower than that of internal combustion vehicles [38].

Impacts of EV Incentive Policies on Reducing Emissions

In recent years, policymakers have become increasingly aware of the importance of taking action to mitigate climate change. Based on the significance of EVs for energy conservation and emission reduction, many countries worldwide have formulated relevant policies to promote the popularization of EVs, achieving notable results in emission reduction [39]. For instance, China promoted EV adoption in the public sector (public transportation and public services) in 2009 by providing subsidies for EV purchases and investing in electric vehicle-related infrastructure. Empirical results show that the policy reduced urban carbon emissions by an average of 16.3% and reduced per capita emissions from urban transport by 28.87 kg, enhancing the penetration of EVs in the public sector and the overall scale of urban passenger traffic [40]. However, from a technological perspective, high battery costs, low range, and inadequate charging technology remain significant factors preventing consumers from choosing EVs. Hence, policy announcements should promote technological development [41]. While transportation electrification is crucial for decarbonization, the impact of other variables, such as electrical energy transition, emission standards, battery recycling, and tax policies, could also be considered to achieve complete decarbonization [42].

Conclusion

This paper examines current research on global EV emission reduction using visual analytics tools such as CiteSpace, VOSviewer, and R-studio-based Bibliometrix. Evidently, international interest in the field has increased steadily over three decades. Particularly since 2017, explosive growth in the number of papers has occurred. The current total of authors

or institutions is relatively small. The results are primarily obtained through collaboration, with notable institutional representatives such as Tsinghua University and the University of Michigan, and authors such as Keoleian, Gregory A. and Kim, Hyung Chul China and the United States have contributed considerably to the study of EV emission reduction. Compared to American scholars, Chinese researchers engage in more transnational collaboration. Regarding keywords, life-cycle assessment is the primary method currently used to analyze EV emission reductions, with the most frequently used keywords mainly related to energy and technology.

Furthermore, research priorities have shifted over time. Before 2010, the focus was on new energy source development. From 2011 to 2017, more attention was paid to EV technology and improving vehicle performance. Between 2018 and 2023, research focused on consumer preferences, environmental protection, and how to achieve sustainable development. The Journal of Cleaner Production has the most publications and citations in this field. Similar journals include Applied Energy, Energy, and the International Journal of Hydrogen Energy. Additionally, much interdisciplinary research is observed among different disciplines, with EV emission reduction research primarily based on environmental science, physics, chemistry, economics, materials science, mathematics, and other disciplines.

Based on visualization, this paper provides an in-depth study of the current state of EV emission reduction, application areas of EVs, and the emission reduction effect of policy promotion. The power source significantly is found to reduce the emissions of BEVs if the BEV's electricity power source is renewable clean energy. The emission reduction effect of PHEVs is mainly related to the electric coverage mileage. When its power source primarily comes from electricity provided by clean green energy, reducing the use of internal combustion engines, it can effectively reduce carbon emissions. Regarding the reduction of emissions from FCVs, the main controversy lies in the hydrogen production process. Hence, a need exists to strengthen green cleaning research in hydrogen production technology. Most people are skeptical of EVs in the private car sector due to battery cost, mileage, and inadequate charging infrastructure. Correspondingly, the public transportation sector contributes to emission reductions more than the private vehicle sector. Countries should accelerate the adoption of electric buses, and policies are in place to hasten the transition of taxis to EVs.

Acknowledgments

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authorship Contribution Statement

Wenbo Li developed the original idea for this article and designed the experiment; Ke Cui and Mengzhe Wang collected the data, analyzed the results and wrote the paper. All authors have read and agreed to the published version of the manuscript.

