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Trends in electric vehicles research

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ABSTRACT

Electrification of vehicles has been recognised as a key part of meeting global climate change targets and a key aspect of sustainable transport. Here, an integrative and bird's-eye view of scholarly research on Electric Vehicles (EV) is provided with a focus on an objective and quantitative determination of research trends. The analyses suggest that areas of EV research linked to (i) *charging infrastructure*, (ii) *EV adoption*, (iii) *thermal management systems* and (iv) *routing problem* have been the distinct trending topics in recent years. While *hybrid EV* proves to have been a dominant keyword, its frequency of use has either flattened out in recent years or is notably on the decline across major subfields of EV research. The findings provide objective indications about the directions to which EV research is currently headed. A secondary outcome is the determination of references that have been most instrumental in developing each major stream of EV research.

1. Introduction

The history of Electric Vehicles (EVs) is as old as the history of the automobile. Actually, the first experimental light-weight EVs appeared already in the mid-1830 s, and at the beginning of the 20th century, they were the most common vehicle type in the US. However, by the end of World War I, they had lost the race against the internal combustion engine (ICE) vehicle and disappeared from the market (Høyer, 2008). While a number of factors contributed to the success of the ICE vehicle, limited range and expensive batteries, were major contributors (Duarte et al., 2021; Patil et al., 2022). These two barriers have continued to hinder EVs from gaining real market breakthroughs through the decades (Chakraborty et al., 2020).

There have been waves of EVs during the last 100 years, pushed by policy to address resource constraints related to fossil fuels, primarily during World War II to save fuel prioritised for the military, and during the 70s, due to the oil crisis. From the 90s onward, the curbing of emissions—at first mainly related to local air quality and later carbon emissions affecting climate change—has been the main political motivator. In California, the promotion of EVs started in the 90s to address smog issues, especially in Los Angeles, leading to the Zero Emission Vehicle mandates instituted by the California Air Resources Board. Even though these were amended to Lower Emissions Vehicles, they still had an influence on technological development such as batteries for hybrid EVs (Bedsworth and

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Taylor, 2007).

Commercial modern hybrid vehicles were first available in Japan strongly pushed by governmental initiated R&D support programs to advance, at first, battery EVs, and later, other alternative fuel vehicles (Åhman, 2006). Pushes from the government have either been directed toward R&D support for the industry, not surprisingly prevalent in car-producing countries such as Japan and Germany (Altenburg et al., 2016) and/or market support. The most prominent example of market support is probably Norway which also has the largest market share with 86% of new sold cars in 2021 (IEA, 2022). The background of the success is a long history of high subsidies that started already in the 1990 s making EVs price competitive with conventional vehicles (Figenbaum, 2017). China is one of the countries that has pushed hardest for EVs, especially after 2009. The strong push is motivated both by air quality and the opportunity to leap-frog technical development and seriously compete in the automotive industry (Daina et al., 2017; Altenburg et al., 2022). In the EU, the tightening of tail-pipe CO_2 targets for the automotive industry has in recent years led to increased market shares of EVs (Iwan et al., 2021).

Driven by the political push in several countries, the research and development of EVs have significantly intensified since the 1990 s which can be observed in an increasing number of patents being registered (Wolbertus et al., 2021; Altenburg et al., 2022). The effects of this development on the scientific literature have, so far, not been documented. There have been several reviews concerning EVs, but these have mainly been focused on specific subjects within the field such as consumer preferences (Liao et al., 2017) and adoption (Coffman et al., 2017); incentives (Hardman, 2019); business models (Ziegler et al., 2022); charging infrastructure (Shareef et al., 2016; Funke et al., 2019); connections with the electric grid (Richardson, 2013); environmental impacts (Hawkins et al., 2012a, 2012b). However, there is, to our knowledge, no overall computational review of the literature on EVs, its different components and fields, and connections and how these have developed over time at a broader scope. Different topic experts within the field of EV may have different perceptions about the composition and research trends of the field. The current work is aimed to address this knowledge gap by providing an *objective* and *quantitative* determination of the trends in EV research. We believe that, given the multidisciplinary nature of the research on EV, scholars and practitioners can benefit from a broad-scope computational analysis of the literature, providing insights that otherwise are not obtainable from conventional literature analyis with smaller scope. This can encourage synergy and collaboration between scholars that reside in various sectors of this research, and more importantly, can provide an objective categorisation of research streams within the field along with a quantitative determination of the extent of activities within each stream and their variations over time.[1] This ultimately leads to the determination of hot topics, cold topics and emerging topics within this research field. A side outcome of the analyses is the determination of the fundamental references that have been instrumental to the development of each research stream within the field of EV. This can facilitate future conventional reviews within this field. The analyses identify temporal variations and trends in EV literature based on objective metrics obtained from nearly 34,000 articles on EVs. Overall, the findings of the study provide objective indications as to the directions to which the scholarly literature of EVs is currently headed.

2. Methods and data

Search strategy—The underlying data for the study was sourced from the Web of Science (WoS) Core Collection. The choice of database is based on the fact that WoS data has more specificity, while e.g. Google Scholar is not capable of generating the needed data. WoS and Scopus have shown to have high overlapping content (Mongun & Paul-Hus, 2016). A simple term-based search query string was formulated as (TI=“electric vehicle*” OR AK=“electric vehicle*”) and applied to the Advanced Search section of the WoS.[2] In this query, TI and AK respectively specify Field Tags for Title and Author Keywords of articles. The number of identified items prior to 1990 was insignificant, so the results were confined to 1990–2021. No restriction was set on the document type. Therefore, the search essentially identifies any document indexed by the WoS and published since 1990 till December 2021 that have mentioned electric vehicle(s) in their title or keyword list. Nearly N = 34,000 articles were identified and their details were exported and stored in the form of text files. This information includes for each document, the title, list of authors and their affiliations (country and institute), journal name, year of publication, abstract text, keywords and reference list. All search queries have been made in English which excludes literature only published in local languages and thus might miss some developments and trends happening within national research communities.

Visaluisation of Similarities analysis— Scientometric methods were used on the data to obtain high level insight on the development EV literature. The method of Visualisation of Similarities (VOS) (Van Eck et al., 2010) was employed to discover divisions of the EV literature. Additionally, VOSviewer software and its embedded text mining algorithms were used to identify specific phrases from each publication’s title and abstract and to identify clusters of such terms.

[1] The methodology of computational review suits particularly multidisciplinary topics such as EV, in that, it enables researchers of each subdomain to become familiar with the general trends in other subdomains. For example, in this case, the study introduces research trends generated by transportation researchers to electrical engineers and vice versa. This aim cannot be fulfilled through conventional and manual systematic literature reviews due, simply, to the limited capacity of individual researchers to process, categorise and synthesise large sets of articles.

[2] One should note that that there are alternative terms to "electric vehicle(s)", such as “electric cars”, or “new energy vehicles”, but in order to maximise the specificity of the dataset (i.e., to minimise potential false positives), we only used the mainstream and dominant term in the search query. We investigated the number of articles that mentioned “new energy vehicle(s)” or “electric car(s)” in either title or keywords, but not “electric vehicle(s)”, in order to estimate the number of items that our search might have missed. The answer was 632, which constitutes only 1.8% of the overall size of the existing data.

In the VOS method, the similarity between any two objects i an j is shown by their Euclidean distance, τ_{ij}, and is measured via Equation (1) where σ_{ij} is the number of co-occurrences of objects i and j, while δ_i and δ_j represent their respective number of total occurrences (Haghani et al., 2021):

$$\tau_{ij} = \frac{\sigma_{ij}}{\delta_i \delta_j} \tag{1}$$

A two-dimensional mapping is provided as the outcome of the analysis by minimising the weighted sum of the squared Euclidean distances between all pairs of elements (Equation (2).

$$MinV(\boldsymbol{P}_1, \cdots, \boldsymbol{P}_n) = \sum_{i<j} \tau_{ij} \|\boldsymbol{P}_i - \boldsymbol{P}_j\|^2 \tag{2}$$

An additional constraint is that the average distance between pairs of objects has to be equal to unity. Equation (3) is used to find the spatial locations of items where $\boldsymbol{P}_i = (x_i, y_i)$ is the vector of position for item i in a two-dimensional map, and $\| \cdot \|$ signifies the Euclidean norm.

$$s.t. \frac{\sum_{i<j} \tau_{ij} \|\boldsymbol{P}_i - \boldsymbol{P}_j\|}{n(n-1)/2} = 1 \tag{3}$$

The outcomes of this analysis constitute the core component of the findings presented in the following section, titled “composition and macroscale trends of EV research”.

Document co-citation analysis—Major topics within the EV literature, their temporal trends and influential references were investigated using the methodology of *Document Co-citation Analysis* proposed by Chen (2010). This method essentially investigates the reference lists of all N = 34,000 EV articles and identifies clusters of references that are often cited jointly in EV papers. The method rests on the assumption that groups of reference that are often co-cited represent the *knowledge foundation* of a certain topic/stream. As result, by identifying such clusters, the following can be obtained. (i) One can objectively determine fundamental references of each research stream through the number of times they are referenced in EV papers (i.e., local citation count) as well as sudden spikes in frequency of being referenced (i.e., local citation burst) as well as the frequency of times that they are cited jointly with references of other clusters, known as *centrality*, a metric of the broadness of impact for the reference. (ii) Through inspection of the cohort of EV papers that created (cited) each cluster of references, one can identify the topic that the cluster represents. (iii) By analysing citation activities of these citing articles (i.e., EV papers) over time, one can determine temporal variation in the magnitude of research on each of the topics and determine areas of research that are trending or those that are slowing down. This methodology has been illustrated in an abstract way in Fig. 1. Note that in this context, EV papers within the dataset of N = 34,000 articles are referred to as citing articles, to contrast with their frequently *cited references*. The cited references, clearly, could be EV papers themselves (i.e., be present in the dataset of citing articles too) or be outsiders of EV research, references not necessarily related to EV, but frequently cited by EV papers, and hence important to knowledge development on EV.

The outcomes of this analysis are presented in the section titled “temporal trends and influential references in EV research”.

3. Composition and macroscale trends of EV research

3.1. Geographical and field distribution of EV research

Geographical origins of EV studies were analysed using country affiliation of authors listed on the set of N = 34,000 articles in the data. Data showed that nearly 27.5% of EV articles (n = 9,346 items) have, at least, one author affiliated with institutes of China. Other countries whose authors/institutes have a strong presence in EV research are the USA (n = 5,466), Germany (n = 2,048), India (n = 2,010), and Canada (n = 1,746) (see Fig. 2 (a) and (b) for more details). The dominance of contributions of authors from China over the last decade has been such that the rate of accumulation of studies in this research (i.e., the number of papers published annually) has been constantly consistent with the rate of publications from China (See Fig. 2 (c)). The dominance of research in China shows that the governmental push toward EVs to increase competitiveness of China as an automotive power has had an effect on academia as well (Altenburg et al., 2022). The rate of publications in any other one of the top five countries has been slower than China during the last decade. However, since 2019, the number of EV publications originating from China appears to have flattened out and instead, the biggest (relative) growth rate of EV research is currently observed in India.

The extent of international collaborations was also investigated based on the country affiliation of authors listed in the papers. Articles with at least two authors affiliated with organisations of two different countries were deemed international collaborations. Data showed that only 20.8% of EV research has overall been comprised of international collaborations. Instead, 79.2% of studies have been domestic research (Fig. 2 (d)). This is slightly less than the overall degree of international collaboration in scholarly literature in general, estimated to be around 25% (Haghani et al., 2022). The closest attempt to analysing collaborations in fields adjacent to EV research is the study of Aleixandre-Tudó et al. (2019) where a triangle of international collaboration in Renewable Energy research was identified but no quantitative estimate has been provided comparable to that of the current study.[3]

[3] This type of analysis is currently absent in most other fields and topics, making it difficult to make a direct comparison of the extent of international collaboration across different fields.

