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Electric vehicles and renewable energy for sustainable mobility: Insights from bibliometric, topic modeling, and societal impact analyses

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ABSTRACT

As the global race to meet the Sustainable Development Goals intensifies, research on electric vehicles (EVs), renewable energy sources (RES), and sustainable mobility has grown significantly. This study provides a comprehensive overview of this evolving field using a novel multi-faceted methodological framework that integrates bibliometric analysis, machine learning-based topic modeling, and societal impact analysis. By combining these approaches, this work uniquely explores both research trends and societal implications. We analyzed 122 articles sourced from the Scopus database using Biblioshiny, the R package, and the Overton database to address four key research questions. Findings reveal growing research interest in EVs and RES, with *Journal of Cleaner Production* and *Renewable and Sustainable Energy Reviews* as the most impactful journals by citations and publication frequency. Keywords have evolved from technology-centric terms like "life cycle assessment" to broader societal concerns, including "sustainable mobility" and "carbon dioxide". Six latent research topics were identified, with EV charging infrastructure and renewable energy integration being the most dominant. However, newer topics, such as sustainable EV adoption policies, are gaining traction. Societal impact analysis further reveals that research in this field significantly informs policy, demonstrating its relevance in driving societal change. However, contradictions between societal and research impacts suggest the need for a concurrent evaluation of both to assess real-world implications. This paper outlines theoretical, practical, and methodological implications, advocating for an integrated approach to assess research and societal impacts. Moreover, the proposed methodology guides future research, offering insights into the interplay between academic inquiry and real-world applications.

1. Introduction

The global pursuit of sustainable development goals (SDGs) faces significant challenges, as evidenced by the recent halfway point assessment report. The report indicates a significant gap between current progress and the targets set for 2030, with only 17 % of targets on track. Climate action goal (SDG 13) is particularly concerning, as greenhouse gas emissions continue to rise despite some reductions in developed countries. While progress in affordable and clean energy goal (SDG 7) is evident in the electricity sector with renewables leading the charge, the transport sector lags behind, necessitating urgent and transformative interventions [1].

SDG 7 and SDG 13 share a critical intersection through renewable energy as shown in Fig. 1, which not only promotes clean energy but also serves as a key solution for reducing carbon emissions. The transport sector, second major contributor to carbon emissions (accounting for 25 % and 32 % of emissions in Europe and the United States, respectively [2–4]), underscores the need for such synergetic solutions. Electric vehicles (EVs) when powered by renewable energy sources (RES), offer a transformative opportunity to bridge the gap between SDG 7 and SDG

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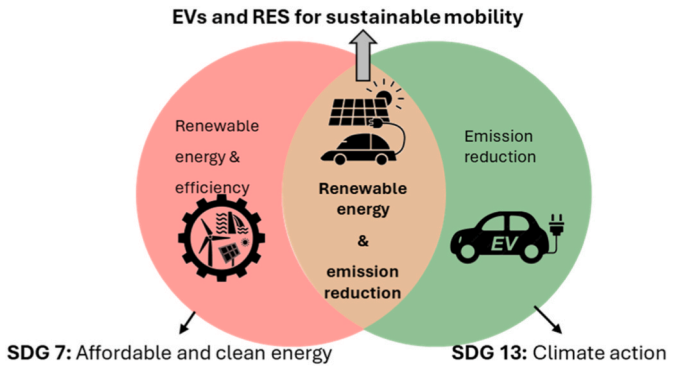

Fig. 1. The role of EVs and RES in supporting SDG 7 & SDG 13.

13 by reducing reliance on fossil fuels and lowering emissions [5–11]. However, realizing this dual benefit requires seamless integration of EVs and RES, which is full of challenges.

The integration of RES with EVs is critical for ensuring that the shift to electric mobility genuinely reduces the carbon footprint rather than transferring emissions from the tailpipe to the power plant. For instance, in Germany, grid bottlenecks and energy distribution misalignments have led to increased renewable energy curtailments and rising re-dispatch costs [12]. Likewise, in the United States, surplus photovoltaic (PV) and wind power during peak production periods is often curtailed due to inadequate storage solutions [13]. These challenges highlight the need for EVs to act as distributed energy storage, balancing intermittent RES supply and grid demand. Addressing these issues is essential to unlock the full potential of sustainable mobility.

Sustainable mobility, defined as transportation systems that are environmentally friendly, economically viable, and socially equitable, relies on the effective synergy between EVs and RES. Given the critical nexus of EVs and RES for sustainable mobility, research in the field of EVs and/or RES has expanded significantly in recent years, driven by the overarching goal of achieving global carbon neutrality and contributing to SDGs. This surge in research has reshaped the research landscape and opened new avenues for exploration [14]. To comprehensively understand the current state of the art, a comprehensive review of the existing body of knowledge is imperative. Such a review will synthesize findings, identify emerging trends, and highlight potential research directions.

Early studies on EVs began appearing in the Scopus database as early as the late 1970s [15,16]. However, a substantial increase in EV-related research and reviews emerged approximately four decades later. This research has encompassed various aspects, including reviews on EVs [17–19], the integration of EVs and RES [20,21] and various other prospectives on sustainable mobility [22–24]. While previous review studies have focused on EVs and/or RES, a comprehensive review of the field is still lacking.

A variety of approaches exist for conducting literature reviews, including narrative, systematic, and bibliometric reviews. While narrative reviews arbitrarily collect evidence on a specific topic to synthesize the existing knowledge, these suffer from thoroughness and risk of bias [25]. On the other hand, systematic and bibliometric reviews are the most prevalent these days. Both approaches are based on a clearly defined research question/strategy, accompanied by transparent justification for the inclusion/exclusion of studies to ensure replicability and/or reproducibility. However, these differ in scope and depth. Systematic reviews, often regarded as the gold standard, provide in-depth analysis of a limited body of literature. Conversely, bibliometric reviews adopt a broader perspective, examining large datasets to identify research trends and patterns. This paper aims to enrich the standard bibliometric review by incorporating a machine learning-based approach. Given the burgeoning utilization of machine learning within bibliometric reviews, it is reasonable to anticipate a paradigm shift from conventional literature reviews towards machine learning-driven approaches in the future [26]. A substantial corpus of literature, including narrative, systematic and bibliometric reviews exist focusing on EVs and/or RES for promoting sustainable mobility. The following subsections describe a few key contributions within this domain, highlight research gaps, and articulate the novel contributions of this study.

1.1. Narrative reviews on EVs and/or RES for sustainable mobility

The history of EVs traces back to the early days of the automobile, yet their widespread adoption has been hindered by limitations in range and expensive battery technology for decades [27]. However, a combination of political support and financial incentives has spurred EV uptake over the past two decades. This growth has consequently stimulated related research, including a substantial body of review literature.

A diverse array of narrative reviews exploring various aspects of EVs can be found in the literature. For instance, authors in Ref. [28] have investigated various factors affecting EV adoption, identifying the lack of public charging infrastructure as a critical barrier. Likewise, other research has highlighted the challenges and opportunities for EV expansion in specific regions, such as Pakistan [29], and explored the reasons behind low adoption rates in developing countries [30]. Recommendations to expedite the expansion of the EV industry are also provided. Additionally, research has examined the impact of economic incentives on EV uptake [31]. Several socio-economic, psychological, and social factors in shaping consumer preferences are also discussed [32]. Technological advancements in EV components, including storage systems, battery management, power electronics, and charging infrastructure, have also been comprehensively reviewed, alongside the exploration of EVs' potential contributions to SDGs [7]. Furthermore, the role of RES in EV charging, and the implications of large-scale EV integration into future smart cities have been subjects of investigation [21,33]. Research trends and future research agenda on conventional and artificial intelligence-based hosting capacity analysis methods for EVs during the last decade are also analyzed in Ref. [24]. Moreover, articles discussing broader aspects of EVs for future green mobility are also available in the literature [14]. While these narrative reviews offer valuable insights, their reliance on author-selected studies rather than systematic search strategies limits their generalizability and potential for bias.

1.2. Systematic reviews on EVs and/or RES for sustainable mobility

Complementing the narrative review approach, a series of systematic reviews have delved into specific EV-related domains.

For instance, a review of 28 articles over five years examined the social aspects of EVs in relation to SDGs, identifying SDG 13 as a current priority and anticipating the growing importance of SDG 11 [8]. Manzolli et al. conducted a systematic literature review of 445 articles published between 2008 and 2020 on electric bus vehicles, exploring main research streams, methods, and gaps in the field [19]. Schvartz et al. examined 430 articles to identify factors influencing EV purchase decisions in the Brazilian market, finding environmental performance to be a key motivator while highlighting charging times, autonomy, and infrastructure as barriers [34].

Another aspect of EVs, life cycle assessment, has been reviewed to offer understanding of their environmental impact, energy usage, and resource utilization [35]. After analyzing 122 articles, the authors emphasized the potential for additional emissions reduction through extended lifespans and advanced battery technologies. Moreover, a study examining the grid integration implications of increased EV adoption and charging infrastructure analyzed 724 papers from Web of Science (WoS) and IEEE Xplore, identifying seven research topics for future investigation [36].

The above overview demonstrates that systematic reviews are typically conducted on a particular aspect of a research subject. These

studies, therefore, provide a deeper understanding of a narrowly defined subject. Bibliometric reviews, however, provide a more comprehensive perspective on a broader subject. A summary of bibliometric reviews on EVs and/or RES research is given in the following section.

1.3. Bibliometric reviews on EVs and/or RES for sustainable mobility

The advent of information technology has facilitated the growth of bibliometric reviews, enabling a broader examination of research fields. The EV domain is no exception, with a proliferation of bibliometric studies. These studies have encompassed various EV subtopics, including energy management strategies for hybrid and electric vehicles [17,37], the energy efficiency and environmental impact of EVs [38], the dynamics of EV adoption [39], integration of RES and EVs within power systems [20,40–42], motivators and barriers of EV adoption [43], the emission reduction potential of EVs [44], and the broader social, economic, and environmental implications of EV adoption [23]. These studies have typically analyzed a few hundred articles, providing valuable insights into specific aspects of EV research.

Some bibliometric studies have adopted a more expansive approach, aiming to capture the overall landscape of EV research. For instance, studies analyzing over 29,000 [18], 3962 [22], 10,426 [45], 17,150 [46], 34,000 [47], and 2180 [48] articles have offered overviews of EV trends and developments across different time periods. These studies covered current trends in EV research with a more general focus.

1.4. Research gap and key contributions

It is evident that there is a significant number of review articles that try to encapsulate the recent trends in individual aspects of EV research. As summarized in Table 1, these studies have explored diverse topics, including energy management, environmental impact, and adoption factors. Although these contributions provide valuable insights, a notable gap exists in comprehensively examining the nexus between EVs and RES within the context of sustainable mobility. Only a limited number of studies have partially addressed this topic, with a focus on either narrative reviews or bibliometric analyses of specific aspects [20,21].

Furthermore, existing review studies often rely on either titles, keywords, abstracts, or citations for analysis, limiting their ability to capture the full depth and breadth of research within the field. To the best of our knowledge, none of the review articles consider the full text of the articles in their analysis. To bridge the gap and enrich the existing body of knowledge, this paper aims to make a contribution in this direction. Alongside this, we aim to present a comprehensive review of the subject using a machine learning approach. There is a significant potential for “machine learning-based review”, an emerging trend in big data research, given the current capacity of bibliometric databases and the rapid advancement of machine learning algorithms [26]. This approach leverages text mining algorithms to reveal latent topics, addressing key limitations of traditional bibliometric reviews, which primarily focus on macro trends but often overlook nuanced insights within the field. By revealing latent topics, machine learning enables a deeper understanding of the state of the art in addition to identifying research trends. While bibliometric reviews excel in mapping trends and key contributors, the machine learning approach categorizes extensive corpora of literature into fewer, coherent topics, offering advantages similar to systematic reviews. A few studies have also recognized this as an effective method to combine the strengths of systematic and bibliometric reviews [49,50]. Despite its potential, no bibliometric study complemented by a machine learning approach to uncover latent topics in EV and RES research has been reported to date. This gap highlights the novelty and importance of this study in advancing understanding within this field.