References

1. GUO M., CHEN S., ZHANG J. Environment Kuznets Curve in transport sector's carbon emission: Evidence from China. Journal of Cleaner Production. **371**, 133504, **2022**.
2. XIA X., LI M., WANG W. Impact of three emission reduction decisions on authorized remanufacturing under carbon trading. Expert Systems with Applications. **216,** 119476, **2023**.
3. FARIA R., MARQUES P., MOURA P., FREIRE F., DELGADO J., DE ALMEIDA A.T. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renewable & Sustainable Energy Reviews. **24**, 271, **2013**.
4. RANGARAJU S., DE VROEY L., MESSAGIE M., MERTENS J., VAN MIERLO J. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. Applied Energy. **148**, 496, **2015**.
5. KOURIDIS C., VLACHOKOSTAS C. Towards decarbonizing road transport: Environmental and social benefit of vehicle fleet electrification in urban areas of Greece. Renewable and Sustainable Energy Reviews. **153**, 111775, **2022**.
6. XU Z., HUANG L., LIAO M., XUE J., YOSHIDA Y., LONG Y. Quantifying consumption-based carbon emissions of major economic sectors in Japan considering the global value chain. Structural Change and Economic Dynamics. **63**, 330, **2022**.
7. GUO X., SUN Y., REN D. Life cycle carbon emission and cost-effectiveness analysis of electric vehicles in China. Energy for Sustainable Development **72**, 1, **2023**.
8. HAWKINS T.R., SINGH B., MAJEAU-BETTEZ G., STROMMAN A.H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology. **17** (1), 53, **2013**.
9. KITTNER N., TSIROPOULOS I., TARVYDAS D., SCHMIDT O., STAFFELL I., KAMMEN D.M. Chapter 9 - Electric vehicles, in Technological Learning in the Transition to a Low-Carbon Energy System, M. Junginger and A. Louwen, Editors. Academic Press. 145, **2020**.
10. KRISHNAN V.V., KOSHY B.I. Evaluating the factors influencing purchase intention of electric vehicles in households owning conventional vehicles. Case Studies on Transport Policy. **9** (3), 1122, **2021**.
11. NELSON T., KELLEY S., ORTON F. A literature review of economic studies on carbon pricing and Australian wholesale electricity markets. Energy Policy. **49**, 217, **2012**.
12. CHEN C., HU Z., LIU S., TSENG H. Emerging trends in regenerative medicine: a scientometric analysis in CiteSpace. Expert Opinion on Biological Therapy. **12** (5), 593, **2012**.
13. ONAT N.C., KUCUKVAR M., TATARI O. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. Applied Energy. **150**, 36, **2015**.
14. TAGLIAFERRI C., EVANGELISTI S., ACCONCIA F., DOMENECH T., EKINS P., BARLETTA D., LETTIERI P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. Chemical Engineering Research & Design, **112**, 298, **2016**.
15. HAWKINS T.R., SINGH B., MAJEAU-BETTEZ G., STROMMAN A.H. Environmental impacts of hybrid and electric vehicles-a review. International Journal of Life Cycle Assessment. **17** (8), 997, **2012**.
16. GRANOVSKII M., DINCER I., ROSEN M.A. Economic and environmental comparison of conventional, hybrid, electric and hydrogen fuel cell vehicles. Journal of Power Sources. **159** (2), 1186, **2006**.
17. HOLMBERG K., ERDEMIR A. The impact of tribology on energy use and CO_2 emission globally and in combustion engine and electric cars. Tribology International. **135**, 389, **2019**.
18. HANNAN M.A., LIPU M.S.H., HUSSAIN A., MOHAMED A. A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations. Renewable & Sustainable Energy Reviews. **78**, 834, **2017**.
19. PETERS J.F., BAUMANN M., ZIMMERMANN B., BRAUN J., WEIL M. The environmental impact of Li-Ion batteries and the role of key parameters - A review. Renewable & Sustainable Energy Reviews. **67**, 491, **2017**.
20. RAJAEIFAR M.A., RAUGEI M., STEUBING B., HARTWELL A., ANDERSON P.A., HEIDRICH O. Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies. Journal of Industrial Ecology. **25** (6), 1560, **2021**.
21. RUPP M., HANDSCHUH N., RIEKE C., KUPERJANS I. Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: A case study of electric buses in Germany. Applied Energy. **237**, 618, **2019**.
22. BICER Y., DINCER I. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resources Conservation and Recycling. **132**, 141, **2018**.
23. THOMAS C.E. Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy. **34** (15), 6005, **2009**.
24. DAWOOD F., ANDA M., SHAFIULLAH G. M. Hydrogen production for energy: An overview. International Journal of Hydrogen Energy. **45** (7), 3847, **2020**.
25. TIAN X., HUANG G., SONG Z., AN C., CHEN Z. Impact from the evolution of private vehicle fleet composition on traffic related emissions in the small-medium automotive city. Science of The Total Environment. **840**, 156657, **2022**.
26. SECINARO S., CALANDRA D., LANZALONGA F., FERRARIS A. Electric vehicles' consumer behaviours: Mapping the field and providing a research agenda. Journal of Business Research. **150**, 399, **2022**.