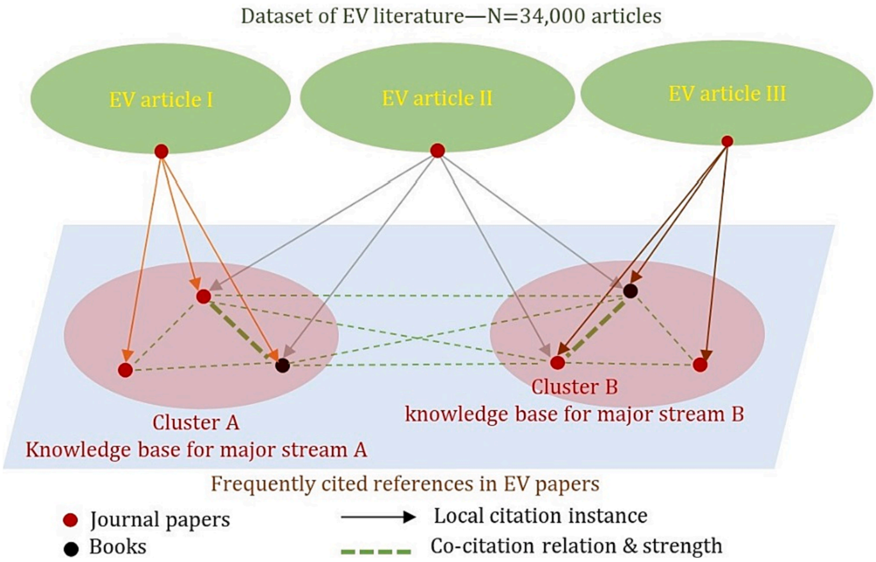


Fig. 1. An abstract illustration of the concept of document co-citation network.

Data also shows that the gap between domestic and international publications has been increasingly widening. Strikingly, during 2021, the number of internationally collaborated EV papers showed a drop compared to 2020 whereas the number of domestic papers continued to grow strongly, an observation that appears to be in contrast with most other areas of scholarly research (Haghani and Bliemer, 2023), and an indication that the state of international collaboration in EV research may still not be quite strong compared to many other research fields and topics.

The strongest link of collaboration between countries is observed between China and USA with n = 870 joint papers. This is followed by collaborations between China and England, China and Canada, USA and Canada, and USA and South Korea. These constitute the five strongest links of country collaboration in EV research (Fig. 2 (e)).

The impact of international collaboration on the overall impact of research has been a matter of investigation by several studies. It has been shown that research that entails international collaboration is overall more impactful than purely domestic studies (Van Raan, 1998). This is an indicator that in most fields, including EV, more impactful findings can emerge as a result of a higher level of international collaborations between scholars of that field. This may be particularly the case in a multidisciplinary topic such as EV.

The distribution of EV research across various fields of research was also investigated. To this end, the WoS categories in which the source (journal) of each article has been indexed, were used as the main determinant. The number of such categories was very large, but the majority of the fields could be aggregated across five major disciplines: **(1) Electrical Engineering & Computer Science** (comprised of WoS categories Engineering Electrical & Electronic, Telecommunications, Computer Science & Information Systems, Computer Science Theory & Methods, Computer Science Artificial Intelligence, Computer Science Interdisciplinary Applications, Computer Science Hardware Architecture, Computer Science Software Engineering, Computer Science Cybernetics) **(2) Energy & Fuels** (comprised of the WoS category Energy and Fuels), **(3) Environmental Studies** (comprised of WoS categories Environmental Studies, Environmental Sciences, Engineering Environmental and Green & Sustainable Science Technology), **(4) Transportation** (comprised of WoS categories Transportation Science & Technology, and Transportation), and **(5) Materials Science & Chemistry** (comprised of WoS categories Materials Science Multidisciplinary, Materials Science Coating Films, Materials Science Characterization Testing, Chemistry Physical, Electrochemistry, Chemistry Multidisciplinary, Chemistry Analytical, Chemistry Applied, Chemistry Inorganic Nuclear, Chemistry Organic, Engineering Chemical, Materials Science Composites, Materials Science Biomaterials, and Nanoscience Nanotechnology).

In determining the allocation of each study, only those that purely belonged to the subcategories of only one of these five major/aggregate disciplines were considered and not those of any other. Results showed clearly that EV is predominantly Electrical Engineering research, followed by Energy & Fuels, Environmental Studies, Materials Science & Chemistry and Transportation (See Fig. 2 (f), (g)). Since 2010 especially, EV research has been growing very steeply in Electrical Engineering, although since 2017 this trend has changed and there are signs of research developments slowing down in Electrical Engineering (Fig. 2 (f)). Instead, in more recent years (i.e., 2016 and onwards), the growth of EV research within the Energy & Fuels as well as Environmental Studies disciplines has been most notable. The growth of EV research in the Transportation as well as Materials Science domains remains relatively modest and fluctuating.

4. Keywords in EV research

Top keywords in EV research were identified based on their frequency of mention as well as the percentage of frequency, relative to the total number EV papers (Fig. 3). Keywords that are simple variations of one another (e.g., "battery" and "batteries", or "vehicle to

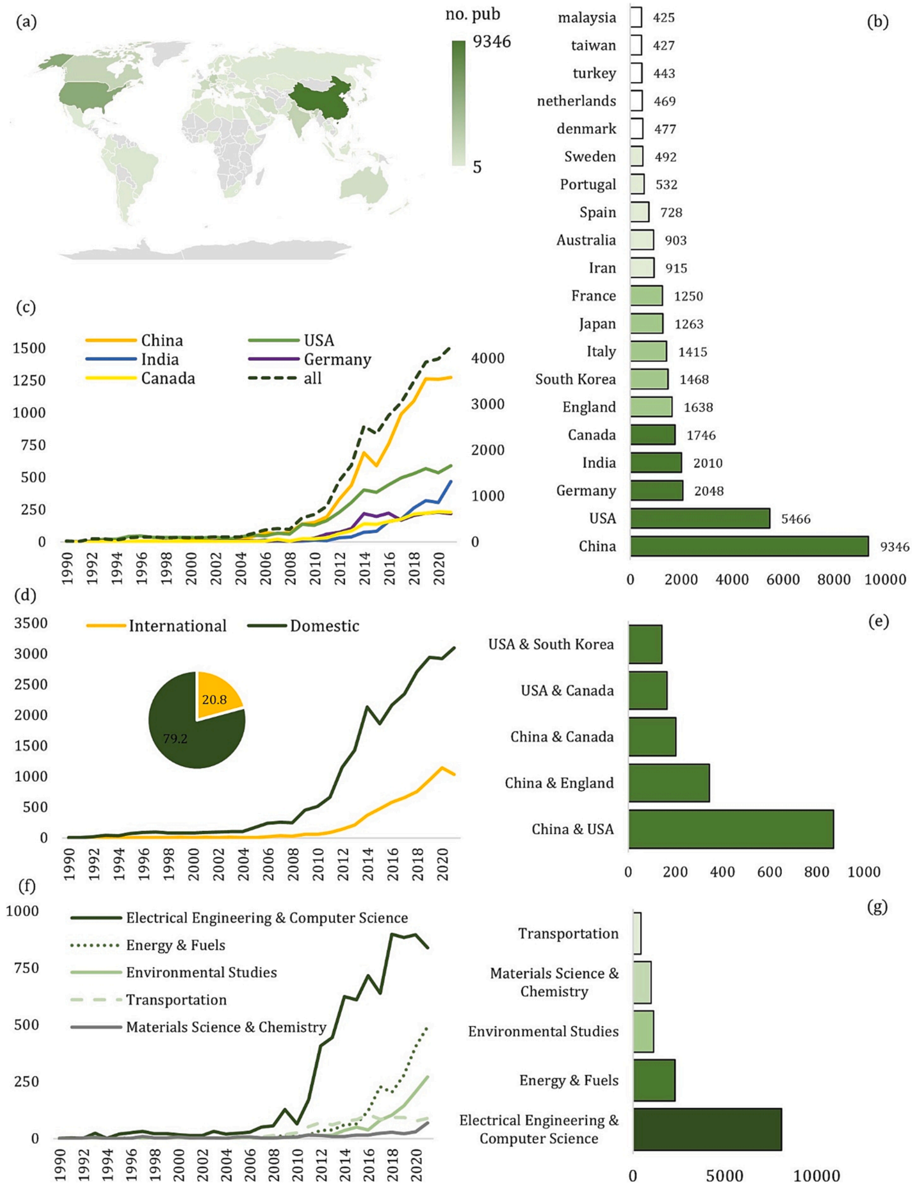


Fig. 2. (a) Primary origins of EV research based on the number of scholarly publications, (b) top twenty countries active in EV research, (c) variation of the magnitude of EV research in in top five countries over time, (d) the extent of domestic and international collaboration in EV research and its variation over time, (e) strongest links of country collaboration in EV research, (f) variation in the magnitude of EV research activity (reflected in the number of publications) across major disciplines, (g) the share of EV publications distributed across major disciplines.

grid", "V2G" and "vehicle-to-grid" or "optimisation" and "optimization") were combined. The frequency of keywords was also quantified separately for publications of the top five countries (Fig. 4) as well as separately for publications emerged during time periods of 5 years since 1990 (Fig. 5). Same determination was also made for publications across the top five major disciplines identified earlier (Table 1). For the discipline-based analysis, the average year of publication of each keyword was also calculated, by averaging publication year of the papers on which each keyword has been listed. The obvious and dominant keywords of "electric vehicle(s)" was ignored in these analyses.

The most dominant keyword in the EV literature was, by a large margin, "hybrid EV". However, an interesting observation was noteworthy. The keyword "hybrid EV" is distinctly older than any other major keyword in the EV literature. The average year of publication of "hybrid EV" in the overall literature is 2014.40 (note that the fraction is the result of averaging). Among these top keywords, the followings, on the other hand, are comparatively the youngest: "optimisation" (2017.61), "charging station" (2018.14), "wireless power transfer" (2018.07), "EV charging" (2019.33). Among the major keywords, the most cited one is "lithium-ion battery" (average citation of 34.45 and average normalised citation of 2.48). A frequency heatmap of all major keywords of EV research can be