Besides this, the impact of research in traditional bibliometric analysis is determined by the number of citations or the impact factors of the

Table 1
Review articles on EVs and/or RES.

Ref.	Key contributions	Approach	Databases(s)	Sample/ Year range
[17]	The analysis of research trends on energy management approaches for hybrid EVs is conducted using bibliometrics.	Bibliometric review	WoS	575/1998-2014
[29]	Significant challenges associated with the adaptation of EV in Pakistan are highlighted and suggestions for the rapid expansion of the EV industry across the country are provided.	Narrative review	-	-
[8]	Social aspects of EVs in relation to SDGs are discussed.	Systematic review	WoS	28/2015-2019
[37]	Optimized energy management approaches for EVs are reviewed and future trends are identified.	Bibliometric review	Scopus	100/2010-2021
[7]	Key technological advancements in storage systems, battery management systems, power electronics and charging infrastructure for EVs are presented. In addition, various SDGs associated with the EV applications are explored.	Narrative review	-	-
[19]	Research on electric bus is comprehensively reviewed to unveil main research streams, methods and gaps of field.	Systematic review	Scopus, WoS	445/2008-2020
[18]	The main themes related to EVs in current research are quantitatively analyzed.	Bibliometric review	WoS	29304/ 2000-2021
[45]	Various technical, social and economic factors relevant to EVs in the last three decades are discussed.	Bibliometric review	WoS	10426/ 1989-2020
[36]	The impacts of adding EVs and charging stations on the grid reliability are discussed.	Systematic review	WoS, IEEE Xplore	724/no restriction on year
[21]	EV’s charging infrastructure, the role of RES as a viable charging alternative, utility interest and associated challenges and opportunities are comprehensively reviewed.	Narrative review	-	-
[46]	Trends in EVs research during last decade are reviewed.	Bibliometric review	Scopus	17150/ 2011-2022
[38]	The energy efficiency and impacts of emission reduction of EVs are investigated through bibliometric analysis.	Bibliometric review	Scopus	403/2003-2022
[39]	Thematic patterns of EVs adoption in transition to sustainable transportation are	Bibliometric review	Scopus	1800/2011-2022

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Table 1 (*continued*)

Ref.	Key contributions	Approach	Databases(s)	Sample/ Year range
	comprehensively reviewed and analyzed.			
[47]	Scholarly trends in EVs research during last three decades are identified.	Bibliometric review	WoS	34000/ 1990-2021
[20]	A bibliometric evaluation on the integration of RES and EVs into power systems is carried out.	Bibliometric review	Scopus, WoS, Google Scholar, IEEE Xplore	175/2009-2023
[30]	Various reasons for low adoption rate of EVs in developing countries are identified and suggestions to stimulate the adoption are provided.	Narrative review	-	-
[24]	Conventional and AI-based hosting capacity analysis methods for EVs are reviewed and future directions are provided.	Narrative review	Scopus, Google Scholar	2014–2023
[14]	Various types of EVs, charging infrastructures, methods for charging and types of storage systems are evaluated for future green mobility.	Narrative review	-	-
[33]	The impact of high number of EVs in future smart cities is investigated and various advantages and bottlenecks are described.	Narrative review	-	-
[34]	Various factors of influencing purchase decisions of EVs in Brazil market are reviewed.	Systematic review	Scopus, WoS, Science Direct	430/2018-2022
[35]	Life cycle assessment of EVs is systematically reviewed to offer insights into their environmental impact, energy usage, and resource utilization.	Systematic review	Scopus	122/2012 onwards
[43]	The most influential factors that affect the consumers' intention to adopt EVs are reviewed.	Bibliometric review	Scopus, WoS, Science Direct, Google Scholar, ProQuest	537/2011-2022
[44]	The future of EVs is assessed and analyzed with respect to emissions reduction capacity and various adoption drivers.	Bibliometric review	WoS	63/1989-2023
[23]	EV adoption with regard to economic, social and environmental factors is discussed and various societal, policy and managerial implications are provided.	Bibliometric review	Scopus	191/2003-2023
[22]	Evolution of electric mobility in Kuwait during last two decades is analyzed.	Bibliometric review	Scopus	3962/2000 onwards
[48]	Bibliometric, thematic and content analyses of sustainable green logistics and its subdisciplines are conducted.	Bibliometric review	Scopus	2180/2008-2023

journals. While these indicators are effective for assessing research impact within the academic community, they do not provide a comprehensive evaluation of the research's influence on society broadly. The societal impact can be measured by examining how research in a specific field is being referenced or utilized in policy-making and regulatory frameworks. To the best of our understanding, none of the review articles found in the literature discussed this particular aspect. This paper is the first to address the societal impact of research in addition to the academic impact.

There has been a significant surge in interest in EVs and RES research on Scopus. The growing interest in the topic highlights the importance of capturing current trends in a thorough and comprehensive manner. Our research intends to provide a comprehensive review of the nexus of EVs and RES for sustainable mobility by employing a machine learning approach to discover latent topics. This will be achieved by analyzing the full text of the articles. Furthermore, we aim to evaluate the societal impact of research. This is accomplished through an analysis of policy documents to identify citations to research pertaining to the topic. To guide this investigation, the following four research questions have been formulated.

RQ#1: What is the distribution of research interest and impact within the EVs, RES, and sustainable mobility domain? Furthermore, who are the most productive contributors to this field?

This research question will allow us to understand the interest and impact of the scientific community in this topic, as measured by publication volume, citation analysis, and journal impact factors. It will also help to identify which authors and countries are the most influential in shaping the EV and RES research field.

RQ#2: How have research keywords evolved over time?

Through this question, we will be able to understand the trends and shifts in keyword usage over the study period.

RQ#3: What are the latent topics within the EVs and RES field and their evolution over time?

Bibliometric analysis hides significant informational value. Extensive insightful information could be revealed by analyzing topic prevalence of extracted topics using a machine learning-based text mining approach. Based on the synthesis of findings, we tried to identify research gaps and future research directions for this field.

RQ#4: What is the societal impact of EVs and RES research, as evidenced by its uptake in policy and practice?

This will help in highlighting the practical implications of research on policy making.

To summarize, this study offers both practical and methodological contributions.

- From a methodological standpoint, the methodology presented in this work is both adaptable and scalable, making it applicable to any research field and sample size. By systematically analyzing trends

and research topics in the field of EVs and RES, this study identifies key contributors, trends and shifts in research priorities, and the societal impact of research. The value of this systematic assessment is further validated by highlighting research gaps and providing actionable future directions that guide researchers, policymakers, and industry stakeholders.

- Practically, this review provides a comprehensive and up-to-date overview of the EV and RES research landscape, aligning its findings with the global agenda of sustainable development. In particular, the study underscores the relevance of EVs and RES in achieving SDG 7 and SDG 13. As global efforts to meet SDGs intensify, especially in the areas of sustainable mobility and climate action, understanding the nexus between EVs and RES for sustainable mobility is both timely and essential. This study thus serves as a valuable resource for identifying pathways toward a more sustainable future.

The remainder of this paper is structured as follows: Section 2 outlines the methodology employed for data collection, selection, and analysis. Section 3 presents the findings in response to the above research questions. Research implications are explored in Section 4. Research limitations are discussed in Section 5, and Section 6 concludes the paper by summarizing the key findings.

2. Materials and methods

The multi-faceted methodological framework for this research is outlined in four steps in Fig. 2. First, the process for data collection and selection is elucidated. Next, we outline the methodology for conducting bibliometric analysis on our dataset. The subsequent section provides a detailed description of the machine learning approach employed for topic modeling. The process for analyzing the societal impact of our research is presented at the end.

2.1. Data collection and selection

The first step in any research is planning, which entails choosing relevant keywords, structuring the search string, and selecting a suitable database for retrieving articles. In this study, the relevant keywords, including “electric vehicles”, “renewable energy”, and “sustainable mobility”, were identified. Additional keywords such as “renewable”, “solar”, “wind”, “clean energy”, “sustainable transportation”, and “green mobility” were also included to broaden the search scope. The search string was constructed as follows:

Search string: ("electric vehicles") AND ("renewable energy" OR "solar" OR "PV" OR "photovoltaic" OR "Wind" OR "renewable power" OR "renewable") AND ("sustainable mobility" OR "sustainable transportation" OR "low-carbon transportation" OR "green mobility").

After selecting the keywords and search string, the next step involves choosing the appropriate database. Presently, Scopus is considered one of the most extensively utilized databases, along with Google Scholar and WoS. Scopus is particularly notable for its wide indexing of documents and ability to offer more granular information [51]. This database indexes over 94 million documents from more than 29,000 serial titles and over 330,000 books [52]. Therefore, we selected this as the primary data source for this study. A search was conducted on May 31, 2024, utilizing the predefined search string within the titles, abstracts, and keywords of Scopus-indexed documents. This initial search yielded 340 records.

Subsequently, a rigorous screening process was applied based on publication year (2014–2024), document type (journal articles and review papers), and language (English). This process resulted in the exclusion of 195 records. A subsequent title and abstract screening phase led to the elimination of an additional 17 records deemed irrelevant. The final stage involved a.

full-text assessment of the remaining articles, resulting in the exclusion of 16 records. The final dataset comprised 122 articles, with their metadata exported in CSV format for subsequent analysis (it is

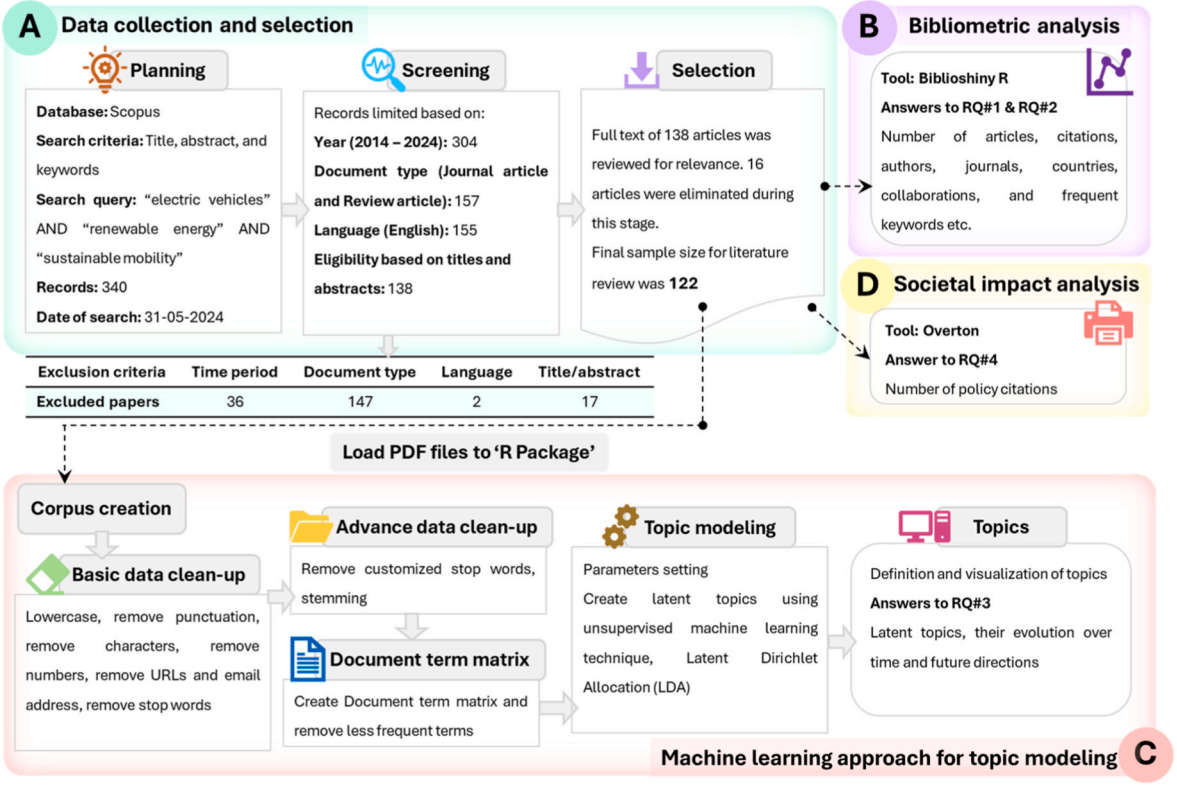


Fig. 2. Multi-faceted methodological framework for this research.

provided in supplementary data). Furthermore, the full text of the articles was saved in PDF format to identify research domains, as explained in the following sections. The flow of information during the data collection and selection step is depicted in Fig. 2.