27. WANG S.Y., WANG J., LI J., WANG J.P., LIANG L. Policy implications for promoting the adoption of electric vehicles: Do consumer's knowledge, perceived risk and financial incentive policy matter? Transportation Research Part a-Policy and Practice. **117**, 58, **2018**.

28. NING,W., GUO J., LIU X., PAN H. Incorporating individual preference and network influence on choice behavior of electric vehicle sharing using agent-based model. International Journal of Sustainable Transportation. **14** (12), 917, **2019**.

29. ASADI S., NILASHI M., SAMAD S., ABDULLAH R., MAHMOUD M., ALKINANI M.H., YADEGARIDEHKORDI E. Factors impacting consumers' intention toward adoption of electric vehicles in Malaysia. Journal of Cleaner Production. **282**, 124774, **2021**.

30. MUKHERJEE S.C., RYAN L. Factors influencing early battery electric vehicle adoption in Ireland. Renewable & Sustainable Energy Reviews. **118**, 109504, **2020**.

31. GARCÍA A., MONSALVE-SERRANO J., LAGO SARI R., TRIPATHI S. Pathways to achieve future CO_2 emission reduction targets for bus transit networks. Energy. **244**, 123177, **2022**.

32. ALKHEDER S. Promoting public transport as a strategy to reduce GHG emissions from private vehicles in Kuwait. Environmental Challenges. **3**, 100075, **2021**.

33. SHAO S., TAN Z., LIU Z., SHANG W. Balancing the GHG emissions and operational costs for a mixed fleet of electric buses and diesel buses. Applied Energy. **328**, 120188, **2022**.

34. MINGOLLA S., LU Z. Carbon emission and cost analysis of vehicle technologies for urban taxis. Transportation Research Part D: Transport and Environment. **99**, 102994, **2021**.

35. KINSELLA L., STEFANIEC A., FOLEY A., CAULFIELD B. Pathways to decarbonising the transport sector: The impacts of electrifying taxi fleets. Renewable and Sustainable Energy Reviews. **174**, 113160, **2023**.

36. GOLDSCHMIDT R., RICHTER A., PFEIL R. Active stakeholder involvement and organisational tasks as factors for an effective communication and governance strategy in the promotion of e-taxis. Results from a field research lab. Energy Policy. **135**, 110848, **2019**.

37. LOEB B., KOCKELMAN K.M., LIU J. Shared autonomous electric vehicle (SAEV) operations across the Austin, Texas network with charging infrastructure decisions. Transportation Research Part C: Emerging Technologies. **89**, 222, **2018**.

38. LI Y., LI X., JENN A. Evaluating the emission benefits of shared autonomous electric vehicle fleets: A case study in California. Applied Energy. **323**, 119638, **2022**.

39. WU X.K., HE X.Z., YU G.Z., HARMANDAYAN A., WANG Y.P. Energy-Optimal Speed Control for Electric Vehicles on Signalized Arterials. Ieee Transactions on Intelligent Transportation Systems. **16** (5), 2786, **2015**.

40. ZHANG J., JIA R., YANG H., DONG K. Does electric vehicle promotion in the public sector contribute to urban transport carbon emissions reduction? Transport Policy. **125**, 151, **2022**.

41. PEISELER L., CABRERA SERRENHO A. How can current German and EU policies be improved to enhance the reduction of CO_2 emissions of road transport? Revising policies on electric vehicles informed by stakeholder and technical assessments. Energy Policy. **168**, 113124, **2022**.

42. SUN D., XIA J. Research on road transport planning aiming at near zero carbon emissions: Taking Ruicheng County as an example. Energy. **263**, 125834, **2023**.