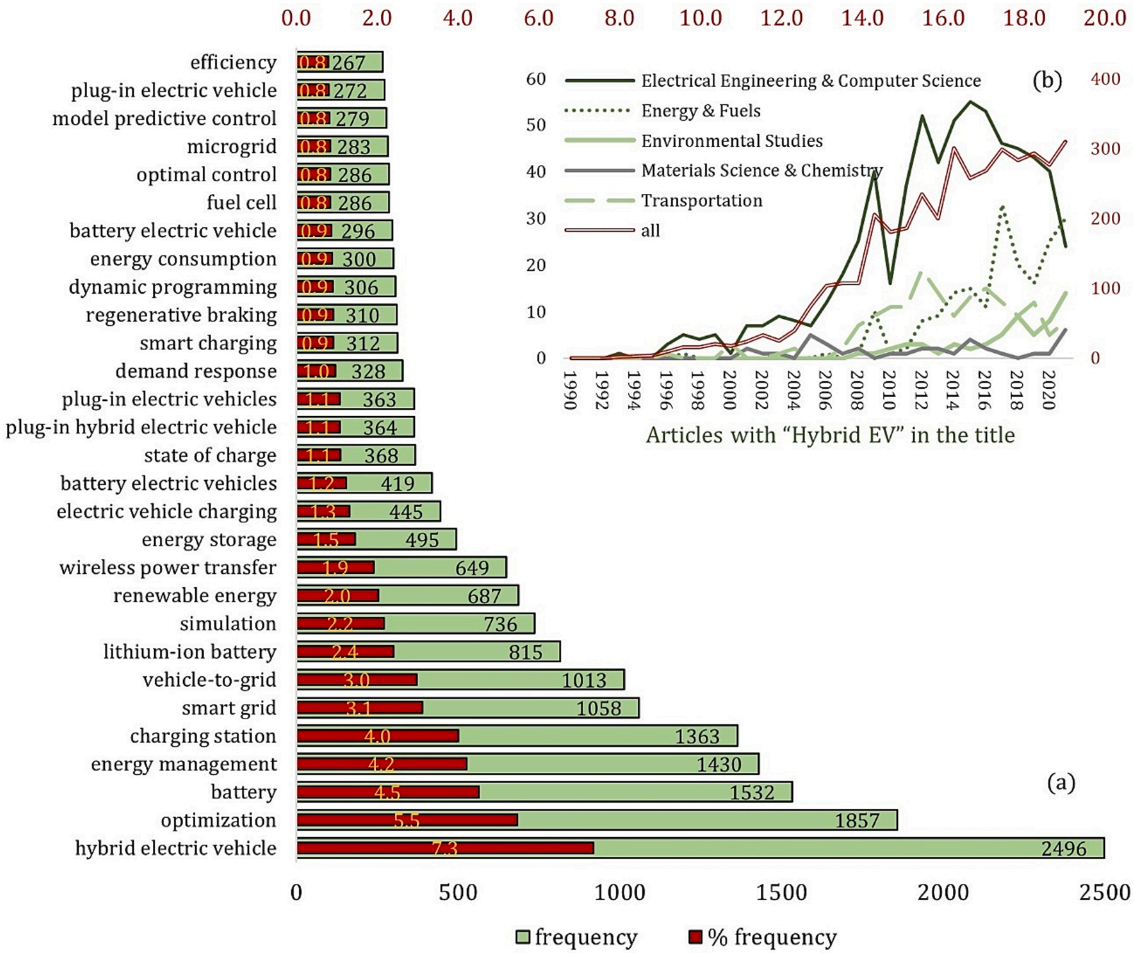


Fig. 3. (a) Most frequent keywords in EV research along with their percentage of frequency (normalised by the total number of papers, N = 34,000), (b) variation in the frequency of the term combination "Hybrid EV" in titles of EV articles across time and various major disciplines.

downloaded from this link. Hybrid EVs were the first modern commercialised electrified vehicles resulting from policy pushes in California and Japan (Åhman, 2006; Bedsworth and Taylor, 2007). Thus, hybrids formed the base for a lot of the empirical research. As battery technology has improved, these have been replaced by plug-in hybrid electric vehicles (PHEV) and battery electric vehicle (BEV), hence the decrease in importance for the research community.

Further analysis confirmed that the frequent mention of "hybrid EV" as a keyword is not confined to a specific country or specific discipline. In all those subsets, this keyword is distinctly the oldest compared to other frequent keywords. The keyword is the top keyword of publications from China and USA and the second top keyword of publications from India and Germany and the third most frequent keyword of publications from Canada. In other words, in countries whose EV publications are relatively younger (e.g., India, Germany and Canada), the prominence of this keyword is less distinct.

A similar observation was made when considering the five major disciplines. Environmental Studies is relatively the youngest domain of EV research (as demonstrated earlier), and as such, the EV literature presents many relatively young top keywords in that domain and the prominence of "hybrid EV" is less distinct in that discipline. As Fig. 3 also shows, the frequency of the use of this keyword has been notably declining in Electrical Engineering sector of EV research since 2015. To further re-affirm this observation, top keywords over four time periods were determined (Fig. 5). While during the first three periods, "hybrid EV" is the most dominant keyword, in the most recent period, its position has been replaced by "optimisation".

The shift in keywords is partly reflective of the development of the EV industry and policies that have experienced significant changes in recent years. Policy pushes in California and Japan led to the commercialisation of hybrid EVs in the early 2000 s, resulting in the dominance of the keyword "hybrid EV" in early EV research. However, as battery technology improved, hybrid EVs were replaced by plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), leading to a decline in the prominence of the keyword "hybrid EV" in recent years. This shift in focus is reflected in the emergence of keywords such as "optimisation" and "wireless power transfer," suggesting a shift towards optimising and improving the efficiency of EV technology. Additionally, the increasing prominence of keywords such as "EV charging" and "charging station" reflect the growing importance of infrastructure development in

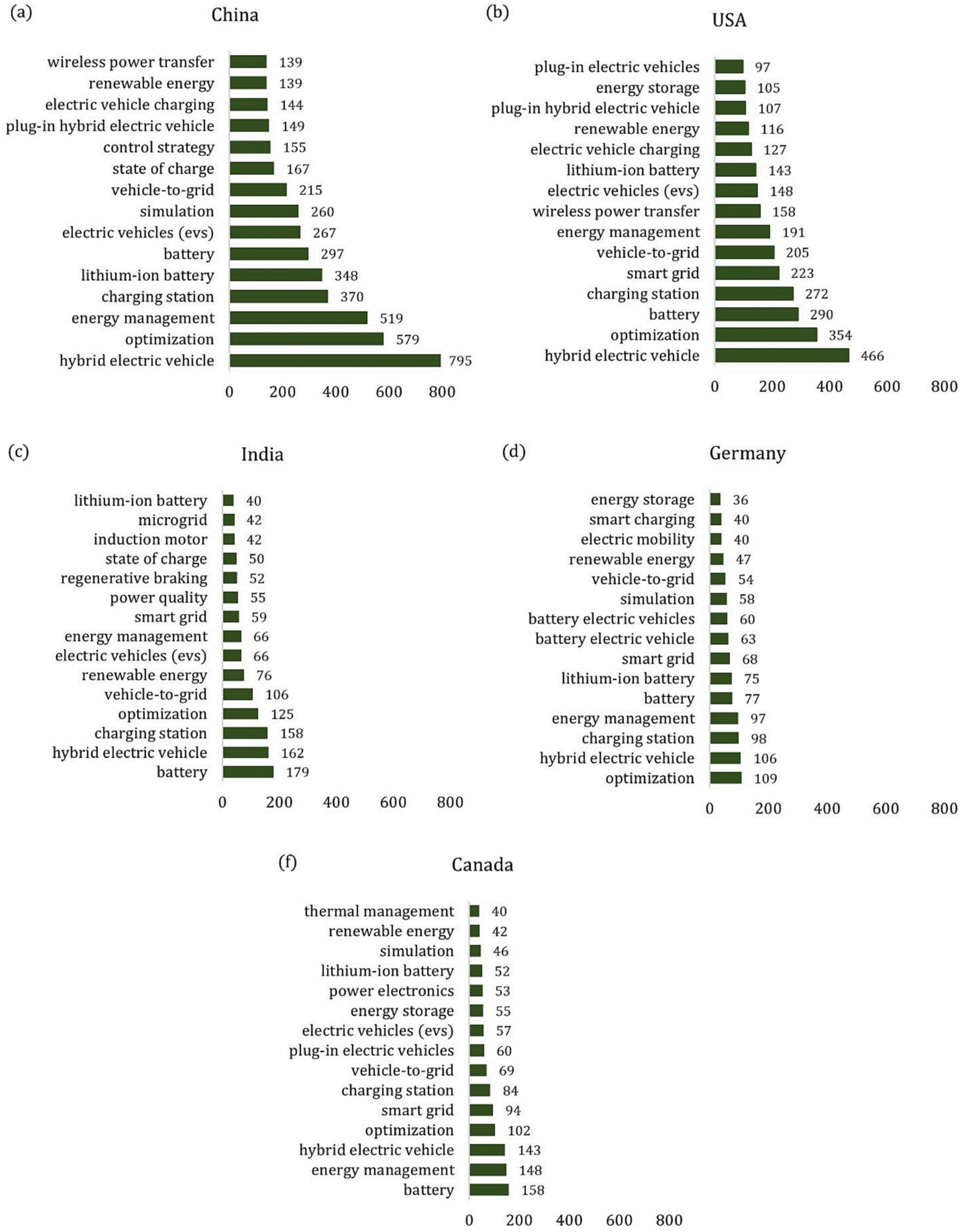


Fig. 4. Top keywords across five countries that contributed the most to EV research: (a) China, (b) USA, (c) India, (d) Germany and (e) Canada.

the EV industry.

The shift towards BEVs and PHEVs is also reflected in government policy development. Many countries have implemented policies to promote the adoption of EVs, including tax incentives, subsidies, and mandates for automakers to produce a certain percentage of

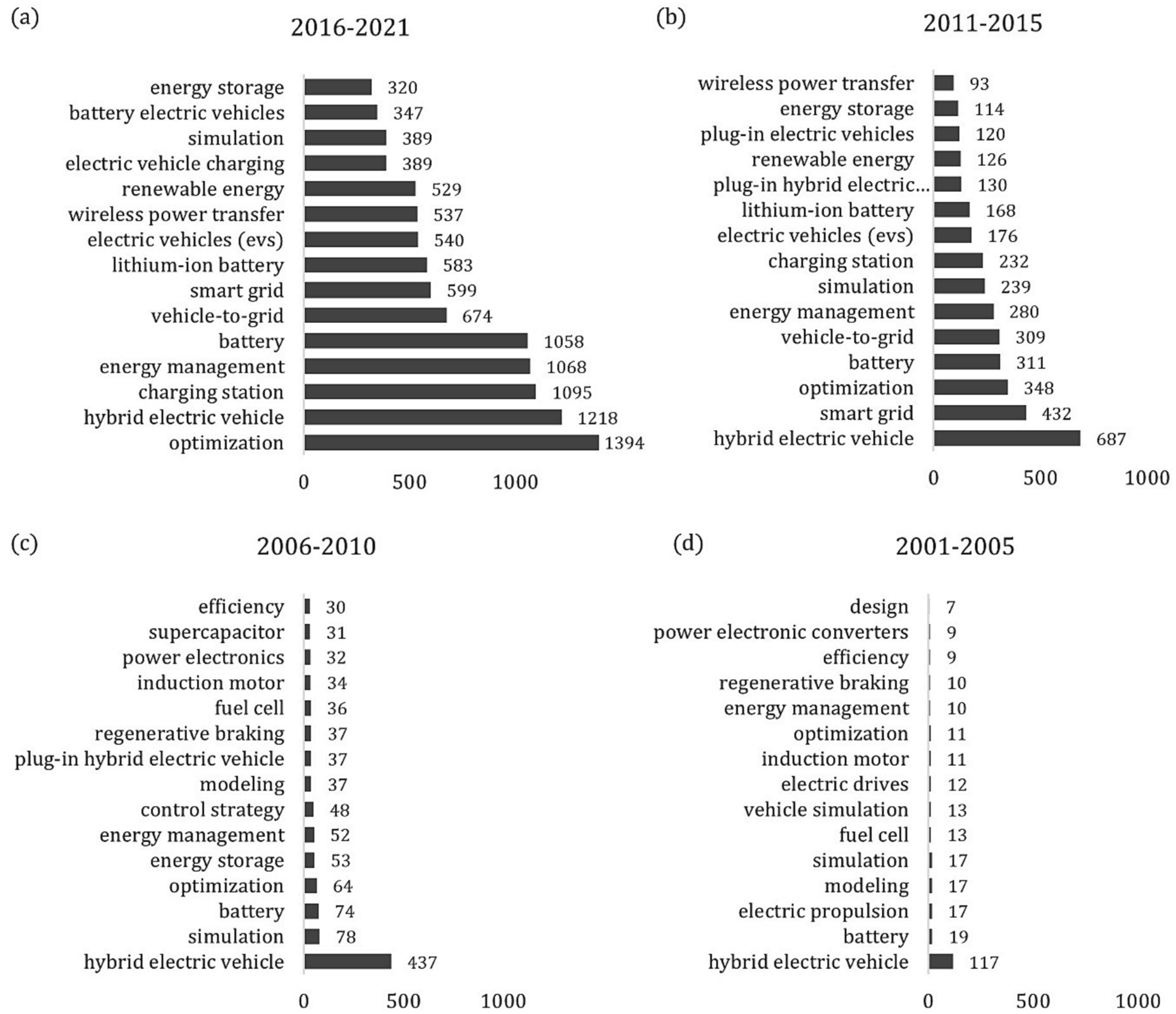


Fig. 5. Keyword frequency in EV research across various time periods: (a) 2016–2021, (b) 2011–2015, (c) 2006–2010, (d) 2001–2005.