2.2. Bibliometric analysis

As illustrated in Fig. 2, the subsequent step involved conducting a bibliometric analysis. Biblioshiny, an R-based software package, was employed to facilitate data import, exploration, and visualization [53]. The previously exported CSV file containing metadata of the 122 selected articles is imported into Biblioshiny. This file typically includes title, authors, abstract, keywords, publication year, journal, document type, and other relevant metadata. This imported data is then cleaned to ensure accuracy and consistency. This involves correcting inconsistencies in author names and standardizing publication years.

While meta-analysis is a valuable method for aggregating quantitative data across studies, it was not applicable to our research due to the nature of the data. Our study is based on bibliometric indicators such as metadata, citation counts, and document-level attributes, rather than quantitative effect sizes or numerical outcomes. Therefore, we employed bibliometric analysis to explore research trends and patterns, measures of research output over time, academic impact (citations, journal impact factors), author productivity, country contributions, and keyword analysis. The evolution of keywords over time was also examined. The results obtained from the bibliometric analysis were interpreted in relation to the above-defined research questions, enabling the identification of emerging trends, research gaps, and potential areas for future research.

2.3. Machine learning approach for topic modeling

To complement the traditional bibliometric analysis, a machine learning-based approach was employed to uncover latent topics within the selected document corpus. Conventionally, topic identification for review articles has been a manual process, demanding significant time investment and domain expertise. Recent advancements in machine learning have facilitated the development of automated topic modeling techniques, reducing human intervention and error [26]. Topic modeling, an unsupervised machine learning approach, has been widely applied to analyze text data from various sources, including social media, news articles, and books. However, its application within academic research, particularly for identifying research topics, remains relatively underutilized despite its potential to streamline the review process and enable the analysis of large datasets.

Given the potential of topic modeling to reveal underlying topics within the corpus, Latent Dirichlet Allocation (LDA) was selected as the method for this study due to its widespread adoption and simplicity [54–56]. The topic modeling was performed in R that is an open-source tool for statistical computing and graphics. The following packages were utilized for text analysis and visualization: pdftools, tm, SnowballC, dplyr, servr, topicmodels, stringr and ldavis. The following stages outline the topic modeling process using LDA (also depicted in Fig. 2).

Corpus creation – The full text of the selected articles was extracted from PDF format using the pdftools library in R. At this stage, all papers were converted to plain text, with images and tables removed. The resulting data contains 122 rows, with each row corresponding to one document from the final selected dataset.

Basic data clean-up – Following the corpus creation, the subsequent step is to clean the data. This was achieved by using the tm library. The basic data clean-up involves standard steps such as tokenization, lowercasing, and the removal of punctuation, characters, numbers, URLs, email addresses, and English stops words.

Advance data clean-up – Customized stop words, which are words that have a general meaning, were eliminated during the advance data clean-up step. These terms include "need," "use," "studies," "review," "gap," "paper," "article(s)," and "author.", among others. This is followed by stemming, which is the process of truncating words to their original base terms.

Creation of document term matrix (DTM) – Subsequently, we created a DTM that represents the frequency of each word in each document. At this stage, we removed rare terms, i.e., the terms that appeared less than five times in the whole corpus. This was done to reduce the computational burden, as the results were not substantially affected by the removal of rare terms. The resulting DTM contains words with semantic information ready to be used for LDA method.

Application of LDA for topic modeling – The LDA model was applied to the reduced DTM using the topicmodels library. The definition of the number of topics, k, is a prerequisite for the LDA method. There are two ways of selecting k: by calculating specific metrics, such as the perplexity score, and by relying on expert opinion. We used the perplexity score to evaluate the model performance in terms of clustering the document texts into meaningful topics. Based on the results, we selected the value of k.

Having determined the value of k, LDA was implemented in R using the Gibbs sampling method. Due to the probabilistic model, we discarded the first hundred iterations. The LDA was executed five times, with the best result saved each time. For reproducibility, the list of seeds is as follows: (3, 98, 749, 4861, 558331). The application of LDA resulted in a group of similar words, which created topics. Terms with varying frequencies were present in each topic, and a single term could appear in multiple topics. The probability of each document being associated with each topic was determined. The outcome was a 122 by k matrix of topic probabilities. The final assignment of the document to the topic was based on the highest probability value. The output is the data file with assigned topic to each document. This was then analyzed in Microsoft Excel for further synthesis of the results.

Definition and visualization of topics – Following the LDA, it was necessary to provide a sufficient description of the topics. Give the terms and their estimated term frequency (ETF) in each topic, a combination of terms and a title review was used to define the topic names. Having named the topics, these were visualized with the inter-topic distance map using the ldavis library.

2.4. Societal impact analysis

Building upon the traditional bibliometric analysis, this study delved into the societal impact of the research articles within the selected corpus, complementing the exploration of academic impact discussed in Section 1. Policy documents serve as valuable data sources for assessing research's influence on policymaking [57]. By tracking citations to the identified research articles within policy documents, we aimed to evaluate the extent and nature of their impact on policy development.

Altmetric.com and Overton databases offer capabilities for tracking policy document citations. However, Overton is recognized for its superior coverage and broader range of information sources, encompassing government documents, think tanks, non-governmental organizations, and intergovernmental organizations [58]. Consequently, Overton was chosen for collecting policy citations in this study [59]. The DOIs of the articles, previously retrieved during the data collection stage, served as the input for this analysis.

After the retrieval of policy citations, the data was organized in a Microsoft Excel spreadsheet for further analysis. To quantify the societal impact of the research, three indices proposed in Ref. [60] were employed: coverage, density and intensity. Coverage represents the percentage of publications within the corpus that have received at least one citation from a policy document. Density reflects the average number of policy document citations received by all publications, including both those cited and not cited in policy documents. Intensity signifies the average number of policy document citations received by publications that have been cited at least once in policy documents. This analysis extended beyond these core indices. The study also investigated

the most influential contributors to societal impact, including articles, prominent journals, and associated countries. Additionally, the characteristics of research articles cited within policy documents were explored to gain deeper insights into the type of research driving policy decisions. We also provided qualitative insights into how the cited articles influence policymaking and societal change by analyzing the themes of policy sources where these articles have been cited.

The following section provides a comprehensive overview of the findings from each of the above-mentioned analyses.

3. Results and discussion

The dataset for this study comprised 122 articles published between 2014 and 2024, primarily consisting of peer-reviewed journal articles (94 %). These articles were disseminated across 70 journals, exhibiting an annual growth rate of 13 %. The corpus included a total of 453 author keywords and 920 index keywords, generated by 420 individual authors. While a small proportion of articles (7.4 %) were authored by single authors, a significant level of global collaboration (27 %) was observed. The subsequent sections delve into the research findings, organized according to the research questions.

3.1. *RQ#1: what is the distribution of research interest and impact within the EVs, RES, and sustainable mobility domain? Furthermore, who are the most productive contributors to this field?*

3.1.1. *Distribution of research interest over time*

The distribution of research interest in EVs and RES research over time is depicted in Fig. 3, illustrating a clear upward trend. This positive trajectory reflects the growing interest of the scientific community in this field. Notably, approximately 60 % of the articles were published between 2021 and May 2024, up to the date of data extraction. To project the number of publications for the entire year of 2024, a third-order polynomial was fitted to the data, with the corresponding equation and R^2 value displayed on the graph. Based on this model, the number of publications in 2024 is expected to reach 39. This forecast highlights the ongoing and growing interest that EVs and RES continue to draw in academic research.

3.1.2. *Distribution of research impact*

Research impact is typically measured by the number of citations and journal impact factors. At the time of data extraction, the selected papers had received a total of 3843 citations, averaging 31.5 citations per article. In terms of journal impact factors, 16 % (20) of the articles were published in journals without an impact factor, while the remainder appeared in journals with impact factors ranging from 0.8 to 16.3.

To better understand the research impact of EVs and RES in sustainable mobility, we focused on the most influential journals in which this work was published. Table 2 presents an overview of the top ten journals ranked by total citations. Additionally, the table includes the impact factor of each journal, the number of published articles, citation efficiency (citations per article), and the citations of the top-cited paper within each journal. Among the top-performing journals by total citations, the *Journal of Cleaner Production* leads with 598 citations, highlighting its significant influence in this field. *Renewable and Sustainable Energy Reviews* follows with 426 citations from just five papers, demonstrating a high citation efficiency that underscores its authority. Other notable journals include the *International Journal of Hydrogen Energy* and *Energy*, which also show high citation counts, indicating their importance in the research landscape.

When considering citation efficiency, *Applied Energy* emerges as the leader, followed by the *International Journal of Hydrogen Energy*. *Renewable and Sustainable Energy Reviews* averages 85.2 citations per paper, reflecting the high impact of papers published in this journal. Conversely, Sustainability and Energies, despite having published 7 and 9 papers respectively, have moderate citation counts, suggesting they are more accessible but less impactful compared to journals with higher impact factors.

To further illustrate these findings, Fig. 4 depicts the relationship between the number of papers, total citations, and impact factors, with the impact factor represented by the size of the bubble. The *Journal of Cleaner Production* not only has the highest total citations but also a substantial number of published papers, underscoring its pivotal role in the field. Similarly, *Renewable and Sustainable Energy Reviews* is prominent due to its high citation count, impact factor, and publication frequency.

Fig. 5 illustrates the impact of individual research articles, showing the citations of the most-cited articles alongside the respective journals and years of publication. The most-cited article is published in the *International Journal of Hydrogen Energy* receiving 300 citations so far, followed by articles in *Energies* and the *Journal of Cleaner Production*. While it is generally perceived that older articles accumulate more

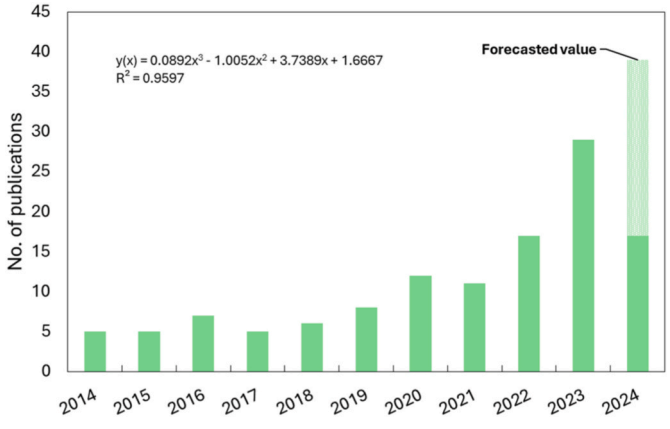


Fig. 3. Distribution of research interest.

Table 2
Top journals with the highest impact on the field.