EVs. For example, China has set a goal for new energy vehicles, including EVs, to account for 20% of all car sales by 2025 (Guo et al., 2022). The European Union has recently decided to completely phase out the sales of internal combustion engine vehicles by 2035.[4]

4.1. Term co-occurrence and bibliographic coupling in EV research

Patterns of terminology co-occurrence were investigated using the VOS methodology to determine major divisions of EV research through semantic aspects. In doing so, the texts of titles and abstracts of EV papers were analysed. The analysis determined clusters of terms frequently co-mentioned in the titles and abstracts of EV papers, thereby identifying major sectors/divisions of the field. This methodology resulted in four clusters each representing a major division of EV research (Fig. 6 (a)). These divisions can be characterised as the following: *cluster (i) infrastructure, adoption, market, policy and network* (shown red), *cluster (ii) experimental division* (shown green), *cluster (iii) control systems and strategy* (shown blue) and *cluster (iv) batteries* (shown grey). Each cluster can be considered to represent a major division of the EV literature.

In terms of terminology use, cluster (i) has a very specific set of terminologies that are not often shared with other clusters. This cluster represents a more applied division of this field, studying markets and actual use of the vehicles, while the other clusters are more related to the technical development of the vehicle and its components. As such, on the term co-occurrence network, cluster (i) resides remotely from the other three clusters. Terminologies of the three other clusters/divisions, however, are more intertwined. An overlay of the average year of publication of these terms (Fig. 6(c)) also demonstrates that cluster (i) is overall comprised of relatively younger terms and thus representative of a relatively younger division of EV research compared to the three other clusters.

[4] https://eur-lex.europa.eu/eli/reg/2023/851/oj.

Table 1
Top keywords of EV research across major disciplines along with their average year of publication.

Electrical Engineering & Computer Science	Avg year	Energy & Fuels	Avg year	Environmental Studies	Avg year	Materials Science & Chemistry	Avg year	Transportation	Avg year
battery	2018.03	optimization	2019.12	life cycle assessment	2019.3	battery	2016.5	hybrid electric vehicle	2014.44
optimisation	2018.04	hybrid electric vehicle	2017.3	charging station	2019.81	hybrid electric vehicle	2011.9	charging station	2018.32
hybrid electric vehicle	2014.99	lithium-ion battery	2019.35	lithium-ion battery	2019.57	lithium-ion battery	2017.78	optimization	2016.46
smart grid	2016.27	energy management	2018.81	battery electric vehicle	2019.25	fuel cell	2016.8	simulation	2015.46
charging station	2018.06	charging station	2019.33	renewable energy	2019.94	state of charge	2017.4	energy management	2015.62
vehicle-to-grid	2016.94	vehicle-to-grid	2019.3	optimization	2019.77	charging station	2018.1	PHEV	2014.01
energy management	2017.52	battery	2018.87	hybrid electric vehicle	2018.01	energy storage	2017.6	battery electric vehicle	2017.17
electric vehicle charging	2019.24	renewable energy	2019.32	sustainability	2019.71	induction motor	2016.9	plug-in hybrid EV	2014.59
renewable energy	2018.3	smart grid	2018.08	recycling	2019.79			dynamic programming	2016.67
wireless power transfer	2018.09	energy storage	2019.43						
energy storage	2016.6	wireless power transfer	2019.02						

The three other clusters all include terms that that can be considered relatively the oldest terms in EV research, demonstrating that they constitute pioneering areas. However, within clusters (ii-iv), a few distinctly young terms are also identifiable including “wireless power transfer” (2018.07) (with the number in bracket showing the average year of publication) and “model predictive control” (2018.4). An overlay of the average normalised citations to the terms (normalised based on their age) shows that clusters (i) and (iv) embody more highly cited terms. The highest cited terms are “lithium” and “lithium-ion battery” (in cluster (iv)) and “greenhouse (gas) emission” and “survey” (in cluster (i)). Readers can access and explore an online interactive version of the term co-occurrence network through the link provided in the caption of Fig. 6.

An alternative way to objectively determine divisions of EV research is to apply the VOS methodology to the reference lists of EV articles, i.e., to investigate a network of bibliographically coupled articles (Haghani et al., 2022), those that have high degrees of similarities in their reference lists. This calculation has been made and shown in the bottom left part of Fig. 6 (Fig. 6 (b)). This provides a less aggregate way of partitioning this research topic, as this analysis maintains the individuality of the articles.

In the network of article bibliographic coupling shown in Fig. 6, each node represents an individual paper, one of the items in the dataset of N = 34,000 articles. Readers can reproduce an interactive version of this network on an online platform using the source files provided in the Online Supplementary Material. An examination of the content of this network determines that there are two clusters in this network that can be regarded as the source for the division of *infrastructure, adoption, market, policy and network* (i.e., cluster (i)) in the term co-occurrence network (shown in different tones of red in Fig. 6 (b)). In other words, the cluster/division of *infrastructure, adoption, market, policy and network* gets split into two-subdivision in the article bibliographic analysis. The explanation for this split is that, there are two subdivisions within this division that are openly identifiable through their patterns of referencing, but they share highly overlapping terminologies (hence, their merging with each other in the term-cooccurrence network). This means that, there is heterogeneity within that division that goes undetected when terminologies are considered as the entity of analysis. There are two subdivisions of this division that use different sets of references while using similar languages. When analyses are conducted at the level of terms, the distinction between the two is undetectable. But when analysis is conducted at the level of individual articles (and the similarity of their reference lists), then this distinction is manifested.

A similar pattern is observable with respect to the *experimental division* splitting into two subdivisions at the level of article bibliographic coupling (clusters shown in two different tones of green). Divisions of *control systems* and *batteries*, however, each have a single representative at the level of article coupling. In terms of the patterns of referencing, the division of *control systems* appears to not have much in common with the rest of the body of EV literature, reflected in its respective cluster located far apart from the mainstream body of the network. An overlay of the year of publications (Fig. 6 (d)) shows that, consistent with our observations based on term co-occurrence, the *experimental, control systems* and *battery* divisions have a relatively higher concentration of relatively older papers, showing that they are pioneering divisions of this research.

5. Temporal trends and influential references in EV research

At the lowest level of aggregation, trends in EV research were analysed using patterns of document co-referencing. This provides the highest level of resolution and details amongst all analyses presented in this work on EV research. Outcomes of this analysis are the

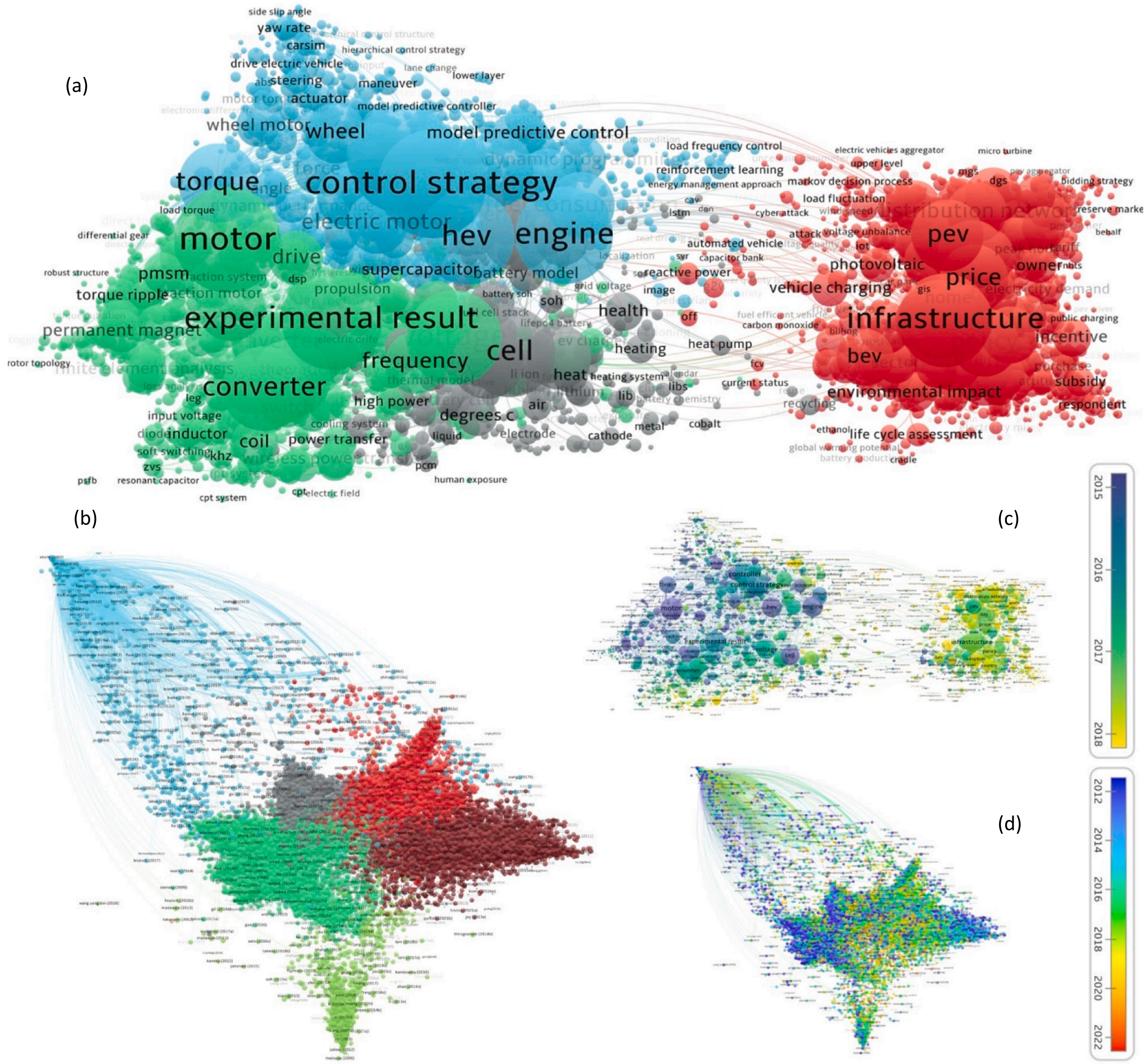


Fig. 6. Structure and major divisions of EV research based on (a) patterns of term co-occurrence (top) and similarity of article references, i.e., (b) bibliographic coupling (bottom left). An overlay of average publication year has been provided on both term co-occurrence (c) and bibliographic coupling maps (d). An interactive version of the term co-occurrence network can be accessed via this link. Via source files provided in the Supplementary Material, readers will be able to create an interactive version of the bibliographic coupling network in the online VOS platform.

determination of major stream/topics/themes of EV research, influential references for each stream, and the time-related variations in activities for each stream, thereby objectively determining trending and pioneering topics as well as those that are losing traction. The analysis results are presented in Fig. 7 in both network view (Fig. 7(a)) and timeline view modes (Fig. 7b)), and further details are also included in in the A**ppendix. The state of the document co-citation network has also been displayed at various points in time since 1990 (across periods of five years) in Fig. 8. The link in the caption of Fig. 8 also provides a dynamic year-by-year visualisation of the state of the network.