Journal	Total citations[a,b]	Impact factor	No. of papers	Citation efficiency	Top paper citations[a]/ Ref.
Journal of Cleaner Production	598	9.7	15	39.87	169/[61]
Renewable and Sustainable Energy Reviews	426	16.3	5	85.20	127/[62]
International Journal of Hydrogen Energy	364	8.1	3	121.33	300/[63]
Energy	343	9	5	68.60	107/[64]
Applied Energy	247	10.1	2	123.50	166/[65]
Sustainability (Switzerland)	236	3.3	7	33.71	111/[66]
Energies	217	3	9	24.11	176/[67]
International Journal of Life Cycle Assessment	183	4.9	2	91.50	124/[68]
Sustainable Production and Consumption	162	10.9	2	81.00	144/[69]
IEEE Transactions on Sustainable Energy	101	8.6	1	101.00	101/[70]

[a] As of date of extraction.
[b] Total citations for the selected papers published in these journals.

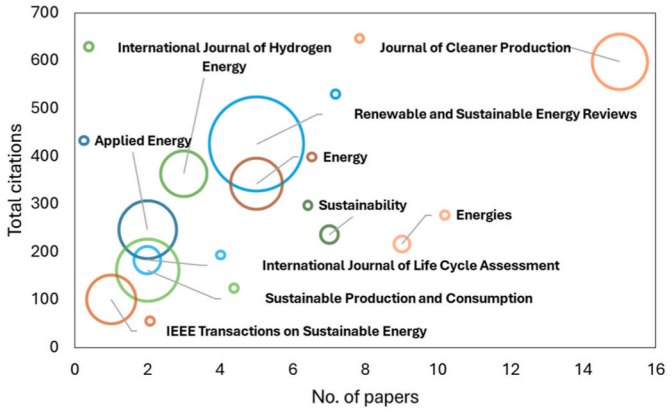


Fig. 4. The relationship between the number of papers, total citations, and impact factors of the journals. The size of the bubble reflects the impact factor of the journal.

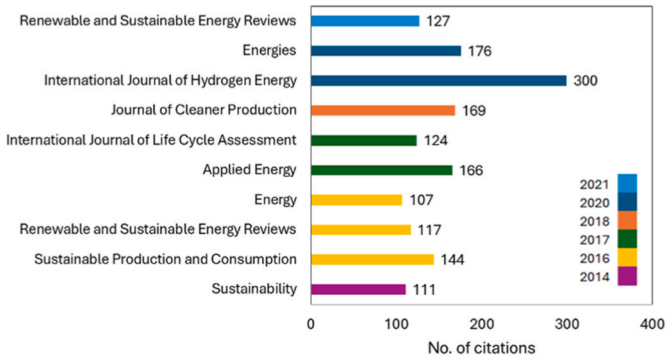


Fig. 5. The citations of the most cited papers and respective journals.

citations, Fig. 5 demonstrates that newer articles can also achieve high citation counts when they have a significant research impact. It is important to mention that the societal impact of research is not explored here. It will be discussed in the following sections.

3.1.3. *The most productive authors*

The selected dataset includes contributions from 420 unique authors. Notably, 93.8 % of these authors published only one article on EVs and RES research, highlighting a dynamic and evolving research landscape with many new contributors entering the field. The remaining 6.2 % of authors published multiple papers: 4.8 % contributed two papers, while 1.4 % authored three or more. Fig. 6 illustrates the publication history of authors with more than three publications. Among them, Kucukvar M. emerges as the most prolific, with seven publications, followed by Onat N.C. with six. Additionally, Brenna M. demonstrates consistent productivity over the years, whereas Zhang H. appears to be a new entrant to the field with recent publications.

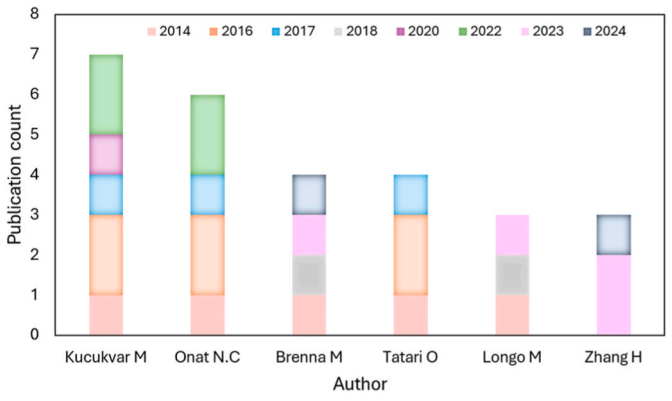


Fig. 6. Top authors production over time.

The analysis also reveals a strong trend of collaboration within this research area. Approximately 7.4 % of the articles were authored by a single individual, 19.7 % involved two authors, and 18 % featured three authors. The remaining articles were co-authored by four or more researchers, with some publications including up to 11 authors. The predominance of multi-authored publications underscores the interdisciplinary nature of this field and the importance of collaborative efforts. The trends in international collaboration along with the most productive countries in this area, are discussed in the subsequent section.

3.1.4. *The most productive countries*

To analyze the geographic distribution of publications, each article was attributed to a country based on the corresponding author's address. The analysis indicates that 122 publications originated from authors in 33 different countries. Notably, 15 countries (45.4 %) contributed only one publication each, while 15 % and 18 % of the countries published 2 and 3 articles, respectively. The remaining 21 % of the countries produced more than 3 publications. Fig. 7(a) highlights the countries with more than 3 publications, as well as the distribution between single-country publications (SCP) and multiple-country publications (MCP).

India and Italy emerge as the most productive countries in this field, each with 13 publications. However, international collaboration, as reflected by MCPs, is more prevalent in India. The United States also demonstrates substantial contributions, with an equal distribution between SCPs and MCPs. In addition to examining the most productive countries, we analyzed the most influential countries based on total citation counts, as shown in Fig. 7(b). The United States leads in terms of total citations, although it has a relatively lower average citation count per article. Interestingly, while Turkey is not among the most productive countries, it holds a significant position in terms of research influence, ranking second in the list of influential countries.

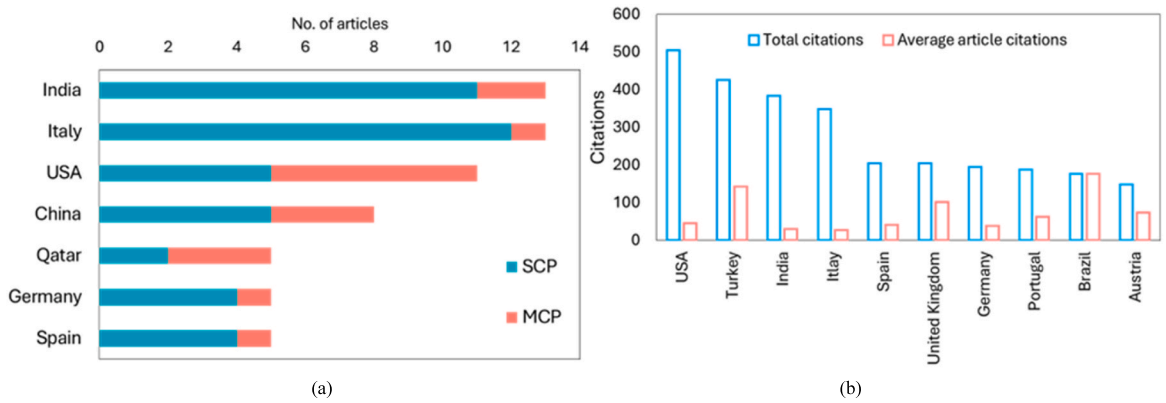
This analysis suggests that while some countries, like India and Italy, are highly productive in terms of publication volume, others, such as the United States and Turkey, exert substantial influence through their research impact. This highlights the importance of both collaboration and quality in advancing the field of EVs and RES for sustainable mobility, underscoring the role of international cooperation in enhancing the global reach and impact of research outputs.

By examining the distribution of research interest, research impact, and the contributors within the field of EVs and RES for sustainable mobility, we have comprehensively addressed our first research question.

3.2. ***RQ#2:*** *how have research keywords evolved over time?*

To answer this research question, we segmented our dataset into three distinct time periods: 2014–2017, 2018–2021, and 2022–2024. The thematic evolution of keywords within these time spans is depicted in Fig. 8. Terms such as "electric vehicles" and "vehicle EVs" appear consistently across all three periods, indicating their centrality to the research domain. Conversely, certain keywords like "dynamic programming" and "cycle assessment" have waned over time, reflecting a decline in their relevance. A strong thematic link is observed between "renewable energy" in the 2014–2017 period and "electric vehicles" in the 2018–2021 period, indicating a well-established and growing focus on the integration of RES with EVs. The emergence of new keywords like "carbon dioxide" and "sustainable mobility" in the later periods points to an increasing concern with environmental impacts and sustainability within the research field.

This thematic evolution highlights a shift from technology-centric topics, such as "dynamic programming" and "battery charging",



(a) (b)

Fig. 7. Top countries in this field: (a) The most productive countries, (b) The most influential countries.

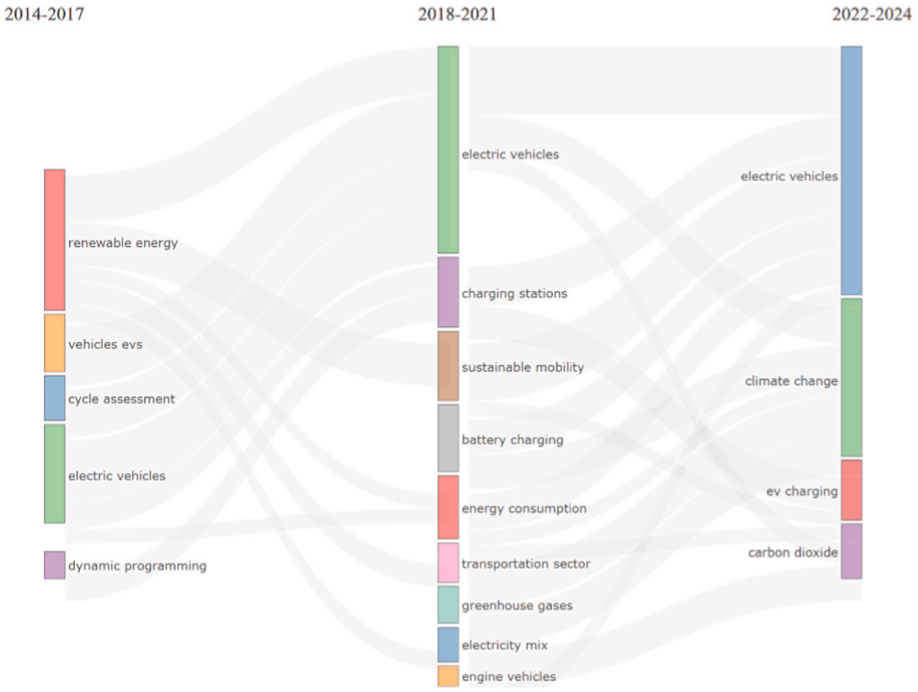


Fig. 8. Thematic evolution of keywords within the EVs and RES research domain, categorized across three time periods (2014–2017, 2018–2021, 2022–2024).

toward broader environmental and societal issues like "climate change" and "sustainable mobility". While foundational concepts, particularly those related to EVs, remain central, the research focus has gradually broadened to address more complex challenges related to sustainability and societal impact. Overall, this visualization highlights the dynamic nature of research in EVs and RES for sustainable mobility. It illustrates the persistence of core topics along with the emergence of new themes, emphasizing the changing priorities in the field. It emphasizes the importance of addressing both technological innovations and their broader implications for society and the environment. This analysis successfully answers our second research question.