The document co-citation analysis identifies 17 major themes/streams within the EV literature. In the networks presented in Fig. 7, each theme is represented by a specific cluster. Each cluster is comprised of frequently co-cited references in the EV literature. Each of those references are represented by a node and the links connecting them represent instances of co-citation by EV articles. The size of each node is proportional to the number of local citations to that reference, i.e., the number of times that the reference has appeared in the reference lists of EV articles. Nodes that are marked with a red ring represent those to which a burst (sudden spike) in local citations has been recorded. Each burst is characterised by the year of onset, its duration, and its strength. The thickness of the red rings is

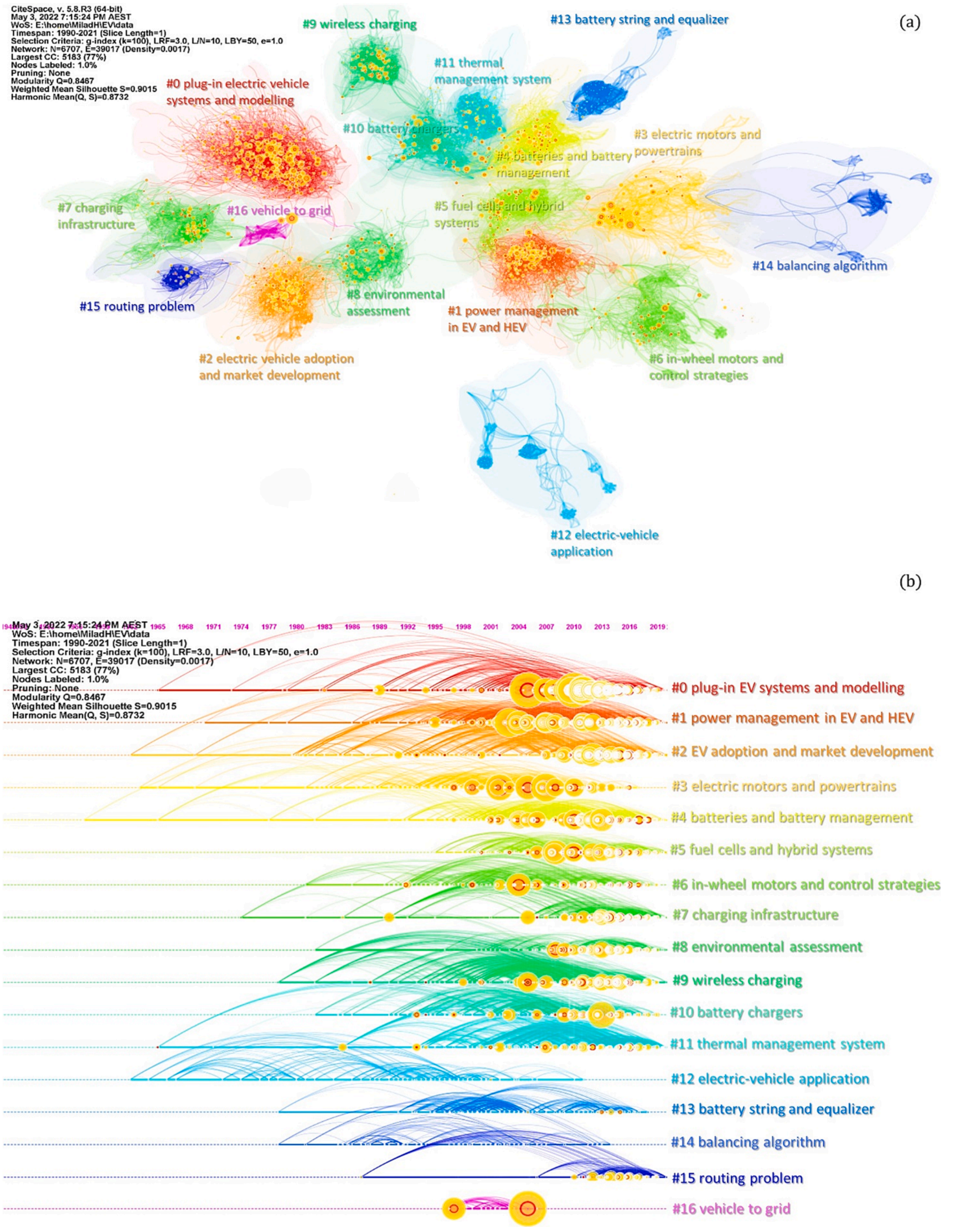


Fig. 7. Clusters of co-cited documents in EV research in (a) network view mode and (b) timeline view mode.

proportional to the burst's duration. For each cluster, the number of cited references, the average and range of the year of cited references, as well as the average and range of the year of citing articles have been calculated (see the A**ppendix). Clusters whose average/range of year of cited references is a smaller number generally have a relatively older knowledge foundation. Clusters whose

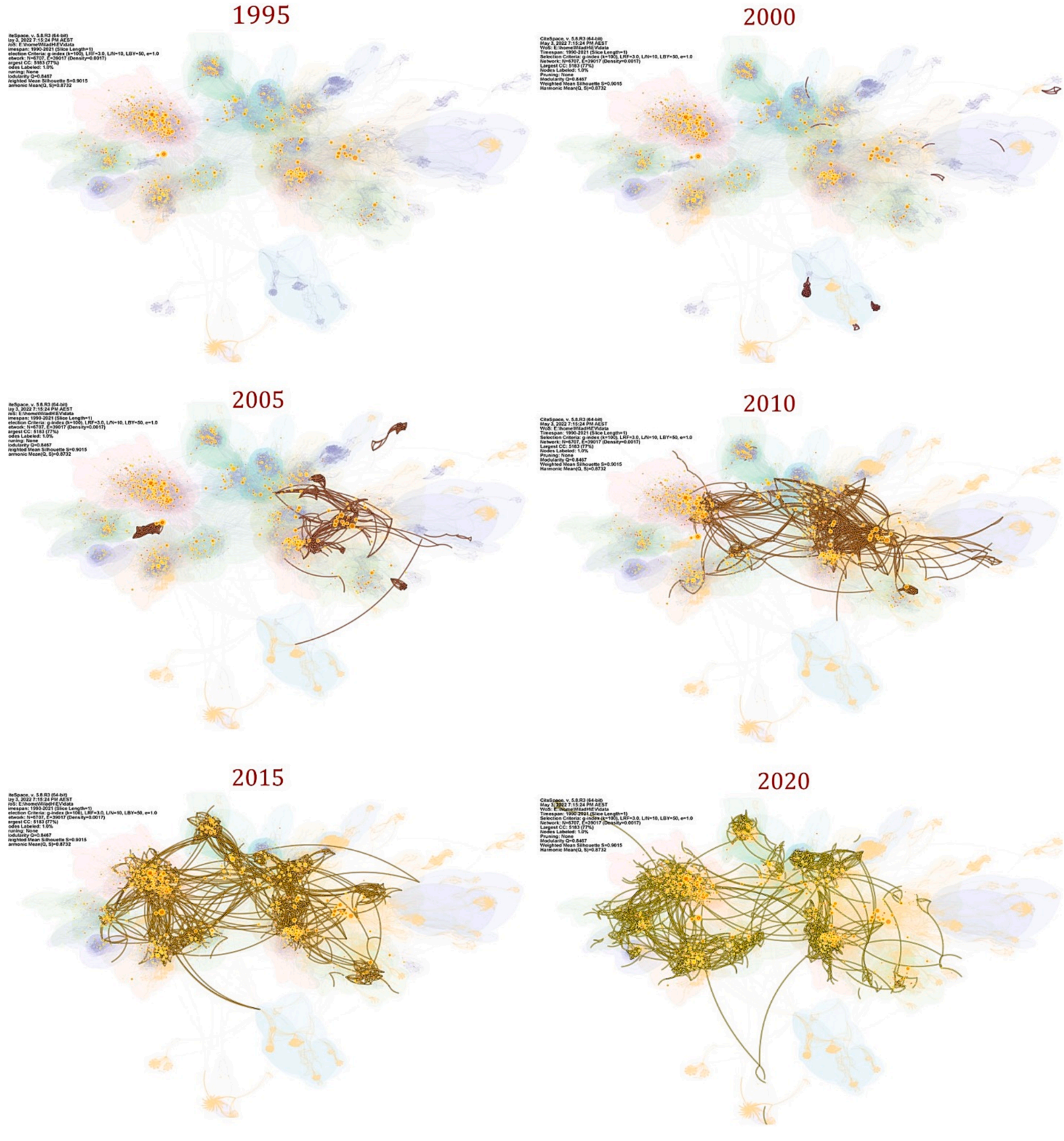
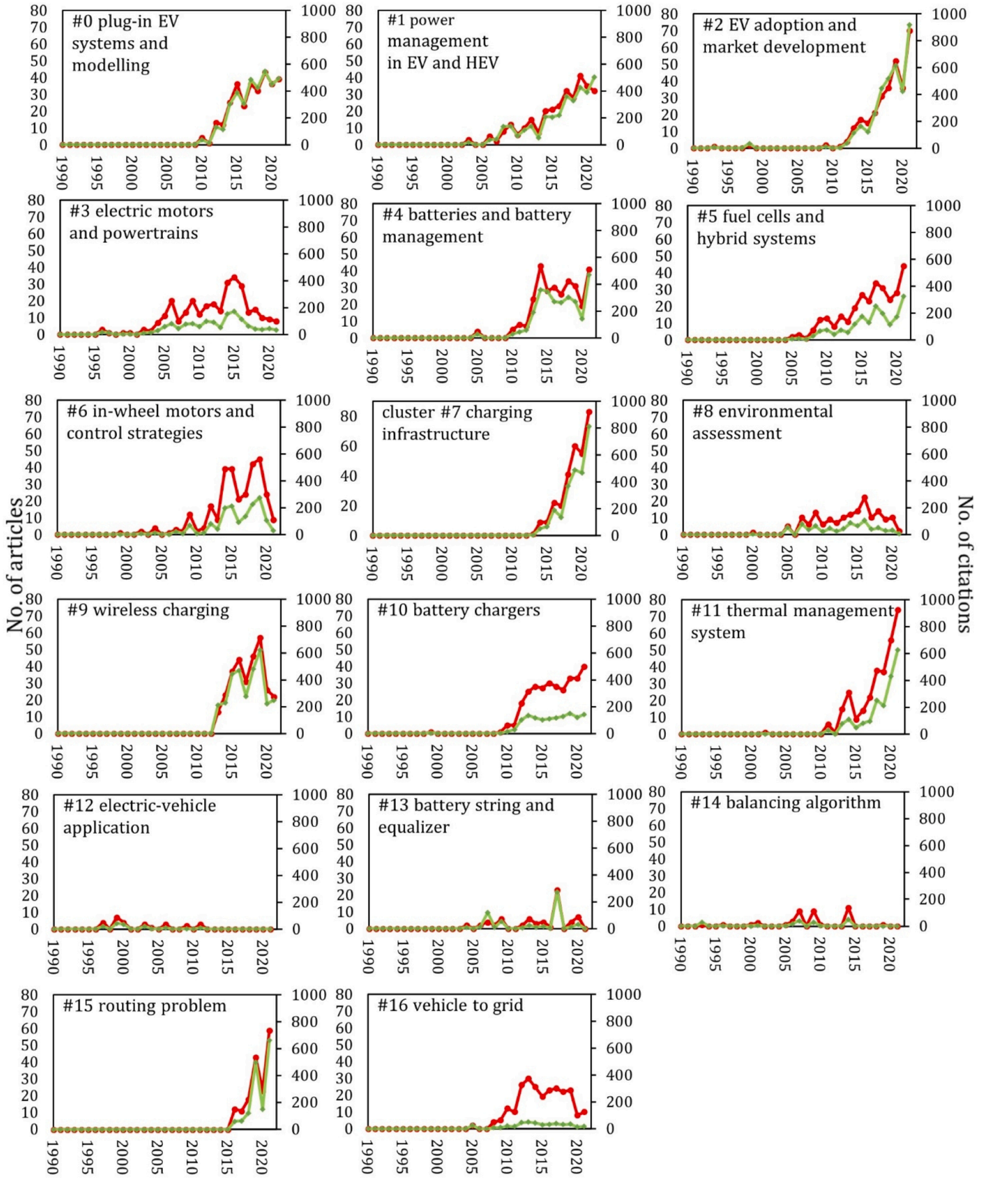


Fig. 8. The state of EV research at various points in time over the last two decades. A year-by-year dynamic visualisation of the state of document co-citation network can be accessed in the Online Supplementary Material as well as this link.

average/range of year of citing articles is a larger number, are generally younger clusters.

It is important to differentiate between the age of a cluster (as represented by its citing articles) and the age of its knowledge foundation (as represented by its cited references). Theoretically, a cluster can be relatively new but have a relatively old knowledge foundation. At the bottom of Fig. 7, the timeline view presents insights about the age of knowledge foundation of clusters by aligning references of each cluster based on their year of publications (Fig. 7(b)). By contrast, in the network view (top part of the figure), clusters that are thematically closer are visualised spatially closer (Fig. 7(a)).

For each cluster, by extracting frequent terms and noun phrases from the titles of the citing articles, a number of top objectives/ algorithmic descriptors have been determined. This algorithm takes into account the frequency of appearance of each term in the titles of the citing articles as well as the *coverage* of the citing article (i.e., the number of references of the cluster that the citing article cites)



eq

Fig. 9. The magnitude of research activities of each of the major topics of EV research (as determined by document co-citation clusters) in terms of the number of citing articles (red lines, left vertical axes) and total coverage to the references of each cluster (green lines, right vertical axes). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

while giving more weight to terms extracted from citing articles with higher coverage. Guided by these objectively determined terms and by examining the content of citing articles of each cluster, an author-defined descriptor/label has also been determined for each cluster and presented on the network. In Fig. 8, links that are made visually salient on the network represent areas of the network that have been active (co-citation occurring) during a specific year. Activities of the citing articles of each cluster (i.e., the total number of citing articles that cite references of each cluster, as well as the total number of references that they cite (total coverage)) were also calculated for each year during the period of 1990–2021. This outcome is presented in Fig. 9 and is key for determining hot topics, cold topics and emerging topics of the field on an objective basis.

Nine out of 17 clusters have increased their activity especially after 2010 (namely clusters #0,1, 2, 5, 7, 10, 11, and 15). These clusters cover different areas of EV research ranging from modelling of the system, battery management, fuels cells and hybrid systems as well the development of charging infrastructure and market. There are four clusters that have had the strongest development in recent years, and those are cluster #2 (EV adoption and market development), #7 (charging infrastructure), #11 (thermal management system) and #15 (routing problem).

Research activity in cluster #2 (EV adoption and market development) took off around 2010, corresponding with the development of the commercial market for EVs and has been increasing steadily since then. While the cluster itself is more recent, it relies on references from further back in time (see Fig. 7(b)). Cited references that have generated the highest burst are related to cost projections and developments (Thiel et al., 2010), especially of batteries (Nykvist et al., 2015), and consumer perceptions (Axsen et al., 2010; Cocron et al., 2011).

Cluster #7 is about the development and needs related to the charging infrastructure with related areas such as transportation networks and urban areas. Activity within this stream started to grow after 2012, i.e., around the start of the growth of the commercial market for EVs. Cited articles with the strongest burst develop different methods and algorithms to optimally allocate charging stations (Shahraki et al., 2015; Dong et al., 2016; Xiang et al., 2016).

Cluster #10 and #11, as well as #4 all deal with research related to batteries. While cluster #10 and #11 have continued to increase, cluster #4 (batteries and battery management) fluctuated more over time. The general growth of these clusters occurred after 2010. Cluster #4 is more general related to lithium-ion batteries and battery management systems, while cluster #10 looks more specifically into DC converters and battery chargers, and cluster #11 concerns thermal management of batteries. Thus, we can see that battery-related research has developed more specific clusters rather than clusters consisting of the broader articles. The articles with the strongest burst are related to the determination of state-of-charge of batteries (Piller et al, 2001); battery degradation in connection to V2G applications (Peterson et al., 2010a, 2010b); EVs impact on the grid (Rahman et al, 1993); and a more general article concerning batteries and ultracapacitors (Burke, 2007).

Cluster #15 covers areas related to the development of algorithms for vehicle routing problem and location-routing problem. This cluster, along with clusters #2, #7 and #11, constitute the trendiest research topics of EV literature at the moment. This trend and the rapid accumulation of papers on this topic is also reflected in several review articles that have been published on the topic in the recent years (Erdelić et al., 2019; Asghari et al., 2021; Qin et al., 2021). The most popular reference of this research stream is the study of Schneider et al. (2014).

Five clusters seem to have peaked in activity and are no longer that productive. Cluster #3 (electric motors and powertrains) and #6 (in-wheel motors and control strategies) both concern motor solutions. Cluster #3 is of more general character and cluster #6 regards specific solutions such as in-wheel motors and control strategies. For these two clusters, the most cited references are from the early 2000 s. Chan (2002) is an overview paper on EV technology, while Hori (2004) focuses more on motion control techniques applied to EVs. Clusters #9 and #16 are instead related to charging solutions, namely wireless charging and vehicle to grid. While these are still being discussed in the public domain, the research interest in the subjects seems to have dwindled.

Another cluster with decrease in activity is cluster #8 concerned with the environmental assessment of electric vehicles especially concerning emissions of greenhouse gases and life-cycle emissions. The decrease in activity in recent years could be an effect that the environmental benefits of EVs have been established and are less questioned today compared to early on in the development process. Interestingly, the papers with the highest citation burst are concerned with the environmental effects of PHEVs (Samaras et al., 2008; Bradley et al., 2009; Shiau et al., 2009).

Clusters #12 (electric vehicle application), #13 (battery string and equalizer), and #14 (balancing algorithm) all have had much smaller activity than the other clusters. Cluster #12 and #14 are more related to early technical EV research related to specific solutions such as semi-controlled batteries and inverters, while #13 seems to still have some activities.

6. Discussions and conclusions

Electrification is a key technology within the transport field to reach climate goals. While the history of electrification is as old as the history of the automobile, it is not until the last 20 years that we see that the research has really gained momentum. In this paper, we have studied the scholarly research trends by analysing patterns of document co-referencing of the period 1990–2021. Our results show several interesting trends, gaps, and need for future development of EV research, industry, and policy.

The dominant research fields have been electrical engineering & computer science. We see a certain leveling off in research activity in these fields during recent years. However, we believe this might be a temporary result given the continued need for research and development of autonomous driving technologies in EV. These will be necessary to improve transportation safety and efficiency and to minimise energy consumption by optimising driving patterns and reducing traffic congestion. However, this development needs to be aligned with policies not to induce more traffic and thus energy demand (Sprei, 2018).

Energy & fuels and environmental studies are gaining in activity (even though the narrower environmental assessment of EVs has peaked). With more EVs on the road, the demand for electricity to power these vehicles will increase, impacting the energy sector. Thus, we see that this is an area with expected growth, especially related to the integration of renewable energy. For example, research trends in the United States have shown that EV adoption is driving a transition to cleaner sources of electricity generation, such as wind and solar power (Taalbi et al., 2021).

In addition, the development of new battery technologies for EVs has led to innovations in energy storage, which has applications beyond the transportation sector. Advances in battery technology could lead to the creation of more efficient and cost-effective energy storage solutions for renewable energy sources like wind and solar power. In China, the government is investing heavily in the development of advanced battery technologies for both EVs and energy storage applications (Li et al., 2019).

Furthermore, the adoption of EVs will also impact the oil and gas industry as it reduces the demand for fossil fuels used in transportation. This shift towards electric vehicles will create new challenges and opportunities in the energy industry, requiring a comprehensive understanding of the relationship between EVs and energy-related fields. Future research could develop this further by investigating how EV research trends compare to other energy-related fields to better understand the broader implications of EVs on the energy sector. By studying the trends and identifying the uniqueness of EV research, we can develop a comprehensive approach to meet the energy needs of the future while reducing carbon emissions. This can be achieved by analysing and comparing research trends in other domains, such as renewable energy, energy storage, and sustainable transportation. Overall, the relationship between EVs and energy-related fields is complex and multi-dimensional. As such, a comprehensive understanding of this relationship is essential to effectively address the challenges and opportunities posed by the growing adoption of EVs.

We find relatively low international collaboration within EV research compared to other fields. Thus, further efforts can be made to improve this since, generally, research with international collaboration is more impactful than purely domestic studies (Van Raan, 1998). Special efforts should be made to incorporate researchers from emerging economies and developing countries that also need to transition to EVs to reach climate targets. Even from an industrial strategic point of view, international collaboration is required to achieve standardisation, reduce costs, increase interoperability, and ensure safety and reliability for consumers. This requires greater collaboration between governments, industry, and academia to align regulations and incentives with technological advancements and consumer needs.

EV adoption and market development is one of the growing research clusters and is predicted to continue growing given the challenges lying ahead to reach 100% BEV penetration in all markets. While most of the research, so far, has focused on early adopters, more focus is needed on reaching mainstream consumers and laggards. Increased public education and awareness are needed about the benefits of EVs in reducing greenhouse gas emissions and combating climate change. Thus, more research is needed to understand how this is done effectively and relates to attitudes in different socio-demographic groups. Research is also needed on how incentives can be implemented in different markets, the effects on government revenues and expenditures, and how incentives in the end should be phased out.

Closely related to EV adoption and market development is the development of charging infrastructure where we find a growing research activity that is not expected to saturate in the near future given the policy interest among others in the EU with the new Alternative Fuel Infrastructure Regulation (AFIR) mandating the deployment of charging and hydrogen refuelling in its member states. Challenges related to charging infrastructure deployment will be even more prominent with the electrification of heavy-duty vehicles as well.

Our findings are in line with other reviews such as (Broadbent et al., 2022) that identified gaps in the areas of battery technology, charging infrastructure, and policy frameworks to support the uptake of EVs. Other researchers have emphasised the need for interdisciplinary research to address complex issues related to EVs. For instance, in Debnath et al. (2021), it is argued for more research on the social, economic, and political dimensions of EV adoption, including issues related to equity and access to charging infrastructure.