3.3. RQ#3: what are the latent topics within the EVs and RES field and their evolution over time?

3.3.1. Results of topic modeling approach

In alignment with the methodology detailed in Section 2, latent topics within the research landscape of EVs and RES were identified using the machine learning approach, LDA. Before applying LDA, the optimal number of topics, denoted by the parameter k, was determined by computing the perplexity score. We conducted this computation by varying k from 2 to 20 in increments of 1. The results, illustrated in Fig. 9, indicate that $k = 6$ was chosen as the most suitable number of

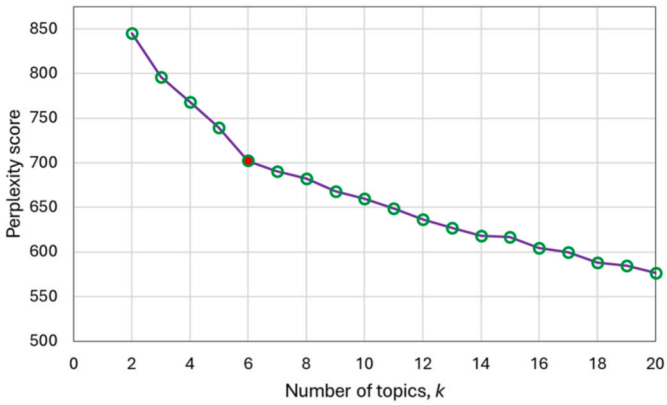


Fig. 9. Perplexity score for various values of k.

topics, as this value corresponds to the most significant drop in perplexity, thereby indicating substantial improvement in model performance.

With the value of *k* determined, LDA was executed, resulting in the identification of distinct groups of related terms, referred to as topics. The probability of each document belonging to a particular topic was calculated, and documents were subsequently assigned to the topic with the highest probability. The inter-topic distance map, along with the top terms and their respective ETF for each topic, is presented in Fig. 10. Each topic is represented by a uniquely colored circle, where the size of the circle corresponds to the number of publications categorized within that topic (see Fig. 10(a)). The number of papers per topic is also indicated at the bottom of the inter-topic distance map. The topics identified by LDA are notably distinct and sufficiently heterogeneous, allowing for clear differentiation between them.

As previously mentioned, topic assignment is based on the highest probability value. For instance, a paper might have a 30 % probability of belonging to Topic 1 and a 35 % probability of belonging to Topic 2. In such cases, the paper would be assigned to Topic 2. This probabilistic approach can lead to some overlap between topics, as reflected in Fig. 10 (a).

Fig. 10(b) illustrates the top ten terms associated with each topic, alongside their corresponding ETFs. It is important to note that these terms are presented in their stemmed forms, e.g., "electr" for "electrical" and "sustain" for "sustainable" or "sustainability". Given the centrality of EVs, RES, and sustainability to the research domain, these terms are prevalent across multiple topics. Based on the structure of terms and their frequencies within each topic, as previously discussed, we proceeded to assign descriptive names to the topics. This process involved analyzing both the terms in Fig. 10(b) and the titles of the papers included within each topic. The final results are summarized in Table 3, which lists the theme of each topic along with the corresponding papers. The temporal evolution of these topics and a detailed discussion of their implications will be presented in subsequent sections.

3.3.2. *Evolution of topics over time*

The categorization of topics using the LDA method has enabled a detailed analysis of the evolution of research themes over time, particularly in terms of the number of publications reflecting research interest. The results of this analysis are presented in Fig. 11, which illustrates the trends in research focus across different topics. These trends can be classified into three categories: rising, stable, and declining.

Rising topics exhibit an increasing trend in research interest over

Table 3
Themes for topics identified by LDA.

Topic	Theme	Papers
1	Life cycle sustainability and environmental impact assessment of EVs	[62,66,68,69, 71–79]
2	Technological advancements in EV charging infrastructure and renewable energy integration	[65,67,70, 80–115]
3	Emission reduction through EVs and renewable energy utilization	[21,61,63, 116–135]
4	Optimal energy management of EVs within renewable energy systems	[136–148]
5	Challenges and policies for sustainable EV adoption	[149–158]
6	Sustainable mobility and the economic viability of EVs	[64,159–181]

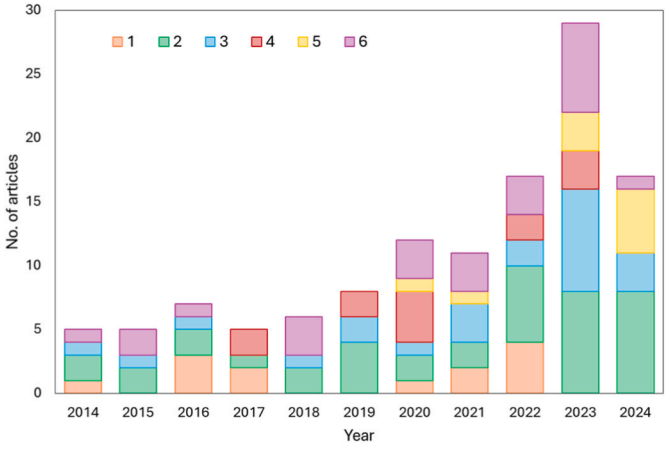
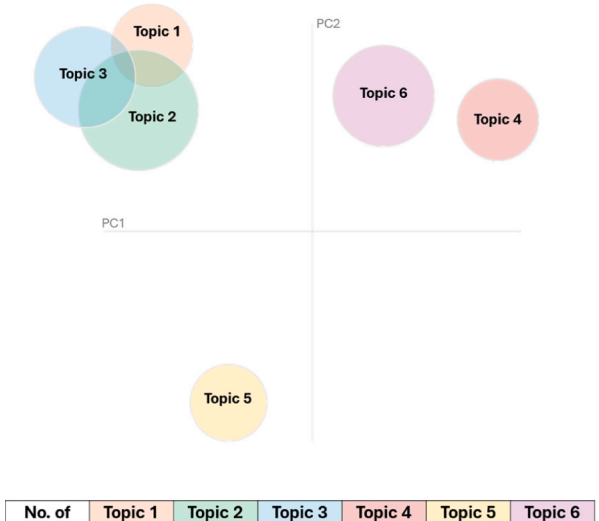
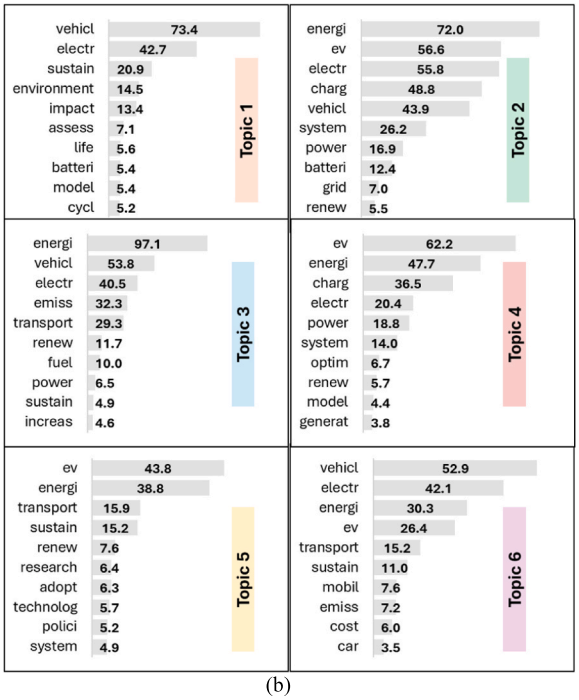


Fig. 11. Evolution of topics over time.



No. of papers	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6
	13	39	23	13	10	24

(a)



(b)

Fig. 10. Results of topic modeling using LDA method: (a) Inter-topic distance map, (b) Terms and their ETF within each topic.

time, signifying a growing focus within the academic community. This category contains Topic 6 and Topic 5 (denoted by purple and yellow colors, respectively). Topic 6 shows a significant rise in publications, especially from 2018 onwards, potentially reflecting the global emphasis on sustainable mobility and the economic aspects of EV adoption. Likewise, Topic 5 has shown substantial growth in recent years, indicating an increased focus on the challenges, strategies, and policies essential for the sustainable adoption of EVs.

Stable topics have maintained a consistent presence throughout the years, indicating their continued relevance in the field. This category includes Topic 2 and Topic 3 (colored in green and blue, respectively). The stability of Topic 2 underscores the ongoing importance of developing robust charging infrastructure for EVs, while Topic 3 reflects a sustained interest in emission reduction through the integration of EVs with RES.

Declining topics are those that have seen a decline in the number of publications over time, suggesting a shift in research focus. This is evident in Topic 1 and Topic 4 (shown in orange and red color, respectively). This decline suggests a move away from focused studies towards broader integration challenges, as mentioned in keywords also.

Overall, the observed trends suggest an evolving research focus that increasingly encompasses emission reduction, sustainable adoption, and integration strategies. These findings align with the evolving keywords within the field of EVs and RES, as discussed in the previous section.

3.3.3. *Discussion of topics*

This section provides an in-depth review of the research themes listed in Table 3. If necessary, each theme is segregated into sub-themes based on the content of the articles within each theme. Based on the findings of each theme, we suggest one potential future research direction. Fig. 12 summarizes the themes, sub-themes, and potential direction for future research for each theme. In this figure, each theme can be recognized by a unique color and sub-themes are shown below each theme. A summary of each topic is given below.

Topic 1: Life cycle sustainability and environmental impact assessment of EVs

Topic 1 focuses on the comprehensive environmental implications of EV adoption, spanning the entire lifecycle from production to end-of-life disposal. This topic also provides guidance for policymaking and decision processes aimed at fostering the sustainable adoption of EVs. To delve deeper into the literature, this topic is further segregated into two sub-themes: life cycle sustainability assessment and environmental impact assessment.

The life cycle sustainability assessment approach evaluates EVs across multiple sustainability dimensions: environmental, economic, and social. Numerous studies have utilized various decision-making frameworks and hybrid models to assess these dimensions, with a particular focus on the full life cycle of EVs, i.e., from manufacturing through to battery disposal. Notably, much of this research comes from the same group of authors who examine EV sustainability across different regions. For example, the authors in Refs. [69,73,74] applied multi-criteria decision-making frameworks to assess the sustainability of EVs by considering various indicators. Besides this, battery degradation and second-life management have emerged as critical factors in life cycle sustainability assessment studies, as indicated by Ref. [68], which highlights the importance of sustainable management of EV batteries to minimize environmental impact in the long run.

The second sub-theme, environmental impact assessment, centers on evaluating the global warming potential, emissions, and overall environmental efficiency of EVs compared to traditional internal combustion engine vehicles. These studies also explore the influence of the regional electricity mix on the environmental performance of EVs. For instance Ref. [79], assesses EV efficiency across 27 European countries, illustrating how the composition of electricity sources (renewable vs. fossil-based) affects the net environmental benefits of EVs. The findings within this sub-theme generally indicate that while EVs outperform internal combustion vehicles in terms of operational emissions, their environmental impact during the production phase, particularly in battery manufacturing, can offset these benefits. The integration of RES is therefore critical for ensuring that EVs serve as a long-term solution for reducing greenhouse gas emissions, as demonstrated by Ref. [77].