From the research clusters, we find, not surprisingly, that different battery-related research has been central to EV research. Research and development efforts should continue to focus on improving battery technology to continue to decrease the cost of EVs. In addition, increased investment in the recycling and reuse of EV batteries is necessary to reduce waste and minimise the environmental impact of the EV industry. We thus see a continuous need for interdisciplinary research combining areas such as environmental research, chemical and material sciences, and electrical engineering on this topic.

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.

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Appendix A

Appendix. —Clusters of co-cited references in EV research

Cluster ID Descriptor Top terms	Cluster statistics - size - silhouette score - mean year - year range - mean year (citing) - year range (citing)		Influential references Highest local citation count		Strongest citation burst (strength, duration)			Highest centrality		Highest coverage citing articles	
Cluster #0	S	1006	Clement-Nyns et al. (2010)	1165	Kempton et al. (2005a)	86.06	2009–2014	Göransson et al. (2010)	0.02	Mahmoudzadeh Andwari et al. (2017)	50
plug-in electric vehicle systems and modelling	SS	0.799	Kempton et al. (2005b)	725	Clement-Nyns et al. (2010)	73.46	2012–2015			Ahmadian et al. (2020)	49
- plug-in electric vehicle	MY	2012	Lopes et al. (2011)	540	Tomić et al. (2007)	51.96	2008–2016			Chang et al. (2018)	46
- smart grid	YR	1965–2020	Pieltain Fernandez et al. (2011)	536	Lopes et al. (2011)	43.35	2012–2015			Aghaei et al. (2016)	46
- hybrid electric vehicle	MY(citing)	2017	Qian et al. (2011)	505	Sortomme et al. (2011)	40.12	2012–2015			Ashique et al. (2017)	46
- distribution network	YR(citing)	2010–2021	Sortomme et al. (2011)	494	Sekyung et al. (2010)	38.93	2012–2015			Banol Arias et al. (2019)	43
- distribution system			Deilami et al. (2011)	468	Guille et al. (2009)	33.42	2010–2015			Abdalrahman et al. (2017)	40
			Sekyung et al. (2010)	445	Peterson et al. (2010a)	31.3	2011–2014			Arfeen et al. (2019)	38
			Tomić et al. (2007)	403	Rotering et al. (2011)	30.19	2012–2015			Alshahrani et al. (2019)	38
			Gan et al. (2013)	390						Al-Ogaili et al. (2019)	37
Cluster #1	S	485	Chan-Chiao et al. (2003)	428	Chan-Chiao et al. (2003)	51.17	2005–2012	Baumann et al. (2000)	0.02	Ibrahim et al. (2021)	57
power management in EV and HEV	SS	0.874	Salmasi (2007)	307	Baumann et al. (2000)	43.7	2003–2012	Powell et al. (1998)	0.02	Huang et al. (2017)	38
- hybrid electric vehicle	MY	2009	Sciarretta et al. (2004)	295	Schouten et al. (2002)	40.43	2003–2012	Paganelli et al. (2001)	0.02	Alyakhni et al. (2021)	37
- parallel hybrid EV	YR	1970–2020	Namwook et al. (2011)	269	Sciarretta et al. (2004)	36.48	2005–2013	Qiuming et al. (2008a)	0.02	Hu et al. (2021)	36
- energy management	MY(citing)	2016	Sciarretta et al. (2007)	268	Powell et al. (1998)	31.88	2000–2012			Chen et al. (2021)	33
- plug-in hybrid	YR(citing)	2003–2021	Wirasingha et al. (2011)	256	Delprat et al. (2004)	31.84	2005–2013			Biswas et al. (2019)	32
			Borhan et al. (2012)	238	Emadi et al. (2005)	30.29	2005–2013			*Qiuming et al. (2008b)	31
			Pisu et al. (2007)	219	*Guzzella et al. (2007)	27.08	2009–2016			İnci et al. (2021)	30
			Moura et al. (2011)	217	Chau et al. (2002)	26.05	2006–2013			Enang et al. (2017)	30
			Musardo et al. (2005)	209							
			Jinming et al. (2008)	202							
Cluster #2	S	429	Egbue et al. (2012)	451	Nykvist et al. (2015)	21.21	2016–2019	Heffner et al. (2007)	0.02	Coffman et al. (2016)	44
electric vehicle adoption and market development	SS	0.916	Sierzchula et al. (2014)	324	Thiel et al. (2010)	18.08	2011–2016			Brückmann et al. (2021)	41
- electric vehicle adoption	MY	2010	Hidrue et al. (2011)	312	Axsen et al. (2010)	12.83	2012–2016			Ghosh (2020)	39
- consumer preference											

(continued on next page)

(*continued*)

Cluster ID Descriptor Top terms	Cluster statistics - size - silhouette score - mean year - year range - mean year (citing) - year range (citing)		Influential references Highest local citation count		Strongest citation burst (strength, duration)			Highest centrality		Highest coverage citing articles	
- alternative fuel vehicle - empirical study	YR	1962–2020	Rezvani et al. (2015)	290	Cocron et al. (2011)	12.36	2012–2017			Mahmoudzadeh Andwari et al. (2017)	38
	MY(citing)	2018	Pearre et al. (2011)	244	Williams et al. (2012)	11.95	2013–2016			Fazeli et al. (2021)	34
	YR(citing)	1993–2021	Nykvist et al. (2015)	239	Sovacool et al. (2009)	11.6	2015–2017			He et al. (2018)	31
			Graham-Rowe et al. (2012)	203	Bjerkan et al. (2016)	11.6	2010–2015			He et al. (2016)	31
			Carley et al. (2013)	188	Perujo et al. (2010)	11.44	2018–2021			Axsen et al. (2018)	30
			Sovacool et al. (2009)	185			2012–2015			Hardman et al. (2018)	30
			Al-Alawi et al. (2013)	170						Broadbent et al. (2018)	30
Cluster #3 **electric motors and powertrains**	S	409	Chan (2007)	529	Chan (2002)	83.19	2002–2014	Ehsani et al. (1997)	0.02	Das et al. (2017)	23
- reluctance motor - hybrid electric vehicle	SS	0.869	Chan (2002)	339	Ehsani et al. (1997)	37.24	2005–2013			Chan et al. (2010)	22
	MY	2002	Chan et al. (2010)	257	Wipke et al. (1999)	36.52	1999–2012			Chau et al. (2008)	20
- permanent magnet	YR	1963–2017	Chau et al. (2008)	248	Chan (2007)	35.78	2004–2012			*Dang Hoang et al. (2014)	18
- induction motor	MY(citing)	2012	Markel et al. (2002)	202	Markel et al. (2002)	35.58	2008–2014			Chau et al. (2007)	16
	YR(citing)	1996–2021	Zhu et al. (2007)	194	*Chan et al. (2001)	35.38	2005–2012			*Hu et al. (2015)	15
			*Larminie et al. (2003)	172	Chau et al. (2008)	27.89	2003–2013			Estima et al. (2012)	15
			Wipke et al. (1999)	171	Lukic et al. (2004)	26.09	2009–2014			Doucette et al. (2011)	14
			de Santiago et al. (2012)	152	*Larminie et al. (2003)	25.55	2005–2012				
							2005–2013				
Cluster #4 **batteries and battery management**	S	366	Plett (2004)	612	Piller et al. (2001)	30.39	2005–2015			Ibrahim et al. (2021)	48
	SS	0.905	Lu et al. (2013)	406	Peterson et al. (2010b)	29.09	2011–2016			Cuma et al. (2015)	40
- lithium-ion batteries	MY	2009	Chen et al. (2006)	245	Sun et al. (2016)	25.23	2016–2018			Farmann et al. (2015)	35
- battery management	YR	1957–2020	Peterson et al. (2010)	227	Plett (2004)	24.29	2004–2014			Hannan et al. (2017)	34
system- equivalent circuit model	MY(citing)	2016	Hu et al. (2012)	217	Chen et al. (2006)	20.09	2009–2014			Jaguemont et al. (2016)	32
	YR(citing)	2005–2021	Wang et al. (2011b)	203	Hannan et al. (2017)	19.59	2018–2021			Alyakhni et al. (2021)	31
			Vetter et al. (2005)	194	Plett (2004)	19.35	2004–2015			Mahmoudzadeh Andwari et al. (2017)	31
										How et al. (2019)	31
Cluster #5 **fuel cells and hybrid systems**	S	343	Emadi et al. (2008)	326	Emadi et al. (2008)	35.5	2009–2014	Affanni et al. (2005)	0.02	Ibrahim et al. (2021)	40
- hybrid energy storage system - fuel cell	SS	0.897	Tie et al. (2013)	317	Khaligh et al. (2010)	29.86	2012–2016	Amjadi et al. (2010)	0.02	Hoque et al. (2017)	27
- hybrid electric vehicle	MY	2010	Khaligh et al. (2010)	254	Moreno et al. (2006)	21.32	2010–2016			Hemmati et al. (2016)	26
- plug-in electric vehicle- energy	YR	1995–2020	Jian et al. (2012)	245	Lukic et al. (2008)	20.62	2006–2013			Alyakhni et al. (2021)	25
management	MY(citing)	2016	Lukic et al. (2008)	228	Ortuzar et al. (2007)	20.42	2009–2012			İnci et al. (2021)	24

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Cluster ID **Descriptor** **Top terms**	**Cluster statistics** **- size** **- silhouette score** **- mean year** **- year range** **- mean year (citing)** **- year range (citing)**		**Influential references Highest local citation count**		**Strongest citation burst (strength, duration)**			**Highest centrality**		**Highest coverage citing articles**	
	YR(citing)	2005–2021	Moreno et al. (2006)	177	*Judek et al. (2008)	19.33	2008–2015			Mahmoudzadeh Andwari et al. (2017)	23
			Hannan et al. (2014)	146			2017–2021			Ghosh (2020)	23
			Trovão et al. (2013)	112						Das et al. (2017)	20
			Song et al. (2015)	104						Kasimalla et al. (2018)	20
Cluster #6 **in-wheel motors**	S	322	Hori (2004)	319	Hori (2004)	32.81	2005–2015	*Gillespie (1992)	0.03	Chen et al. (2018)	14
and control strategies	SS	0.928	Zeraoulia et al. (2006)	150	Sakai et al. (1999)	30.01	2002–2015			Chen et al. (2019)	14
- in-wheel motor - independent-	MY	2007	Deb et al. (2002)	146	Terashima et al. (1997)	20.64	2003–2014			Goggia et al. (2015)	13
drive electric vehicle	YR	1981–2019	*R (2012)	118	Hori et al. (1998)	19.77	2000–2012			Cao et al. (2017)	13
- direct yaw-moment control-	MY(citing)	2016	Wang et al. (2011a)	112	Zeraoulia et al. (2006)	17.44	2008–2014			Lin et al. (2019)	13
rear wheel	YR(citing)	1999–2021	Sakai et al. (1999)	110	Shimizu et al. (1997)	17.4	1999–2012			De Filippis et al. (2018)	12
			Cong et al. (2009)	97	Mutoh et al. (2007)	14.78	2008–2011				
			Zhai et al. (2016)	87							
Cluster #7 **charging**	S	250	Liu et al. (2013)	237	Xiang et al. (2016)	15.14	2018–2021	Eberle et al. (2010)	0.02	Kchaou-Boujelben (2021)	59
infrastructure - charging station - charging	SS	0.941	He et al. (2013)	223	Dong et al. (2016)	13.31	2018–2021			Asghari and Mirzapour Al-e-hashem, 2021	44
infrastructure - transportation	MY	2015	Dong et al. (2014)	211	Shahraki et al. (2015)	12.92	2018–2021			Fazeli et al. (2021)	27
network - urban area	YR	1974–2020	Sadeghi-Barzani et al. (2014)	183	Zhang et al. (2016)	11.91	2018–2021			Jang (2018)	27
	MY(citing)	2019	Zheng et al. (2014)	162	Sioshansi (2012)	11.46	2014–2017			Aghalari et al. (2021)	25
	YR(citing)	2013–2021	Kuby et al. (2005)	161	Li et al. (2016)	11.2	2017–2021			Bilal et al. (2020)	24
			Wang et al. (2013)	151	Andrenacci et al. (2016)	10.78	2018–2021			Ju et al. (2019)	24
			Lam et al. (2014)	151	Awasthi et al. (2017)	10.65	2018–2021			Ahmad et al. (2017)	23
			Mak et al. (2013)	138						Al-Hanahi et al. (2021)	23
			Frade et al. (2011)	134							
Cluster #8 **environmental assessment**	S	238	Hawkins et al. (2012a)	307	Samaras et al. (2008)	40.57	2009–2015			Asghari and Mirzapour Al-e-hashem, 2021	40
- greenhouse gas emission	SS	0.914	Samaras et al. (2008)	206	Bradley et al. (2009)	28.27	2009–2013			Ibrahim et al. (2021)	40
- life cycle - environmental	MY	2013	Bradley et al. (2009)	166	Stephan et al. (2008)	24.33	2009–2015			Asef et al. (2021)	23
benefit	YRHardman et al. ()	1982–2020	Hawkins et al. (2012b)	142	Shiau et al. (2009)	22.02	2010–2014			Habib et al. (2018a)	19
	MY(citing)	2018	Notter et al. (2010)	140	Silva et al. (2009)	18.9	2010–2014			Haram et al. (2021)	18
	YR(citing)	2010–2021	Wu et al. (2015)	128	Shiau et al. (2010)	13.12	2011–2013			Cusenza et al. (2019)	17
			Neubauer et al. (2014)	127	*Kalhammer et al. (2007)	13.1	2008–2015			Habib et al. (2018b)	17
			Fiori et al. (2016)	108						Franzò et al. (2021)	17