The research contributions in Topic 1 collectively underscores the need for integrated policy approaches that focus on life cycle management, battery sustainability, and renewable energy integration to fully leverage the potential of EVs in reducing global emissions. Based on the discussion of topic 1, one potential future research direction can be the

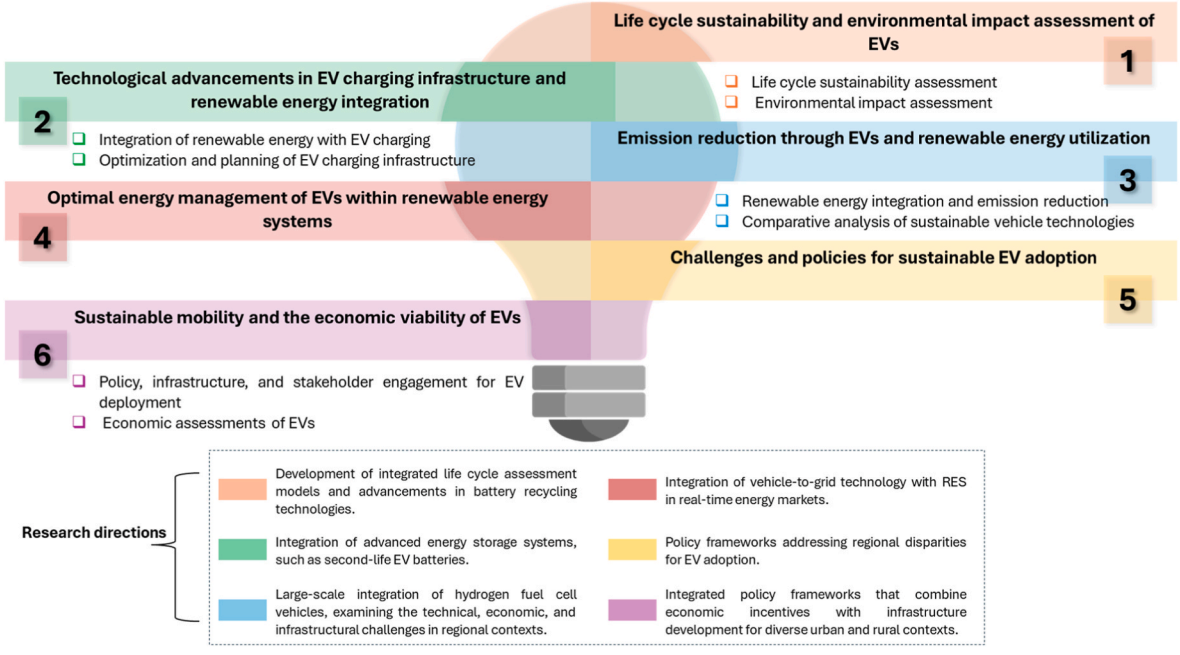


Fig. 12. Research themes, sub-themes and future research directions.

development of integrated life cycle assessment models that account for regional variations in energy sources and advancements in battery recycling technologies.

Topic 2: Technological advancements in EV charging infrastructure and renewable energy integration

Topic 2 revolves around the intersection of RES integration with EV charging infrastructure, as well as the optimization and planning of charging systems. This is the largest group based on the number of publications (as shown in Fig. 10(a)), indicating the highest research interest within this domain. To further explore the topic, we classified this topic into two sub-themes: integration of renewable energy with EV charging and optimization and planning of EV charging infrastructure.

The integration of renewable energy with EV charging sub-theme addresses how RES, such as PV and wind, are integrated into EV charging systems to promote sustainable mobility. Various articles in this category emphasize the use of PV systems and distributed energy sources to power EV charging stations, such as in Refs. [65,70,84,98]. Overall, research in this sub-theme highlights the potential of RES in creating more sustainable EV infrastructure, with innovations like battery storage systems and bidirectional charging, and second-life EV batteries further enhancing energy management and efficiency.

Second-life EV batteries, repurposed from old EVs, offer a promising solution for enhancing the sustainability of EV infrastructure. These batteries can be utilized as stationary energy storage to store excess renewable energy during periods of low demand and supply it back to charging stations during peak hours, improving grid stability and reducing dependency on non-renewable energy sources. For example, studies like [68] demonstrate the potential of second-life batteries to lower the environmental impact of energy storage by extending their life cycle. However, the widespread use of second-life EV batteries is not without challenges. Key issues include the variability in the remaining capacity and performance of these batteries, which can affect their efficiency and reliability in large-scale applications.

The second sub-theme focuses on technical, economic, and environmental aspects of designing and managing EV charging networks. Authors employ various optimization models and algorithms in this domain to determine the optimal placement of charging stations and the efficient use of energy storage systems. For example, the authors in Refs. [87,88,96,101,113] present optimization frameworks to minimize the costs and energy usage of public EV charging stations as well as wireless charging infrastructures, often considering grid constraints and renewable energy integration. Research in this sub-theme highlights the importance of strategic planning and optimization in supporting the growing adoption of EVs, ensuring that charging infrastructure can meet future demands while remaining sustainable.

To conclude, the findings suggest that the combination of RES with advanced energy storage technologies, including second-life EV batteries, and smart, well-planned charging systems has the potential to significantly enhance the sustainability of the transportation sector. Future research directions could include exploring the development of efficient repurposing processes for second-life batteries, improving their performance in renewable energy storage, and addressing logistical and regulatory challenges to facilitate their integration with renewable energy-powered EV charging networks.

Topic 3: Emission reduction through EVs and renewable energy utilization

The research in this topic includes a comparative analysis of various vehicle technologies, such as EVs, hydrogen fuel cell vehicles, and plug-in hybrid vehicles, while also exploring the synergies between these technologies and RES. The sub-themes in this topic include renewable energy integration and emission reduction and comparative analysis of sustainable vehicle technologies.

The first sub-theme, renewable energy integration and emission reduction, explores how RES, especially hydrogen and PV, can be integrated into the transportation sector to curb emissions. Multiple studies have analyzed the potential of hydrogen as a sustainable fuel source. For instance Ref. [63], provides a comprehensive analysis of hydrogen's role in mitigating global emissions, emphasizing its higher energy density compared to conventional batteries, making it a promising solution for long-haul and heavy-duty transportation. Similarly, paper [133] highlights the potential of hydrogen by offering a techno-economic perspective on hydrogen-based fuel cell vehicles, emphasizing the importance of both renewable and non-renewable energy sources in making hydrogen a viable transportation fuel. Additionally, the article [120], highlights the significance of renewable energy integration with EVs, particularly when aiming to reduce carbon emissions on a global scale. However, several challenges impede the widespread adoption of hydrogen fuel cell vehicles, such as high costs associated with production, storage and distribution remain a significant barrier. In addition, infrastructural limitations, including the scarcity of hydrogen refueling stations, restricts its scalability in many regions [63,120,133]. Besides these, advancements in smart charging infrastructure are essential to fully leverage the synergy between EVs and RES [21,182].

The second sub-theme, comparative analysis of sustainable vehicle technologies, analyzes the environmental performance of various vehicle types. For example [61,121], compare the life cycle impacts of different vehicle technologies to assess their long-term sustainability. Similarly, the paper [116] offers a holistic evaluation of different vehicle technologies, highlighting their potential to decarbonize transportation systems. The studies within this sub-theme emphasize the importance of life cycle assessment in understanding the environmental impacts of EVs, from production to end-of-life.

Overall, the research contributions in Topic 3 underline the need for integrating RES with vehicle technologies and continuing comparative assessments to inform future policy and technological developments aimed at reducing global transportation emissions. Based on these findings, future research agenda could focus on the large-scale integration of hydrogen fuel cell vehicles with renewable energy grids, addressing technical challenges such as high production costs, while also exploring strategies to overcome infrastructural and economic barriers in different regional contexts.

Topic 4: Optimal energy management of EVs within renewable energy systems

This topic explores the techniques for optimizing the charging and energy management of EVs within renewable energy systems, focusing on both environmental and economic efficiencies. The research in this area addresses the integration of RES, such as PV and wind power, into EV charging infrastructure, with a strong emphasis on minimizing costs, reducing emissions, and improving system reliability.

Several studies propose optimization frameworks and stochastic models to handle the inherent uncertainties in RES and EV demand. For example, two-stage stochastic optimization and multi-objective planning methods are applied to determine the cost-minimal and energy-efficient charging of EVs at public stations equipped with PV systems [139,142,145]. These approaches consider various factors, including charging station locations, availability of distributed generators, and impact on unbalanced distribution networks. In addition, advanced approaches such as predictive discrete event modeling and deep reinforcement learning have been employed to develop more effective EV charging schedules in microgrids [138,146]. Moreover, some studies have analyzed the profit maximization for workplace charging station owners, aiming to balance the financial returns of providing charging services with the environmental benefits of renewable energy usage [140]. Beside this, recent technological advancements in vehicle-to-grid technologies, such as peer-to-peer energy trading are reshaping energy management frameworks by providing new opportunities for

bidirectional energy flows and system-level optimizations [147]. Incorporating vehicle-to-grid systems enables EVs to act as mobile energy storage, enhancing grid reliability and accommodating higher shares of RES integration. Similarly, advancements in energy storage technologies improve the cost-effectiveness of managing renewable energy intermittency, making the integration of EVs and RES more seamless.

To conclude, this topic highlights the importance of advanced optimization techniques and control methods for integrating EVs into renewable energy systems, considering both economic and environmental concerns. The studies collectively emphasize the need for intelligent, decentralized energy management systems to accommodate the growing demand for EVs while leveraging RES for sustainable transportation solutions. A potential future research direction in this aspect could involve exploring the integration of vehicle-to-grid technology with RES in real time energy markets.

Topic 5: Challenges and policies for sustainable EV adoption

Topic 5 encompasses the multifaceted challenges and policies associated with the adoption of EVs for sustainable transportation. This body of research highlights regional disparities in EV adoption, emphasizing the need for tailored approaches to address unique socio-economic, infrastructural, and policy challenges.

For example, emerging markets like India, Nigeria, and Indonesia face barriers such as limited renewable energy integration and inadequate EV infrastructure, as highlighted in Refs. [153,156,158]. In Indonesia, the transition to a renewable energy grid capable of supporting EVs represents a critical challenge, mirroring broader regional concerns. The role of social and behavioral factors is another crucial dimension. The authors in Ref. [149] explore the societal norms and behaviors that hinder the widespread uptake of EVs, suggesting that shift in public perception and transportation habits is essential for the successful adoption of EV technologies. This ties in with the broader challenge of driving societal change to support sustainable transportation, a point highlighted in Ref. [152] also, which examines the socio-economic and infrastructural challenges in the Nigerian context.

From a technological standpoint, research [155,157] underscores the need for innovations in smart energy management and renewable energy systems to facilitate EV integration, especially in regions with underdeveloped energy infrastructures. These advancements are key to overcoming the technical barriers hindering sustainable adoption. The integration of alternative fuel vehicles into existing transportation infrastructure presents another challenge, particularly in the areas of charging infrastructure development, grid capacity management, and consumer acceptance [156]. Addressing these issues requires coordinated policy interventions, including incentives for private and public investment in charging networks, grid modernization, and consumer awareness campaigns to build trust about these vehicles.

In addition, global trends like urbanization, changing consumer preferences, and advancements in renewable energy technologies are expected to further shape the future trajectory of road passenger transport [150]. Urbanization increases the demand for sustainable transportation systems, particularly in densely populated areas, making EV adoption critical for alleviating congestion and reducing carbon emissions. The integration of RES into EV infrastructure offers a promising path to further decarbonizing the transportation sector, while shifting consumer preferences toward cleaner mobility options highlights the need for policies that align with emerging societal expectations.

Overall, the research contributions in Topic 5 highlight that while there is significant potential for EVs to contribute to sustainable road transportation, their widespread adoption is contingent on several factors. In this context, future research should prioritize understanding the socio-economic and policy contexts of underrepresented regions to bridge regional disparities. Expanding studies to address region-specific challenges, such as infrastructure limitations, policy inefficiencies, and financial barriers, will help promote equitable energy transitions and enhance EV adoption globally. Furthermore, the effectiveness of policy instruments, such as CO_2 taxes, fuel subsidies, and vehicle registration incentives, in achieving long-term reductions in emissions from the transportation sector, requires deeper exploration. Community-based energy systems, tailored to regional needs, could also provide scalable models for sustainable mobility. Moreover, future research could explore how urbanization trends, including the development of smart cities and AI-enabled transport systems, influence the sustainability and efficiency of mobility solutions. Assessing the socio-economic implications of digitalization will provide insights into harnessing these innovations effectively for equitable energy transitions.

Topic 6: Sustainable mobility and the economic viability of EVs

This topic highlights key areas that drive the adoption and integration of EVs into transportation systems. The evaluation of this topic is organized into two sub-themes: policy, infrastructure, and stakeholder engagement for EV deployment and economic assessments of EVs.

The first sub-theme includes research that explores the role of policies, infrastructure development, and stakeholder participation in the deployment of EVs. Papers in this category address the complexities of public and private sector collaboration in enhancing EV adoption. For instance Ref. [64], discusses key drivers in urban EV adoption, highlighting the need for strategic policy frameworks and infrastructure investment. Several studies examine specific regional initiatives, such as [164], providing insight into policy effectiveness in different contexts. The importance of public perception, as well as the role of electric mobility in public transportation systems, is emphasized in works like [162]. Emerging technologies such as autonomous vehicles have the potential to accelerate the adoption of EVs and other sustainable transportation modes. These can improve the operational efficiency of EV fleets, reduce ownership costs through shared mobility models, and support urban sustainability goals by optimizing traffic flow and reducing energy consumption. Overall, the research in this sub-theme underscores that robust policy measures, combined with effective stakeholder engagement, are critical to creating a sustainable EV ecosystem.

The second sub-theme focuses on the comparative environmental and economic evaluations of EVs in contrast to conventional vehicles. The economic viability is analyzed through various lenses, including life cycle assessments and cost-benefit analyses. Papers such as [161,166] evaluate the environmental benefits of EVs while assessing economic trade-offs. Additionally, research such as [176] offers insight into how different use cases impact the economic sustainability of EVs. These studies emphasize the importance of a holistic understanding of both environmental and financial aspects in promoting sustainable mobility through EVs.

Addressing socio-economic impacts, EV adoption also challenges traditional automotive flexibility, requiring collaborative efforts from stakeholders to mitigate disruptions. For instance, transitioning to EVs may lead to job displacement in conventional automotive sectors. However, it offers opportunities for workforce re-skilling in battery production, EV maintenance, and renewable energy integration, as emphasized in Ref. [181]. Government revenue streams dependent on fossil fuel taxes may require restructuring, as alternative approaches like electricity taxation or mileage-based fees are gaining importance. Additionally, issues related to energy security, especially in regions dependent on fossil fuels, require the development of strategies for the integration of renewable energy sources and the improvement of domestic storage systems. Stakeholder attitudes toward these challenges, as highlighted in Ref. [181], reveal the importance of flexible, coordinated policy frameworks that balance technological, economic, and societal goals.

The interplay between policy frameworks and economic incentives

emerges as a critical factor in supporting the widespread adoption of EVs while addressing sustainability goals. Future research could prioritize investigating the effectiveness of integrated policy frameworks that combine economic incentives with infrastructure development tailored for diverse urban and rural contexts. Additionally, future studies could explore strategies to address socio-economic challenges arising from the transition to EVs, such as workforce transitions, fiscal restructuring, and renewable energy integration.

We were able to identify latent topics within the field of EVs and RES for sustainable mobility by employing an unsupervised machine learning approach, LDA. The evolution of the topics and content of the articles within each theme was also analyzed. This answered our third research question.

*3.4. **RQ#4:** what is the societal impact of EVs and RES research, as evidenced by its uptake in policy and practice?*

3.4.1. Overall trend

The societal impact of research can be gauged by its influence on policy, which is reflected in the number of citations received from policy documents. Using the Overton database, we retrieved policy citations for our dataset. As of August 17, 2024, an analysis of the 122 articles within the corpus reveals that 17 of these publications have been cited in policy documents. This results in a coverage of 13.9 %, indicating that approximately one in seven articles has contributed to policy development. Furthermore, four of these cited articles have been recognized in multiple policy documents, with one publication receiving as many as eight citations. The average number of policy citations per article across the entire corpus, referred to as density, stands at 25.4 %. This suggests that, on average, each article in the dataset has been cited 0.254 times in policy documents.

For those articles that have been cited at least once in policy documents, the intensity is calculated to be 1.82. This implies that, on average, each of these influential publications has garnered nearly two policy citations. These metrics collectively highlight that the research on EVs and RES for sustainable mobility is significantly informing and shaping policy, underscoring the field's relevance in driving societal change.

3.4.2. The most influential contributors to societal impact and comparison with research impact

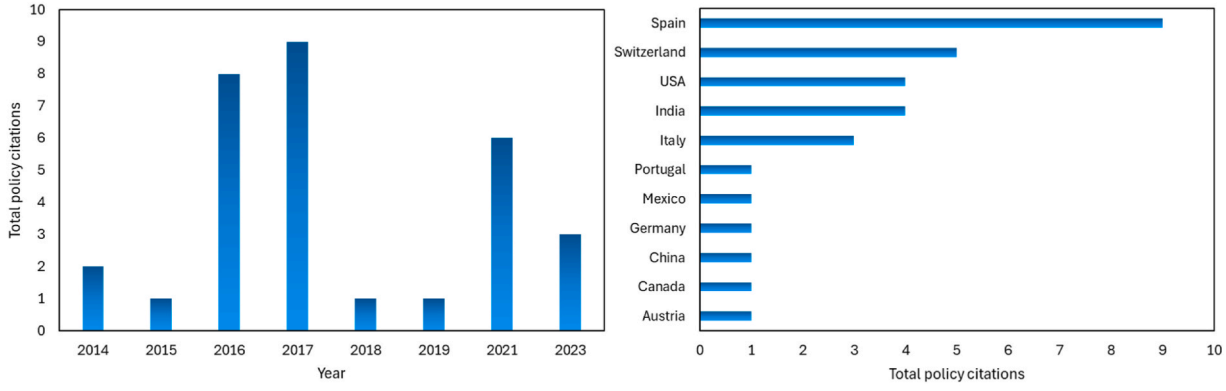
To identify the most influential contributors to societal change, we organized the documents according to the number of policy citations. Fig. 13 represents the overall trend in total policy citations over time and by country. The figure highlights peaks in policy involvement during the years 2016 and 2017 (Fig. 13(a)). Additionally, Fig. 13(b) reveals Spain, Switzerland, and USA, India, and Italy as leading countries, emphasizing the prominent role of these countries in driving policy impact. The policy cited documents are presented in Table 4, along with the year of publication, number of policy citations, citations from Scopus-indexed documents, the journal of publication, and the country of the corresponding author. Consistent with findings from other studies, older articles have generally accumulated more policy citations. However, exceptions exist; for instance, an article from 2023 [175] has also received two policy citations, greater than the policy citations of older articles published in 2014 [66,70].

Interestingly, five articles highlighted in Table 4 are also listed in Table 2, indicating that some highly cited articles are also recognized in policy documents. Nevertheless, discrepancies between research impact

Table 4
Documents with policy citations.

Ref./Year	No. of policy citations	Citations[a]	Journal	Country
[68]/2017	8	**124**	The International Journal of Life Cycle Assessment	Spain
[71]/2016	5	59	The International Journal of Life Cycle Assessment	Switzerland
[99]/2021	3	55	Journal of Energy Storage	India
[175]/2023	2	18	Journal of Operations Management	USA
[66]/2014	1	**111**	Sustainability	USA
[70]/2014	1	**101**	IEEE Transactions on Sustainable Energy	Italy
[174]/2015	1	24	Transport and Sustainability	Germany
[64]/2016	1	**107**	Energy	Austria
[119]/2016	1	37	Energy	Canada
[84]/2016	1	117	Renewable and Sustainable Energy Reviews	Portugal
[65]/2017	1	**166**	Applied Energy	Italy
[80]/2018	1	15	The Electricity Journal	USA
[87]/2019	1	39	IET Power Electronics	India
[75]/2021	1	57	Journal of Cleaner Production	Spain
[121]/2021	1	64	International Journal of Hydrogen Energy	Italy
[168]/2021	1	6	World Electric Vehicle Journal	Mexico
[133]/2023	1	61	Renewable and Sustainable Energy Reviews	China

[a] As of 31-05-2024. These are the citations received from Scopus-indexed documents.



(a) (b)

Fig. 13. Total number of policy citations: (a) Over time, and (b) By country.

(as measured by citations and journal impact factors) and societal impact (as measured by policy citations) are evident.

The three most cited articles in the corpus [61,63,67] have not received any policy citations. Additionally, journals such as the *Journal of Cleaner Production* and *Sustainability*, which contribute significantly to the corpus with 15 and 7 articles respectively (as shown in Table 2), have only one article each cited in policy documents. Notably, the second most contributing journal, *Energies*, with 9 articles, has not received any policy citations. Conversely, *the International Journal of Life Cycle Assessment*, with a moderate impact factor and only 2 articles in the corpus, has received the highest policy citations—8 and 5 citations for [68,71] respectively. Similarly, the *Journal of Energy Storage*, which contributed just one article [99], accumulated 3 policy citations.

Furthermore, articles with fewer citations and those published in journals with lower impact factors, such as [80,168], have still received policy citations, as shown in Table 4. These findings suggest that traditional metrics of research impact, like journal impact factors and citation counts, do not fully capture the societal influence of research. The societal impact, as reflected in policy citations, should be considered to provide a more comprehensive picture of research impact.

In addition to analyzing citations and journals, we examined the countries contributing to policymaking. The USA, Italy, Spain, and India are among the top contributors to policy within the field of EVs and RES for sustainable mobility. These findings partially align with previous results identifying the most productive and influential countries (as shown in Fig. 7). However, Mexico also appears among the countries contributing to policymaking (represented in Fig. 13(b) also), despite not being listed as one of the most productive or influential countries in previous analyses.

Overall, the findings reveal contradictions between research impact and societal impact. Therefore, both dimensions should be evaluated together to accurately assess the real impact of research within a field. The characteristics of the articles making an impact on policy within the field of EVs and RES are discussed next.

3.4.3. Characteristics of articles making societal impact

By analyzing the distribution of articles with policy citations across different topics, we can better understand how various research streams are driving societal change and shaping policy frameworks. The results are presented in Fig. 14. The highest concentration of policy-cited articles is found in Topic 2, which accounts for 35 % of the total distribution. This suggests that research in this area is significantly contributing to the development of policies related to technological advancements in EV charging infrastructure, underscoring its strong connection to practical applications and societal impact. It is important to note that this prominence may also be partially attributed to the larger number of publications within Topic 2, increasing the likelihood of citations.

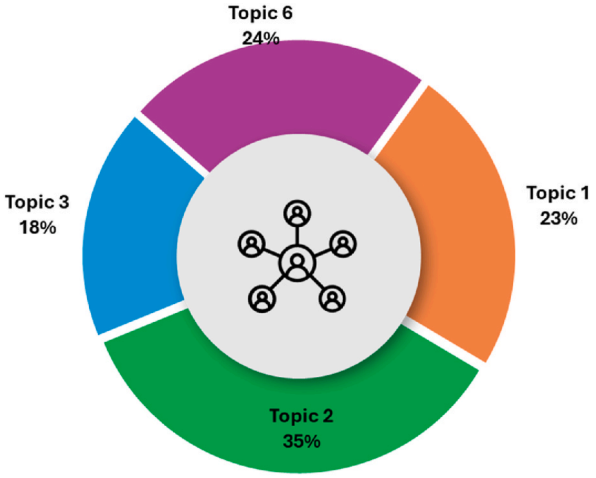


Fig. 14. Distribution of articles with policy citations across different topics.

Topic 1, which focuses on the life cycle sustainability and environmental impact assessment of EVs, also plays a substantial role in informing policy. This is likely because both Topic 1 have reached a level of maturity and development that allows them to exert considerable influence on policy frameworks. These findings align with earlier analyses of keywords and research topics, which indicate a decline in new research in this area due to significant growth and maturity over the years.

In addition, Topic 3 and Topic 6 show notable contributions to policy, albeit to a lesser extent. However, it is worth noting that Topic 4 (optimal energy management of EVs) and Topic 5 (challenges and policies for EV adoption) are absent from the distribution of articles with policy citations. Despite their importance in advancing EV technologies and promoting sustainable mobility, these topics seem to have less influence on policy discussions at present. This may indicate that these areas are still developing or that their policy implications have not yet been fully explored. The absence of these topics from policy-cited research highlights a potential opportunity for future work to focus on the policy dimensions of optimal energy management and the challenges related to EV adoption, potentially bridging the gap between technological innovations and policy implementation.