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Cluster ID Descriptor Top terms	Cluster statistics - size - silhouette score - mean year - year range - mean year (citing) - year range (citing)		Influential references Highest local citation count		Strongest citation burst (strength, duration)			Highest centrality		Highest coverage citing articles	
			Nordelöf et al. (2014)	100						Hung et al. (2021)	17
Cluster #9 **wireless charging**	S	235	Siqi et al. (2015)	282	Covic et al. (2007)	19.46	2011–2016			Machura et al. (2019)	51
- dynamic wireless charging	SS	0.988	Wang et al. (2005)	272	Mi et al. (2016)	18.67	2018–2021			Covic and Boys (2013a)	48
- inductive power transfer- wireless power transfer system	MY	2010	Covic and Boys (2013b)	238	Wang et al. (2005)	18.02	2013–2015			Siqi et al. (2015)	43
	YR	1978–2020	Budhia et al. (2013)	233	Sallan et al. (2009)	16.06	2013–2016			Covic and Boys (2013a)	40
	MY(citing)	2017	Budhia et al. (2011)	214	*Madawala et al. (2011)	15.97	2013–2017			Patil et al. (2018)	40
	YR(citing)	2013–2021	Kurs et al. (2007)	177	*Stielau et al. (2000)	14.8	2013–2017			Ahmad et al. (2018)	36
			Shin et al. (2014)	177	Lee et al. (2010)	14.08	2013–2015			Aziz et al. (2019)	32
			Wang et al. (2004)	148						Bi et al. (2016)	32
										Niu et al. (2019)	31
										Mahesh et al. (2021)	30
Cluster #10 **battery chargers**	S	220	Yilmaz et al. (2013)	758	Rahman et al. (1993)	33.47	2010–2015	Chan et al. (1997)	0.06	Khaligh et al. (2012)	17
- DC convertor - integrated battery charger	SS	0.944	Gomez et al. (2003)	176	Hajimiragha et al. (2010)	19.68	2011–2015	Mullan et al. (2011)	0.02	Habib et al. (2018b)	16
- on-board battery charger	MY	2008	Young-Joo et al. (2009)	165	Morrow et al. (2008)	19.32	2010–2014			Khaligh et al. (2019)	15
	YR	1982–2019	Khaligh et al. (2012)	158	Emadi et al. (2006)	17.09	2007–2014			Gu et al. (2013)	14
	MY(citing)	2017	Hajimiragha et al. (2010)	143	Young-Joo et al. (2009)	16.16	2010–2013			Dusmez et al. (2013)	13
	YR(citing)	1999–2021	Emadi et al. (2006)	125	Mapelli et al. (2010)	14.33	2011–2015			Al-Hanahi et al. (2021)	12
			Etezadi-Amoli et al. (2010)	114	Kramer et al. (2008)	13.12	2010–2014				
			Dubey et al. (2015)	113	Kuperman et al. (2013)	13.07	2014–2016				
			Haghbin et al. (2013)	101	Chan et al. (1997)	12.85	1999–2014				
			Rahman et al. (1993)	100	Egan et al. (2007)	12.25	2011–2015				
Cluster #11 **thermal management system**	S	204	Burke (2007)	137	Burke (2007)	32.62	2008–2013	Brown et al. (2010)	0.03	Lu et al. (2020)	31
- thermal management	SS	0.954	Bandhauer et al. (2011)	122	*Husain (2003)	21	2005–2013	Fuller et al. (1994)	0.02	Ibrahim et al. (2021)	28
- heat pipe - thermal performance	MY	2011	Rao et al. (2011)	119	*Tremblay et al. (2007)	15.21	2013–2016	Amjad et al. (2010)	0.02	Bibin et al. (2020)	27
	YR	1965–2020	Jaguemont et al. (2016)	115	Campanari et al. (2009)	13.29	2010–2015	Doyle et al. (1993)	0.02	Lin et al. (2021)	26
	MY(citing)	2018	Mahmoudzadeh Andwari et al. (2017)	113	Hu et al. (2017)	12.68	2018–2021	Hallaj et al. (2000)	0.02	Kumar et al. (2020)	26
	YR(citing)	2002–2021	Doyle et al. (1993)	110	Bradley and Quinn (2010)	11.93	2011–2016			Mali et al. (2021)	25
			Pesaran (2002)	110	Smith et al. (2006)	11.88	2012–2014			Kannan et al. (2021)	25
			*Tremblay et al. (2007)	104	Gu et al. (2000)	11.51	2013–2016			Kim et al. (2019)	23

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			Bernardi et al. (2019)	101							
Cluster #12 **electric-vehicle application**	S	112	Delucchi et al. (2001)	46	*Rand et al. (1998)	11.97	1999–2008	Delucchi et al. (2001)	0.04	Johansson et al. (2000)	18
- EV application - semi-controlled	SS	0.996	*Rand et al. (1998)	18	Lam et al. (2006)	9.05	2007–2011	*Rand et al. (1998)	0.03	McNicol et al. (1999)	18
battery - charging power	MY	1993	Lam et al. (2006)	14	Delucchi et al. (2001)	8.53	2011–2016			Meissner (1997)	12
converter	YR	1962–2011	Cooper (2004)	8	Cooper (2004)	5.3	2005–2009			Ahman (2003)	11
	MY(citing)	2002			Lam et al. (1995)	4.05	1997–2006			Santini et al. (2000)	9
	YR(citing)	1997–2011									
Cluster #13 **battery string**	S	107	Gallardo-Lozano et al. (2014)	75	Kutkut et al. (1999)	10.56	2007–2014			*Park et al. (2007a)	46
and equalizer - series-connected	SS	0.986	Shang et al. (2015)	50	Lee et al. (2005)	10.51	2007–2015			* Park et al. (2007b)	45
battery string coupling-	MY	2004	Lee et al. (2005)	47	Ming et al. (2000)	8.66	2006–2009			Shang et al. (2017a)	25
capacitor equalizer- using	YR	1978–2018	Kim et al. (2013)	35	Kim et al. (2013)	8.55	2015–2017			Shang et al. (2017b)	24
multi-winding transformer	MY(citing)	2014	Lee et al. (2006)	31	Lee et al. (2006)	8.14	2007–2013			Shang et al. (2017c)	24
	YR(citing)	2004–2020	Baughman et al. (2008)	25	Hong-Sun et al. (2009)	7.56	2013–2017			Shang et al. (2017d)	23
			Hong-Sun et al. (2009)	23	Shang et al. (2015)	7.44	2016–2019			*Kimball et al. (2007)	18
			Imtiaz et al. (2013)	21	Chiasson et al. (2005)	7.06	2006–2011				
			Kutkut et al. (1999)	21							
			Kim et al. (2014)	20							
Cluster #14 **balancing algorithm**	S	82	Takahashi et al. (1986)	26	Jahns (1987)	11.12	1996–2014	Bose et al. (1988)	0.02	Chan (1993)	28
- balancing	SS	0.988	Jahns (1987)	23	Takahashi et al. (1986)	11.06	2006–2015	*Ferdowsi (2007)	0.02	Rahman (2007)	22
algorithm - three-level	MY	1996	Rodriguez et al. (2002)	20	Faiz et al. (2003)	7.18	2005–2010				
neutral point - DC-bus voltage	YR	1978–2014	Soong (1994)	18	Jahns et al. (1986)	6.16	2007–2012				
- three-level inverter	MY(citing)	2009	Nabae et al. (1981)	14	Soong (1994)	6.01	2000–2016				
	YR(citing)	1993–2019	Faiz et al. (2003)	11	Buja et al. (2004)	5.95	2007–2010				
			Jahns et al. (1986)	10	Morimoto et al. (1990)	4.59	2000–2009				
			Buja et al. (2004)	9	*Ehsani et al. (2003)	4.57	2005–2010				
			Teichmann et al. (2005)	9	Casadei et al. (2002)	4	2006–2009				
Cluster #15 **routing problem** - routing problem	S	73	Schneider et al. (2014)	199	Yang et al. (2015)	8.77	2018–2021	*Artmeier et al. (2010)	0.02	Asghari et al. (2021)	36
- partial recharge - green mixed fleet	SS	0.98	Erdoğan et al. (2012)	143	Lin et al. (2016)	8.3	2018–2021			Erdelić et al. (2019)	32
vehicle - location-routing	MY	2015	Goeke et al. (2015)	107	**	5.79				Kucukoglu et al. (2021)	31
problem - green vehicle	YR	1987–2020	Hiermann et al. (2016)	103	Liao et al. (2016)	5.11	2017–2019			Keskin et al. (2019)	28
	MY(citing)	2019	Felipe et al. (2014)	102						Qin et al. (2021)	27
	YR(citing)	2016–2021	Keskin et al. (2016)	97						Rastani et al. (2021)	24

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			Yang et al. (2015)	93					Yang et al. (2021)	23
			Montoya et al. (2017)	87					Duman et al. (2021)	23
			Desaulniers et al. (2016)	82						
Cluster #16 **vehicle to grid**	S	26	Kempton et al. (2005a)	803	Kempton et al. (2005b)	101.43	2009–2014		Kempton et al. (2005a)	14
- vehicle-to-grid system	SS	0.992	Kempton et al. (1997)	298	Kempton et al. (1997)	25.44	2010–2014		Kempton et al. (2005b)	12
- wind power integration	MY	2001	Lave et al. (2002)	16	Lave et al. (2002)	6.98	2008–2015		Ben Sassi et al. (2021)	4
- V2G frequency regulation	YR	1996–2007							Lemoine et al. (2008)	4
- small scale energy	MY(citing)	2015							Sachan et al. (2021)	3
management	YR(citing)	2005–2021								

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2023.103881.

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