The qualitative insights on how these policy-cited articles have been influential in policy development and societal change are discussed below.

3.4.4. Qualitative insights on the societal impact of these articles

In our study, we analyzed policy sources where the cited articles have been referenced, moving beyond citation counts to explore the contextual and societal impact of research findings. By analyzing the themes and regional influences of these references, we identified diverse contributions to advancing sustainable mobility goals. Table 5

Table 5
Policy-cited documents, corresponding policy sources, and key policy themes.

Ref.	Policy sources	Policy themes
[68]	[183–190]	Advancing circular economy goals, shaping battery regulations, and promoting innovation in battery second-life applications.
[71]	[185, 191–194]	Enhancing life cycle standards, sustainable consumer practices, and resource efficiency in transport policies.
[99]	[195–197]	Supporting Sweden's battery swapping feasibility and transport electrification strategies.
[175]	[198,199]	Scaling manufacturing capacity for vehicle fleet transitions and aligning with SDG decarbonization goals.
[75]	[200]	Providing data on life cycle environmental impacts and vehicle trade-offs.
[121]	[201]	Shaping hydrogen adoption strategies and comparing alternative vehicle technologies.
[64]	[202]	Informing EV charging infrastructure investments and urban consumer incentives.
[80]	[203]	Supporting off-peak charging policies to reduce grid stress and enhance EV adoption in India.
[87]	[204]	Integrating advanced energy storage and wireless charging into UK defense logistics.
[65]	[205]	Advancing distributed energy integration and sustainable charging solutions.
[119]	[206]	Repurposing EV batteries for energy efficiency and renewable energy integration.
[168]	[207]	Developing shared mobility frameworks, such as EV taxi co-operatives.
[133]	[208]	Addressing environmental and economic challenges in the Arab region.
[84]	[209]	Evaluating plug-in EV impacts on power networks in Australia's regional adoption programs.
[70]	[210]	Promoting PV-based charging for transport decarbonization in urban areas.
[174]	[211]	Analyzing user preferences to design sustainable mobility services.

summarizes the documents cited in policy, the corresponding policy sources, and the policy themes.

For instance, insights from Ref. [68] have played a significant role in advancing European policy frameworks by shaping circular economy goals, developing battery regulations, and promoting innovation in battery second-life applications. Similarly [71], has contributed to enhancing life cycle assessment standards and improving resource efficiency, aligning with European transport policy debates. These examples illustrate how academic research informs targeted strategies to address sustainability challenges.

The analysis also highlights the regional diversity of policy themes. In Sweden [99], has guided feasibility studies on battery swapping, supporting the digital transformation of transport systems. This reflects the region's commitment to electrifying transport infrastructure and aligning technological innovation with policy planning. In the Arab region [133], has informed policies that address environmental, technological, and economic challenges, transforming them into opportunities for sustainable development in the region. Meanwhile, research contributions in the Asia-Pacific region illustrate varied societal impacts. For instance Ref. [80], supported India's policy strategies to incentivize off-peak charging, thereby reducing peak demand stress and improving grid efficiency. This policy direction enhances EV adoption while mitigating challenges associated with power infrastructure. Likewise [84], guided Australia's Strategic Regional EV Adoption Program by providing insights into the integration of plug-in EVs with RES, reflecting the nation's focus on sustainable energy transitions.

In Spain [121], has shaped strategic frameworks for hydrogen adoption, emphasizing environmental comparisons between hydrogen-fueled vehicles and other technologies. These findings offer valuable lessons for other regions, such as Latin America, seeking to implement alternative fuel strategies. The UK has also leveraged research insights, as demonstrated by Ref. [87], which contributed to the integration of advanced energy storage and wireless charging technologies into strategic defense initiatives, underscoring clean energy's role in national logistics planning. Finally, globally impactful studies include [175], which informed long-term strategies for transitioning passenger vehicle fleets and planning global decarbonization efforts aligned with the SDGs. Similarly [65,119], have supported policies on distributed energy integration and the repurposing of EV batteries, further enhancing the sustainability of energy storage solutions.

Overall, research has had a particularly strong influence on advancing battery-related regulations and policies, including recycling, second-life applications, and life cycle assessments, highlighting the critical role of batteries in sustainable mobility and energy systems. Additionally, contributions have supported infrastructure development, such as EV charging and grid integration, and emerging areas like hydrogen fuel technologies and shared mobility systems. By addressing both technological and societal aspects, this research has significantly shaped regional and global strategies for decarbonization and sustainable development.

By addressing regional challenges and encouraging innovation, academic research has demonstrated its pivotal role in advancing sustainable mobility and energy transitions. Its societal value lies in bridging global knowledge with local applications, contributing to policies aligned with SDGs. Besides this, expanding research to underrepresented regions and underexplored themes, such as policy dimensions of optimal energy management and EV adoption challenges, will be crucial. Specific strategies in these areas can drive equitable energy transitions and inclusive progress toward global climate goals.

Having discussed the societal impact of research within the field of EVs and RES for sustainable mobility, we have effectively addressed our fourth research question. The implications of the research findings within this paper are described next.

4. Research implications

The findings presented in this study carry significant theoretical, practical, and methodological implications, which are discussed in detail below.

4.1. Theoretical implications

- Despite decades of research, the field of EVs and RES for sustainable mobility continues to expand, as evidenced by our results. This growth aligns with the global push to meet the SDGs by 2050, highlighting the critical role of sustainable mobility in achieving environmental targets.
- The increased interest in this field has led to a growing research output in journals focusing on clean energy. These include *Journal of Cleaner Production* and *Renewable and Sustainable Energy Reviews,* serving as key platforms for disseminating influential research.
- The USA, India, Italy, and Turkey have emerged as leading nations driving research and influencing this field. Their contributions, coupled with significant international collaboration, underscore the importance of global cooperation in enhancing the reach and influence of research outputs.
- Our analysis of keywords reveals a notable shift from technology-centric topics, such as "dynamic programming" and "life cycle assessment", toward broader environmental and societal issues like "climate change" and "sustainable mobility". This trend is further confirmed by the topics identified through LDA. These findings align with previous studies that emphasized a strong focus on battery-related research in earlier years [47]. The maturation of this field is evident in its influence on policy decisions also, as demonstrated by our analysis of the societal impact of research.
- One critical emerging theme in life cycle sustainability studies is battery degradation and second-life management. This trend mirrors recommendations from existing literature, which advocate for increased research on battery recycling and reuse to mitigate long-term environmental impacts. Addressing these issues is essential for achieving a sustainable life cycle for EVs and minimizing their ecological footprint.
- This study highlights the need for interdisciplinary research to bridge the gap between technological advancements, environmental science, and policy studies. As the world moves toward cleaner energy solutions and sustainable mobility, a comprehensive approach that incorporates diverse fields of study will be critical in addressing the complex challenges of the EV and RES sectors.
- Additionally, the societal impact analysis underscores the regional diversity in contributions to policy frameworks and highlights the need to evaluate research and societal impacts concurrently. Addressing underrepresented regions and emerging policy themes, such as energy management and EV adoption challenges, will be essential for tailoring strategies to specific sustainability needs.

4.2. Practical implications

- The absence of Topic 4 (optimal energy management of EVs) and Topic 5 (challenges and policies for EV adoption) from the pool of policy-cited research highlights a critical gap. This presents an opportunity for future studies to focus on the policy dimensions of these topics. Addressing these gaps could help bridge the divide between technological innovations and policy implementation, leading to comprehensive and effective policies that support sustainable energy systems and mobility solutions.
- The significant policy engagement seen in mature topics like EV charging infrastructure and life cycle sustainability demonstrates how academic research can directly influence policy frameworks. However, there remains a need for greater focus on emerging areas, which could potentially lead to new policies that enhance industry

practices and contribute to the wider adoption of sustainable technologies.

- Addressing regional disparities is key to achieving equitable energy transitions. Future research should prioritize region-specific barriers, including social acceptance, financial challenges, and infrastructural gaps, to promote inclusive progress toward sustainable mobility. Policy frameworks encouraging community-based energy systems can support sustainable EV adoption in underrepresented regions.

4.3. Methodological implications

- This study's methodology, which combines bibliometric analysis with machine learning-based topic modeling and societal impact analysis, offers a comprehensive framework for tracking the evolution of research trends and assessing research impact. The combination of bibliometric analysis and LDA topic modeling not only identifies the latest research trends but also maps the current state of the art in the field.
- More importantly, our societal impact analysis reveals contradictions between research impact and societal impact. These findings suggest that both research impact and societal impact should be evaluated concurrently to provide a more accurate assessment of the real-world implications of research within this field. This aligns with the recommendations of [39], which advocates incorporating additional datasets along with the traditional bibliometric analysis for a comprehensive evaluation of research outcomes.
- This multi-faceted methodological approach can be adopted by researchers studying other emerging technologies. It provides valuable insights into how academic output influences both theoretical inquiry and practical applications. Moreover, by incorporating societal impact analysis, future researchers can better align their work with societal needs and policy objectives, ensuring that research outputs lead to tangible benefits.

5. Research limitations

While this study offers a comprehensive analysis, several limitations must be acknowledged. First, the dataset was sourced exclusively from the Scopus database, potentially excluding relevant articles from other databases such as WoS and IEEE Xplore. As recommended in Ref. [40], future research should consider using multiple databases for a more thorough examination of the field. Additionally, this study focused solely on research and review articles published in English, thereby excluding conference papers and publications in other languages.

The second limitation relates to the bibliometric analysis conducted using the Biblioshiny tool. There is the possibility of incorrect author identification or misattribution of countries to the articles. Similarly, the topic modeling approach poses another limitation. Misassignment of articles to latent topics can occur. Manual review may suggest that certain articles fit better in different topics, yet due to the nature of topic modeling, where articles are treated as collections of words, assigning articles to one topic with hundred percent certainty is not feasible. Final topic assignments were based on the highest probability values.

Lastly, the societal impact analysis relied on the Overton database to retrieve policy citations. Some policy documents citing the articles may not have been indexed due to Overton's limitations, such as regional policy coverage imbalance. Additionally, policymakers might have used the research without formally citing it. To minimize such discrepancies, future research should consider consulting multiple databases for policy citation retrieval. Despite these limitations, we believe our study offers a robust methodological framework, providing valuable insights into the nexus of EVs, RES, and sustainable mobility.

6. Conclusion

The global pursuit of achieving the SDGs has significantly accelerated research on the nexus of EVs and RES for sustainable.

mobility. This growing field warrants a comprehensive overview to identify trends, research priorities, and areas of future interest. This paper addresses this gap by presenting a novel multi-faceted methodological framework that combines bibliometric analysis, machine learning-based topic modeling, and societal impact analysis. This approach offers a holistic understanding of research trends and the state of the art in EVs and RES studies, using data extracted from the Scopus database. Key findings include the growing research interest in EVs and RES, with the *Journal of Cleaner Production* and *Renewable and Sustainable Energy Reviews* emerging as the most impactful journals, and the United States, India, Italy, and Turkey leading in contributions. An analysis of keyword evolution reveals a shift from technology-centric terms like "life cycle assessment" to broader societal concerns such as "sustainable mobility" and "carbon dioxide". Six latent topics were identified, with technological advancements in EV charging infrastructure and renewable energy integration being the most prominent, while newer topics, such as sustainable EV adoption policies, are gaining traction. Societal impact analysis further underscores the relevance of EV and RES research, demonstrating its significant influence on policy, despite contradictions with research impact metrics. These findings provide theoretical, practical, and methodological implications, offering a guideline for future research and valuable insights for policymakers. Ultimately, this study contributes to advancing progress toward achieving SDG and SDG 13, while advocating for integrated approaches to research and societal impact evaluation.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2025.101827.

Data availability

Data is provided in Supplementary file.

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